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UNIVERSITY OF CALIFORNIA SAN DIEGO

The Detailed Environments around Distant Quasars and Advanced Techniques in Point Spread
Function Reconstruction

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Physics

by

Sanchit Sabhlok

Committee in charge:

Professor Shelley A. Wright, Chair
Professor Adrian Borsa
Professor Dušan Keres
Professor Thomas W. Murphy Jr.
Professor Karin Sandstrom

2024

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The Dissertation of Sanchit Sabhlok is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2024

DEDICATION

To Joey

EPIGRAPH

You have a right to perform your prescribed duties,
but you are not entitled to the fruits of your labor,
Never consider yourself to be the cause of results
of your activities, nor be attached to inaction.

The Bhagavad Gita

Some things you'll do for money and some you'll do for fun
But the things you do for love are going to come back to you one by one.

Love, Love, Love - The Mountain Goats

And Solskjaer has won it! ... Manchester United have reached the promised land!

Clive Tyldesley, at 92:17 Champions League Final, 1999

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I am writing this thesis in a text file on pycharm, which has been an excellent python IDE over the course of my PhD. This is not an ad. And just as I wrote that, the sentence exceeded page boundaries and I spent two minutes figuring out how to enable text wrap. I then gave up. This is what graduate school has broadly been like. Amidst this chaos, there have been a large number of people who have supported me over the last few years, professionally and personally, sometimes an amorphous mixture of the two.

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¹He has other attributes, but you know, the rule of 3 for comedy.

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³Sports stat: The San Diego Padres are 2-5 when Mayia and I go see a game at Petco Park. Maybe we should stop going.

got exposed to computers as very young kids and we learned to use it maybe before a lot of kids our age. In many ways, this thesis is a culmination of the education they started, and for this I will forever be grateful. I would also like to thank my brother because we don't really talk a lot unless it is about Manchester United or video games, and when we hang out we just have a good time or play video games, and we both don't like too many questions before our morning caffeine. He really gets it. Lastly, thanks to Joey for the many, many years of memories of being a really big, dumb dog who would run his head into the fridge because he was too excited to go for a walk, or when he ate three days worth of food at once and passed out, or when he *insisted* to go out for a walk in a thunderstorm and come back in after taking one step outside into the pouring rain. He was a very good boy.

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PUBLICATIONS

“Oxygen Abundance Throughout the Dwarf Starburst IC 10 with KCWI” Maren Cosens, Shelley A. Wright, Karin Sandstrom, Norman Murray, Lee Armus, Jordan N Runco, Sanchit Sabhlok, and James Wiley, Submitted to *Astrophys. J.*.

“Liger at W. M. Keck Observatory: Overall Design and Fabrication Status” Shelley A. Wright, Tucker Jones, James Larkin, Renate Kupke, Marc Kassiss, Aaron Brown, David Andersen, Lee Armus, Bryson Cale, Maren Cosens, Tuan Do, Chris Fassanacht, Deanne Fisher, Michael Fitzgerald, Andrea Ghez, Jenny Greene, Takeru Hayashi, Aurelien Hees, Jessie Hirtenstein, Chris Johnson, Jacqueline Keane, Patrick Kelly, Evan Kirby, Quinn Konopacky, Evan Kress, Jessica Lu, Jim Lyke, Jérôme Maire, Rosalie McGurk, Anne Medling, Maxwell Millar-Blanchaer, Quinn Minor, Reston Nash, Anna Nierenberg, Naveen Reddy, Michael Rich, Jean-Baptiste Ruffio, Nils-Erik Rundquist, Sanchit Sabhlok, David Sand, Ryan Sanders, Karin Sandstrom, Alice Shapley, Ji-Man Sohn, Arun Surya, Tommaso Treu, Eric Wang, Kanaka Warad, Bob Weber, James Wiley, Peter Wizinowich, Michael Wong, Sherry Yeh, and Andrea Zonca, Submitted to *Proceedings of SPIE*, 2024.

“On-axis point spread function reconstruction performance validation for Keck NIRC2” Sabhlok, Sanchit; Wright, Shelley A.; Lu, Jessica R.; Terry, Sean; Wizinowich, Peter; Neichel, Benoit; Kuznetsov, Arseniy. Manuscript in preparation for submission.

“Circumgalactic Environments around Radio-loud quasars at Redshift ~ 2 ” Sabhlok, Sanchit; Wright, Shelley A.; Vayner, Andrey; Simonaitis-Boyd, Sonata; Murray, Norman; Armus, Lee; Cosens, Maren; Wiley, James; Manuscript in preparation for submission.

“Circumgalactic Environments around Distant Quasars 3C 9 and 4C 05.84” Sabhlok, Sanchit; Wright, Shelley A.; Vayner, Andrey; Simonaitis-Boyd, Sonata; Murray, Norman; Armus, Lee; Cosens, Maren; Wiley, James; Kriek, Mariska 2024, *Astrophys. J.*, 964, 84. doi:10.3847/1538-4357/ad2350.

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“Fifteen Years of Millimeter Accuracy Lunar Laser Ranging with APOLLO: Data Reduction and Calibration ” Colmenares, N. R.; Battat, J. B. R.; Gonzales, D. P.; Murphy, T. W.; Sabhlok, S. 2023, PASP, 135, 104503. doi:10.1088/1538-3873/acf787 2023, PASP, 135, 104504. doi:10.1088/1538-3873/aceb2f

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“Kinematics and Feedback in H II Regions in the Dwarf Starburst Galaxy IC 10” Cosens, Maren; Wright, Shelley A.; Murray, Norman; Armus, Lee; Sandstrom, Karin; Do, Tuan; Larson, Kirsten; Martinez, Gregory ; Sabhlok, Sanchit; Vayner, Andrey; Wiley, James 2022, Astrophys. J., 929, 74. doi:10.3847/1538-4357/ac52f3

FIELDS OF STUDY

Major Field: Physics (Specialization in Astronomy)

ABSTRACT OF THE DISSERTATION

The Detailed Environments around Distant Quasars and Advanced Techniques in Point Spread
Function Reconstruction

by

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Doctor of Philosophy in Physics

University of California San Diego, 2024

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Galaxies evolve over cosmic times in tandem with their larger environments ($O(10 - 100$ kpc)), which are influenced by galactic processes such as star formation and outbursts from an accreting supermassive black hole, also known as an Active Galactic Nucleus (AGN). The circumgalactic medium (CGM) is a reservoir of gas that surrounds all galaxies and is the recipient of galactic scale outflows, driven by either star formation or AGN activity, but also supplies the gas needed by the host galaxy to sustain star formation. The larger environment also impacts the CGM brightness, kinematics and metallicity, due to companion galaxy subhalos and mergers, thus offering a unique opportunity to observe the interplay between galactic and environmental

processes.

Our multi-wavelength dataset of seven distant ($z \sim 2$) radio-loud quasars allows us to investigate these interactions. Using data from W. M. Keck Observatory and archival data from the Very Large Array and ALMA radio facilities, and Hubble and Spitzer Space Telescopes, we observe outflows driven by the AGN, spatially resolved host galaxy emissions, CGM $\text{Ly}\alpha$, He II, and C IV emission and the influence of companion galaxies. We find evidence for a two component CGM model, where the inner CGM is directly influenced by the quasar host galaxy, whereas the outer CGM is influenced tidal interactions with companion galaxies and the turbulent motion of the gas.

Adaptive Optics (AO) has enabled higher angular resolution observations from the ground. Understanding the Point Spread Function (PSF) of the telescope limits our ability to disentangle phenomena at small angular resolution. A forward modelled PSF reconstruction represents the “pinnacle” of ground-based observational astronomy, since true knowledge of the observational PSF will reduce uncertainties in photometry and astrometry for all science cases. We investigate a PSF model for the NIRC2 instrument using AO telemetry data on Keck telescope and validate its performance using on-sky data. As a special application, we also investigate the PSF of the Corner Cube Retroreflectors left on the moon by Apollo astronauts, to investigate the performance degradation of these devices over the last 50 years due to dust deposition on their surfaces.

Chapter 1

Introduction to Galactic Environments

1.1 Background

This thesis discusses the importance of the **Circumgalactic Medium (CGM)** and the larger environment in the growth and evolution of massive galaxies to present day since the **Big Bang**. Before diving in, it is useful to briefly describe the constituents of a typical galaxy in the present-day universe. Galaxy evolution as a topic has evolved closely alongside developments in stellar structure and cosmology by its very nature. The topic can be traced back to the Great Debate between Harlow Shapley and Heber Curtis, who argued whether the Milky Way constitutes the entirety of the universe (Shapley & Curtis, 1921). The debate was largely resolved when Edwin Hubble studied Cepheid variables in Andromeda galaxy and established their extragalactic origin (Hubble, 1925). Figure 1.1 shows the Andromeda galaxy. Like the Milky way, Andromeda is a spiral galaxy, with the blue components of the spiral arms representing star forming regions where the gas in the **Interstellar Medium (ISM)** is readily converted to newborn stars. Like most galaxies in the universe, it is home to a **Supermassive Blackhole (SMBH)** at its center (Richstone et al., 1998). The dark lanes between the arms are dim due to the presence of interstellar **dust**. Lastly, the galaxy is surrounded by a halo of faint and diffuse gas, known as the CGM, which extends as far out as the invisible **Dark Matter (DM)** halo.

Andromeda is fairly typical for a spiral galaxy, and by mass is composed approximately 83% dark matter, with only $\sim 16\%$ of the mass being made up of visible matter. For Andromeda,

the DM halo is approximately 10 times the size of the stellar disk, which is approximately 46 kpc in diameter. While most of the baryonic mass is in the form of stars ($\sim 10^{11} M_{\odot}$), the total mass of the gas in the ISM is $\sim 10\%$ of the stellar mass and the total mass in the form of dust is about 1% the mass of the ISM. These fractions are typical for a spiral galaxy of Andromeda's size in the present day universe. While the dust constitutes a small fraction of the total mass, it is important to the study of galaxy evolution for a number of reasons. Firstly, dust is heated by absorbing radiation from luminous sources such as stars, and this heat is re-radiated as infrared radiation, making it an important component of the galaxy's energy budget. Secondly, the dust contains the majority of **metals** produced in the galaxy by star formation. In the astronomical context, metals are any elements heavier than Hydrogen or Helium. While this sounds quite absurd and arbitrary, this is intrinsically linked to the Big Bang. The majority of matter in the universe after the Big Bang was either in the form of Hydrogen or Helium, and all the other elements have subsequently been produced inside stellar cores, accreting blackholes, or mergers of a pair of neutron stars or black holes. Thus, metals represent the elements that have been produced as a direct or indirect result of star formation in the universe, and more importantly, are directly linked to the cosmological evolution of the universe.



Figure 1.1. Our nearest major galaxy Andromeda gives an excellent chance to view the many components of a typical galaxy. While the stellar disk, ISM and dust are readily visible in this image, the SMBH, CGM and DM halos are not. Nevertheless, the evolution of the galaxy is governed by all of the aforementioned components. Also visible are two of Andromeda's satellite galaxies M32 (left of the central bulge) and M110 (on the bottom right). (Photo by Bryan Goff on Unsplash)

While we have discussed galactic components for Andromeda, galaxies come in all shapes and sizes. In addition to Spiral, galactic morphologies can be **Elliptical** or **Irregular**, with spiral galaxies forming 45% of the total galaxy fraction, ellipticals 25% and the remaining classified as Irregular in the present day universe (Tempel et al., 2011). These morphological differences originate from differences in the constituents of the galaxies as spiral galaxies are rich in ISM gas and dust, whereas ellipticals are typically depleted of both. As a result, spiral galaxies continue to form stars and appear blue due to a young stellar population, whereas ellipticals contain an aging stellar population which makes them redder in appearance.

So far, we have only discussed the constituents of a galaxy as seen in the present day. In

order to discuss how things evolve across cosmological timescales, we first need to describe the currently accepted model of cosmology, widely accepted to be well described by the Λ **Cold Dark Matter** (Λ CDM) paradigm. According to this picture, the universe started with the Big Bang 13.6 billion years ago (Hinshaw et al., 2013; Planck Collaboration et al., 2016). The **Cosmological principle** states that the universe, at large enough length scales, is isotropic and homogeneous. As a corollary, this gives us the definition of our **Local Universe**, which is the size of our immediate neighbourhood (around the Milky Way galaxy), where this principle *just* begins to be true. While the universe is largely isotropic and homogeneous in its matter distribution at large enough length scales, gravitational instabilities originating from quantum fluctuations immediately after the big bang have grown into the large scale structures of galaxies we see today. The total mass-energy content of the universe determines the evolution over cosmological timescales and there are three key pieces of the puzzle to take into account. First, the visible baryonic matter, which only constitutes $\sim 5\%$ of the total energy density of the universe in the present day, the dark matter, which constitutes 26% of the energy density and lastly **Dark Energy (DE)**, which is the dominant component of the energy fraction of the universe today at 69%, usually represented by the cosmological parameter Λ as it occurs in Einstein's field equations. These fractions are not constant, but evolve across cosmic times. For example, we know that in the past the universe was matter dominated, i.e. the energy fraction was largely dominated by visible and dark matter instead of dark energy.

Edwin Hubble conclusively showed the expansion of the universe is accelerating (Hubble, 1929), and present day cosmological observations support this hypothesis (Planck Collaboration et al., 2016). There is a subtlety that needs to be discussed here: *What is expanding?* While the natural thing is to assume the universe is an infinitely large empty “space” that all the galaxies are expanding *into*, what cosmological observations show us is that the *space itself is expanding*. This expansion of the universe is called the **Hubble Flow**. This has really interesting (and strange) consequences. For example, if a photon is emitted in one part of the universe and starts to travel, because the space itself is expanding, this results in the wavelength of the photon getting

progressively longer as it travels. As the wavelength always gets longer or “redder”, light from extremely far away galaxies appears to be **redshifted** relative to the **rest frame** of the emitter. This is called the **Cosmological Redshift (z)**. The amount by which light redshifts depends on the cosmological parameters of the universe. So, while we can use the observed redshift to calculate the distance to a source, this requires the cosmological parameters (and by extension, a cosmological model) as inputs. Astronomers tend to discuss the age of the universe in terms of the redshifts and not necessarily time. This is because while new cosmological theories may change the distance of a source, the redshift as a measured quantity remains the same.

The accelerated expansion of the universe is determined by the cosmological parameters, but this alone is not sufficient to describe how the large scale structure of the universe evolves. The reason being that the large scale structure intrinsically depends on the *nature* of Dark Matter itself. The large scale structure is seen in the local universe in the form of groups and clusters of galaxies, but the question is whether the galaxies formed first and accumulated afterwards to form the large structure (bottom-up construction) or whether cluster sized dark matter aggregates fragmented into smaller substructures (the top-down approach). Two categories of Dark Matter can thus be identified, namely “Cold” Dark Matter (CDM), which has non relativistic velocities and negligible self interaction and “Hot” dark matter (HDM) which has relativistic velocities and self interaction. Due to the smaller velocity distribution of CDM, it is possible to form galactic sized halos earlier in the universe than it is for HDM. Since we observe massive clusters at low redshifts but these get progressively rarer as we look at higher redshifts, the observational evidence supports the hypothesis that DM halos around galaxies are largely composed of Cold Dark Matter (Overzier, 2016).

I will now switch from a general introduction to the topic and discuss the key physics behind Active Galactic Nuclei, CGM and the larger environment around galaxies as relevant for this thesis.

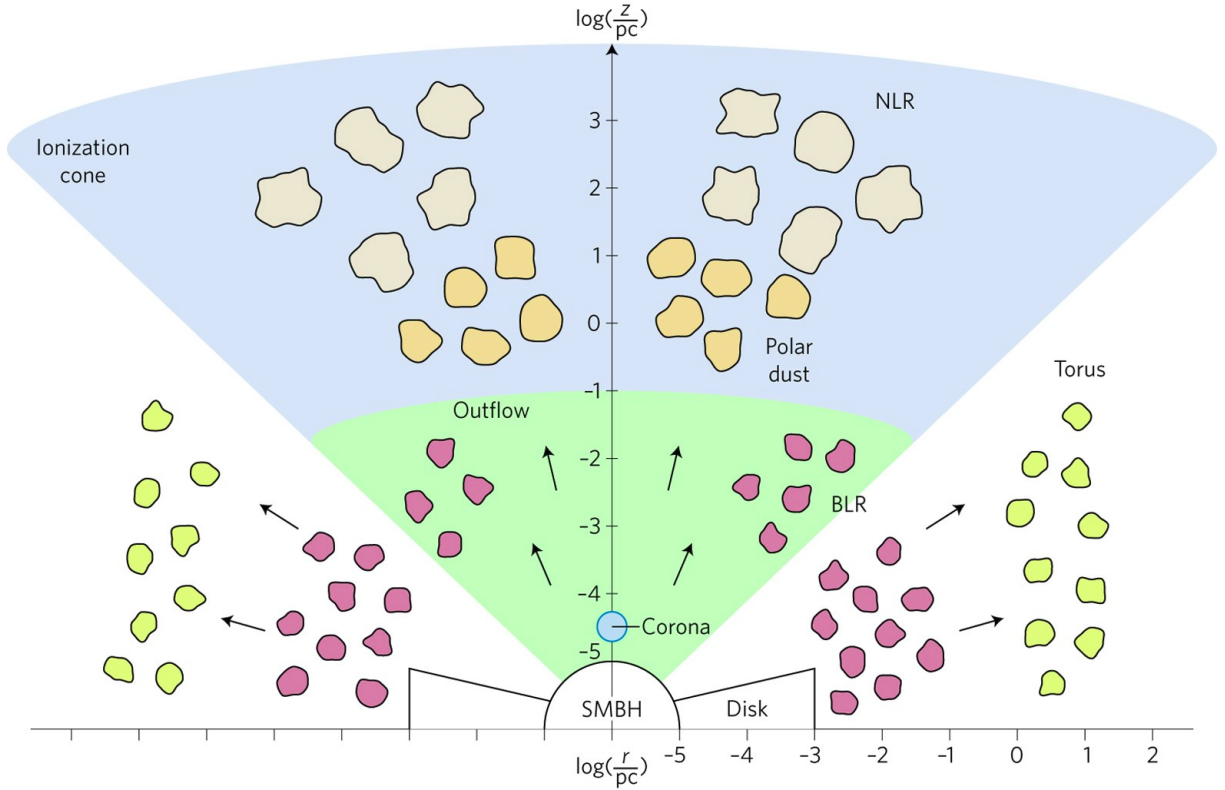


Figure 1.2. The figure shows a typical AGN and the expected structure around it as inferred from observations. The figure shows the relevant length scales of various structures and illustrates how different viewing angles can drastically change the observed electromagnetic radiation seen from an AGN. Also note that the axes are logarithmic, illustrating the importance of physical processes occurring at different length scales. Figure taken from Ramos Almeida & Ricci (2017).

1.1.1 Active Galactic Nuclei

Most galaxies are now widely accepted to harbor **Supermassive Blackholes (SMBHs)** at their center. SMBHs accrete matter in bursts and release vast amounts of energy across the electromagnetic spectrum, turning their galactic centers into what we call **Active Galactic Nuclei (AGN)**. This energy release is accompanied by radiation and pressure feedback, which is initially local but can extend into the galactic environment, potentially suppressing star formation and growth of the galaxy's stellar masses. Figure 1.2 shows a schematic for a typical AGN environment.

The AGN environment is comprised of an accreting SMBH, the surrounding accretion

disk and a resulting Corona along the poles of the SMBH. Due to the intense radiative output of the AGN along the polar direction within the **Ionization cone** of the AGN, no dust can sublimate and the radiation escapes into the ISM of the host galaxy, and if powerful enough, the CGM of the host galaxy. Along the equatorial axis, due to a smaller radiative output, beyond a certain distance interstellar dust can sublimate and this creates the **Dust Torus** around an AGN. Clouds of gas in the immediate vicinity of the AGN travelling at high velocities create a **Broad Line Region**, which is named because emission from this region is believed to create the broad emission lines seen around AGNs. At a greater distance, gas clouds are illuminated by the AGN and emit recombination radiation, but are no longer travelling at high velocities, thus the lines seen from this region are narrower, hence called the **Narrow Line Region (NLR)** of the AGN.

In addition to a large radiative output, AGN can also drive large scale collimated winds, which at large scales appear as jets which emit synchrotron radiation at nearly all wavelengths. When seen in radio emission, these are called **Radio Jets**. While all AGNs are assumed to contain the same components, not all AGNs emit radio waves, giving rise to the **Radio-loud** or **Radio-quiet** dichotomy. Today, we know that approximately 10% of observed AGN are radio-loud, while the majority are radio-quiet.

Lastly, the **Unified AGN Model** explains the diversity in observed colors, luminosities and emission line properties of the AGN (Urry & Padovani, 1995). The model proposes that the appearance of an AGN is largely determined by the viewing angle of the observer. An observer looking along the equatorial axis is looking directly through a dust torus and so the shorter wavelengths from the AGN are largely extinguished, making it appear red and largely devoid of broad line emission. On the other hand, an observer placed along the polar axis within the ionization cone will observe the emission from the accretion disk, BLR and NLR. In fact, the first AGN were detected using the continuum emission from the accretion disk and due to the compact nature of the AGN and the distance from our galaxy, appeared as point sources in images just as stars do but with a completely different spectrum. These were named “quasi-stellar objects”, eventually shortened to **Quasars**.

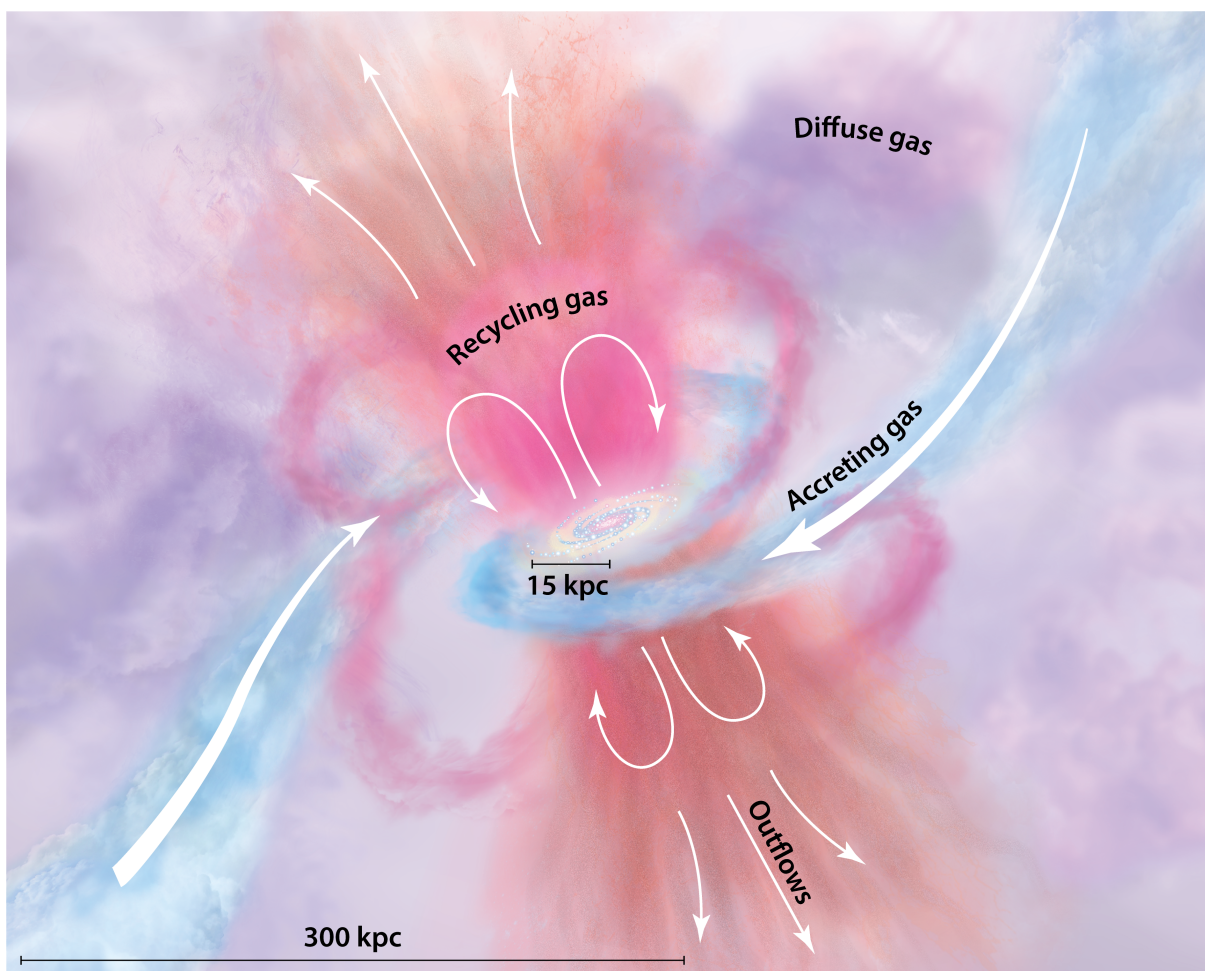
1.1.2 The Circumgalactic Medium

The Circumgalactic Medium (CGM) is a reservoir of gas surrounding most galaxies that extends from the stellar component of the galaxy out to the virial radius of the dark matter halo. The CGM is diffuse: Gas densities in the CGM can be significantly smaller than those in the ISM. Figure 1.3 shows the typical size of a CGM halo and illustrates the relevant interactions with the host galaxy. The CGM is multiphased: it consists of cold (10^4 K), warm ($10^{5-5.5}$ K) and hot (10^6 K and above) components. The multiphased nature of the CGM is partly caused by galactic processes, such as galactic scale outflows, driven by star formation or AGN and AGN photoionization, that can ionize and heat the gas surrounding the host galaxy. Far away from the host galaxy, the kinematics of the CGM are largely dominated by gas turbulence and interaction with Intergalactic Medium (IGM). The CGM is an intermediary between the galaxy and its larger environment, thus it co-evolves with the galaxy *and* the larger environment.

The CGM influences the growth and evolution of the host galaxy in a number of substantial ways. The ISM in a galaxy can only sustain star formation for a limited amount of time (τ_{depl}) before running out of fuel. Yet, star forming galaxies sustain star formation for significantly longer timescales. The additional gas required for this star formation must come from the CGM. In a similar vein of thought, powerful star formation events (Starbursts) or AGN activity can drive galactic scale outflows, which end up in the circumgalactic medium. Depending on the energy and kinematics of the outflow, these can potentially “rain down” on the host galaxy or be powerful enough to be integrated into the CGM. In the latter case, since the outflows consist of the host galaxy ISM, they likely transport metals formed during star formation out of the galactic ISM and enrich the CGM. Thus, the metallicity of a galaxy’s CGM is influenced by the cumulative star formation history of the host galaxy.

An excellent summary of these ideas is quoted here from Tumlinson et al. (2017) -

How galaxies acquire, eject, and recycle their gas are core issues in galaxy evolution, on par with how they evolve in their shapes and how star formation works. To a large extent these gas flows *are* galaxy evolution. The CGM is a



 Tumlinson J, et al. 2017.
Annu. Rev. Astron. Astrophys. 55:389–432

Figure 1.3. A schematic of a typical circumgalactic environment showing the size of a typical CGM halo relative to the stellar component of the galaxy and the various feedback processes involved. Figure taken from Tumlinson et al. (2017).

main venue for these flows: it is potentially the galactic fuel tank, waste dump, and recycling center all at the same time.

Thus, studying the CGM can reveal details about the star formation history of a host galaxy, while also revealing evidence of any ongoing feedback activity, be it star formation or AGN driven outflows or accretion of gas onto the stellar component of the galaxy.

1.1.3 Galactic environments

The CGM in turn is not an isolated gas reservoir, but part of the larger cosmic web, connecting galaxies and dark matter halos with filamentary structures of diffuse gas, with typical gas densities of $O(10^{-3} \text{ cm}^{-3})$. Over larger scales, the CGM transitions into the Inter Galactic Medium (IGM) once the gas motion is no longer dominated by the host galaxy's dark matter halo. If the galaxy is part of a larger cluster environment, the CGM transitions into the Intra Cluster Medium (ICM), potentially containing several galaxies, and resides in dark matter subhalo part of a larger dark matter halo.

The nature of CGM, IGM and ICM is inextricably linked to the growth and evolution of large scale structure in the universe. The large scale structure according to the Λ CDM paradigm is assembled “Bottom-up”, i.e. the smallest structures (galaxies) form first as a result of gravitational collapse, before assembling to form clusters of galaxies, which are the largest gravitationally bound structures we see today. Figure 1.4 shows the Coma Cluster, a cluster of over 1000 galaxies approximately 99 Mpc away from Earth ¹. In the process of forming these large structures, the gas content inside these clusters is *virialized*, i.e. as gas falls into the gravitational potential wells of these massive structures, it heats up due to the conversion of the initial potential energy into kinetic energy until the gas motion is well described by the Virial theorem. Virialization results in heating up the IGM gas to extremely hot temperatures (10^6 K), which is high enough for the gas to emit X-rays. In this environment, smaller galaxies either merge into larger galaxies or get stripped of their gas as a result of shock heating from interacting

¹<https://www.nasa.gov/missions/roman-space-telescope/wfirst-will-add-pieces-to-the-dark-matter-puzzle/>



Figure 1.4. A Hubble Space Telescope image of the Coma Cluster, approximately 99 Mpc away. Image Credit: NASA, ESA, and J. Lotz and the HFF Team (STScI)

with the hot IGM when falling into the central cluster potential well.

The environment can have an outsized impact on the growth and evolution of a galaxy, as the larger environment provides gas for star formation and galaxy growth, but can also quench the star formation in a galaxy. The environment is the recipient of galactic outflows and over cosmic timescales accumulates products of star formation. A cluster environment also provides opportunities for mergers with companion galaxies which can grow the stellar and dark matter mass of the host galaxy, but for smaller galaxies, the tidal interactions can strip away gas from the CGM subhalos as well as the ISM of the galaxy. Thus, the ultimate fate of a galaxy is not determined solely by galactic processes but is largely dependent on the size, luminosity and mass relative to the surrounding environment. This is especially true when studying the CGM, since the CGM is the boundary interface separating the stellar component of a galaxy from the larger environment and thus plays an important role in regulating environmental interactions.

1.1.4 The role of simulations in studying galaxy evolution

It is important to emphasize the importance of complimentary approaches to studying the CGM and the larger environments. While the CGM can be studied observationally using emission or absorption lines, simulations have also investigated the importance of the CGM in galaxy evolution (Kereš et al., 2005). However, simulations have fundamental issues replicating physics across a vast range of length scales due to limited numerical resolution. In an attempt to overcome this limitation, simulations utilize subgrid prescriptions for Molecular Clouds ($O(10-100 \text{ pc})$), supernovae or AGN (Hopkins et al., 2014, 2018). On larger length scales, cosmological simulations simulating Dark Matter halo properties encounter similar issues with resolving the baryonic components of the host galaxies, implementing subgrid models for the multiphase ISM since the resolution at these length scales is really low (Weinberger et al., 2017; Pillepich et al., 2017). Recently, multiple simulations have studied a numerically resolved model of the CGM, investigating the implications of enhanced spatial resolution on the convergence of observable properties of the CGM (van de Voort et al., 2019; Peebles et al., 2019; Hummels et al., 2019; Bennett & Sijacki, 2020; Gronke et al., 2022). They find that enhanced spatial resolution increases total H I covering fraction, increased cold gas content and increased inflowing gas mass flux. These simulations also show that cloud sizes are still not converged and improving spatial resolution could allow for larger observed values of cold gas mass (Cantalupo et al., 2014). Additionally, spatial resolution is important to match the observed distribution of absorber properties (O’Meara et al., 2015) and can affect the predicted total luminosity of $H\alpha$ by a factor of two and by an order of magnitude for other lines such as C III and C IV (Corlies et al., 2020). To clarify this, it is critical to complement our understanding of galaxy evolution gained from simulations with multi-wavelength observations of individual sources to connect the dots between physical processes occurring across a large dynamical range of length scales.

1.2 Recent Work on CGM and Galactic Environments

On the Keck Telescopes, the **Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE)** has enabled targeted surveys such as the MOSFIRE Deep Evolution Field Survey (MOSDEF) (Kriek et al., 2015a) and the Keck Baryonic Sky Survey (KBSS) (Steidel et al., 2014) which build upon the success of the Sloan Digital Sky Survey (SDSS) (York et al., 2000) by extending our understanding of stellar evolution, metallicities and star formation to higher redshifts. Instruments such as the **Keck Cosmic Web Imager (KCWI)** (Morrissey et al., 2018) on Keck and the **Multi Unit Spectroscopic Explorer (MUSE)** (Bacon et al., 2010) on the **Very Large Telescope (VLT)** have come online to present compelling pictures of the CGM surrounding galaxies at $1.5 < z < 4$. Prior to the advent of these instruments, narrow band imaging revealed some of the first observed $\text{Ly}\alpha$ blobs (Hu & Cowie, 1987; Steidel et al., 2000; Heckman et al., 1991b), with follow up long slit spectroscopy revealing spatially extended emission 10s of kpc away (Heckman et al., 1991a). Theoretical work indicated extended $\text{Ly}\alpha$ emission was linked to the multiphase structure of infalling CGM gas (Haiman & Rees, 2001). Additionally, these nebulae were observed in the vicinity of quasars since surface brightness of the nebulae is boosted by the fluorescence emission due to recombination radiation (Cantalupo et al., 2005; Kollmeier et al., 2010). The advent of the Integral Field Spectrographs (IFS) KCWI and MUSE means that instead of narrow band imaging followed by long slit spectroscopy, we can now spatially map out the emission and kinematics of such nebulae around potential targets with greater ease. Borisova et al. (2016) identified 17 radio-quiet quasars in addition to 2 radio loud quasars with extended $\text{Ly}\alpha$ emission using MUSE/VLT finding cold gas ubiquitous around these sources within 50 kpc at $3 < z < 4$. Arrigoni Battaia et al. (2019) identified a sample of 61 $\text{Ly}\alpha$ nebulae around quasars, 15 of which are radio loud, with MUSE/VLT at $z \sim 3$, studying the morphology and sources of ionization for the nebulae. Cai et al. (2019) studied a sample of 16 ultraluminous Type 1 QSOs around $z \sim 2$ using KCWI and suggested that cool gas mass decreases going from $z \sim 3$ to $z \sim 2$. Recent works have investigated the role of

CGM around radio-loud AGN using $\text{Ly}\alpha$ spectroscopy finding evidence for correlation between $\text{Ly}\alpha$ detection and the extent of the radio source (Shukla et al., 2022) and further evidence of companion galaxies around these sources (Vayner et al., 2023). While these observations have established the ubiquity of $\text{Ly}\alpha$ nebulae and their prevalence around quasars, separating the role of the host galaxies in the evolution of these nebulae from their surroundings requires us to study them in tandem with a survey of the larger environment.

Tracing the origins of the most massive clusters remains challenging at high-redshift since identifying gravitationally bound structures requires spectroscopic confirmation. The Visible Multi-Object Spectrograph (VIMOS) Ultra Deep Field (UDF) Survey (Le Fèvre et al., 2005) surveyed 0.61 squared degrees of the night sky using the VLT and identified several large protoclusters of galaxies (Cucciati et al., 2014; Lemaux et al., 2014; Cucciati et al., 2018). However, in the absence of a large spectroscopic survey, searches for these structures need to be conducted by spectroscopic follow-up on imaging data sets. Wylezalek et al. (2013) used *Spitzer* imaging to search for galaxy clusters around radio-loud AGN at $1.3 < z < 3.2$. This study observed an overdensity of sources around these AGN with *Spitzer* Infrared Array Camera (IRAC) imaging, suggesting that radio-loud quasars can be used to look for high redshift protoclusters. These protoclusters are likely to be progenitors of the Brightest Cluster Galaxies (BCG) found at the centers of the largest clusters observed in present-day.

Since the CGM is a large, diffuse, multiphase medium, having as much information about the system being studied would help decipher the impact of different processes on the CGM. Observing the CGM around radio-loud quasars could potentially reveal signatures of companion galaxies, residing in the quasar host galaxy’s dark matter halo. Previous detection of large C IV and He II emission around quasars have provided valuable information regarding the ionizing source of the gas, which has been attributed to star formation (Villar-Martín et al., 2007) and quasar ionization (Falkendal et al., 2021). C IV and He II lines are smaller in extent than $\text{Ly}\alpha$ emission and found to be embedded within the CGM halos of the host galaxy (Villar-Martín et al., 2003; Vernet et al., 2017). Thus, mapping the extent and relative strengths of these lines

with respect to $\text{Ly}\alpha$ may provide valuable insight regarding the ionizing source powering the emission.

1.3 The importance of Quasars, Radio-loud galaxies and a multiwavelength dataset

The study of galaxy evolution is complicated because it is influenced by a host of physical processes across a large range of length scales (from AU for stellar processes, parsecs (pc) for star formation processes, and pc to kpc for galactic processes) and time scales (Myr to Gyr), to account for the observed properties of the galaxy population as observed today. A galaxy cannot continue to grow indefinitely or with unfettered speed due to the presence of regulatory feedback processes. SMBH masses show a tight correlation with the bulge velocity dispersion across three orders of magnitude, implying that galaxies co-evolve with their SMBHs (Kormendy & Ho, 2013). AGN are not the only sources of galactic scale feedback in the galaxy. Star formation activity can result in formation of massive stars, which can drive galactic scale outflows out of the galaxy (Madau & Dickinson, 2014). The CGM supplies the galaxy with a steady supply of gas over billions of years in order to sustain star formation, in the absence of which a galaxy's gas supply would run out and star formation would be quenched within a few Gyrs (Tumlinson et al., 2017). Thus, a complete picture of galaxy evolution requires an interplay of the AGN physics, galactic baryonic processes, ISM conditions, star formation, the gas conditions in the larger CGM surrounding the galaxy and the impact of potential mergers or satellite galaxies on the evolution of the central host galaxy.

To study the growth and evolution of galaxies from $z \sim 2$ to present day, we have constructed a multiwavelength dataset, which captures important processes at the relevant length scales. The galaxies chosen for this sample are all part of the "Quasars Unveiled through high Angular Resolution Techniques" (QUART) Survey. The QUART survey was initially designed to study Quasar host galaxies using the "**OH-Suppressing Infra-Red Imaging Spectrograph**"

(**OSIRIS**) on Keck, an **Adaptive Optics (AO)** enabled integral field spectrograph (Vayner et al., 2016, 2017, 2021b,c). All sources are redshift $z \sim 2$ radio-loud galaxies with compact jets detected in the 3rd, 4th or 7th Cambridge radio catalogs (Smith et al., 1976; Pilkington & Scott, 1996; McGilchrist et al., 1990). Selection of radio loud quasars to study the CGM around the host galaxies offers several advantages. Firstly, the quasar illuminates the CGM and boosts $\text{Ly}\alpha$ fluorescence making the observation of large $\text{Ly}\alpha$ nebulae around these sources easier. Secondly, in an idealized version of the unified AGN model, the orientation of the radio jet is expected to be perpendicular to the accretion disk and the surrounding dusty torus in an AGN. Since $\text{Ly}\alpha$ is expected to be primarily emitting due to quasar photoionization and scattering of light from the AGN and/or the host galaxy, the jet provides a valuable reference orientation against which $\text{Ly}\alpha$ morphology can be compared. Lastly, literature indicates that radio-loud AGN at high redshift are some of the rarest objects in the universe and that they preferentially reside in protocluster environments (Rigby et al., 2011; Wylezalek et al., 2013; Hatch et al., 2014; Lacy & Sajina, 2020). Thus, selection of bright radio-loud quasar hosts allows us to study $\text{Ly}\alpha$ nebulae, and enhances the possibility of detecting companion galaxies around the quasar host galaxies, which can in turn be used to study the importance of larger environments and potential mergers.

1.4 Thesis Outline

In Chapter 2, I discuss my work on the environments around radio-loud quasars 3C 9 and 4C 05.84. I discuss their immediate circumgalactic environments and the identification of their companion galaxies and the corresponding CGM subhalos.

In Chapter 3, I discuss the circumgalactic observations of the entirety of the QUART sample, and compare them to previous observations of the quasar host galaxies and studies of $\text{Ly}\alpha$ nebulae in the literature, highlighting the key distinguishing features of our sample, highlighting potential causes for these differences.

Chapters 4, 5 and 6 discuss my work on Point Spread Function Reconstruction, with

Chapter 4 serving as an introduction and the other chapters describing the two individual projects I have worked on. These will be outlined in greater detail in Chapter 4.

Lastly, Chapter 7 summarizes the results presented in this thesis and outlines possible avenues for future work.

Chapter 1, in part, is a reprint of the material as it appears in *Astrophys. J.*, and the text has been suitably modified for the purposes of this dissertation, Sabhlok, Sanchit; Wright, Shelley A.; Vayner, Andrey; Simonaitis-Boyd, Sonata; Murray, Norman; Armus, Lee; Cosens, Maren; Wiley, James; Kriek, Mariska 2024, *Astrophys. J.*, 964, 84. doi:10.3847/1538-4357/ad2350. The dissertation author was the primary investigator and author of this paper.

Chapter 2

Circumgalactic Environments around Radio-loud Quasars 3C 9 and 4C 05.84

Recent theoretical and observational studies have highlighted the necessity and utility of studying the internal properties of galaxies in conjunction with their larger environment and underlying circumgalactic medium (CGM). The complex interplay between star formation (Madau & Dickinson, 2014), metallicity, dust, active galactic nucleus (AGN) and the subsequent growth of supermassive black holes (SMBH) (Kormendy & Ho, 2013), plays a critical role in a galaxy’s growth. Studying the connection and role of the CGM in the growth of galaxy progenitors is observationally challenging since it requires investigating the underlying physics that operates across a wide range of length scales (parsecs to 100 kiloparsecs) and time scales (Tumlinson et al., 2017). Additionally, it requires understanding the impact of potential mergers or satellite galaxies on the evolution of the central host galaxy, which is largely dominated by the gravitational interaction of dark matter halos in which galaxies reside (Overzier, 2016).

In this chapter, we present new results of two well studied radio-loud quasars, 3C 9 ($z = 2.02$) and 4C 05.84 ($z = 2.32$) using new observations in conjunction with a wealth of ancillary data, described in detail in Section 2.1. Our targets provide a unique opportunity to study the interplay of galactic outflows, radio jets, CGM, and companion galaxies.

This chapter is organized as follows. In section 2.1, we describe the target selection, ancillary data and observations. In section 2.2, we discuss the data reduction techniques employed. In section 2.3, we look at the PSF subtracted $\text{Ly}\alpha$, He II and C IV emission around the quasars. In section 2.4 we discuss the confirmed spectroscopic protogroup/protocluster members in the larger environments around these quasars. In section 2.5, we discuss our findings, considering the impact of the environment on the CGM, sources of ionization powering the nebulae, the mass growth of the two quasar systems, and the inner and outer CGM model as applicable to our observations. We summarise our findings in section 2.6.

2.1 Target Selection

Herein, we present new results on two sources, radio-loud quasars 3C 9 ($z=2.02$) and 4C 05.84 ($z=2.32$). These quasars as part of the "Quasar hosts Unveiled by high Angular Resolution Techniques" (QUART) survey (Vayner et al., 2017, 2021b,c) initially selected for observations with Keck "OH-Suppressing Infra-Red Imaging Spectrograph" (OSIRIS) (Larkin et al., 2006) and the facility laser-guide star adaptive optics system (LGS-AO). 3C 9 is one of the most luminous sources in the 3C radio catalog. Bridle et al. (1994) first observed the detailed radio jet and lobe structure around the quasar using deep VLA observations, whereas Wilman et al. (2000) first detected extended emission lines around the quasar. Chandra observations of 3C 9 revealed extended X-ray emission from the quasar with two sidelobes aligned with the radio lobes observed using VLA. 4C 05.84 was first identified by Gower et al. (1967) as a radio source. Barthel & Miley (1988) carried out detailed radio observations establishing the extent and geometry of the radio jet and the spectral index for the quasar. Barthel et al. (1990) measured the redshift of the source as 2.323 based on an average of observed emission lines ($\lambda_{\text{Ly}\alpha} = 1215.67$; $\lambda_{\text{CIV}} = 1549.06$; $\lambda_{\text{CIII}} = 1908.73$). Heckman et al. (1991b) carried out deep optical imaging of both quasars and detected extended $\text{Ly}\alpha$ nebulae around both 4C 05.84 and 3C 9.

OSIRIS observations of the quasars' host galaxies revealed that either star formation or the AGN could drive outflows in 3C 9, since they are aligned with the radio jet of the quasar but appear to originate in the star forming regions without extending to the quasar host galaxy nucleus. For 4C 05.84, observations revealed the presence of galactic scale outflows most likely driven by either an isothermal shock or due to radiation pressure by the quasar. Follow up ALMA observations of 4C 05.84 (Vayner et al., 2021a) reveal that the outflow in the quasar host galaxy is multi gas phase with the detection of a molecular outflow traced using the CO (4-3) transition. While the majority of the energetics are in the ionized gas phase, most of the mass in the outflow is found in the cold molecular gas phase. The detected outflows are also aligned with the path of the jet indicating that the jet could be responsible for driving the outflow. We found that both quasar host galaxies lie off the local scaling relationship between the mass of the Supermassive Black Hole (SMBH) and the mass of the galaxy (McConnell & Ma, 2013). The stellar mass of both galaxies will require growth by a factor of ~ 10 between redshift of 2 and 0 in order to end up on the local scaling relationship.

To target potential companion galaxies around both quasars using MOSFIRE, we used Spitzer and Hubble imaging to identify potential targets in the environment around the quasars for spectroscopic confirmation and optical nebular line studies. We used publicly available observations from the Hubble Space Telescope (HST) WFC3 and ACS instruments, along with data from the Spitzer IRAC 3.6 μm and 4.5 μm channels to perform an overdensity analysis. All the *HST* data used in this paper can be found in MAST ¹. The Spitzer data products were obtained from Capak; Peter (2019). We have utilized HST WFC3 IR F160 images for 3C 9. No HST data was available for 4C 05.84 at the time of analysis.

We followed the procedure outlined in Wylezalek et al. (2013) to analyse the Spitzer archival data. We performed a color cut $[3.6]_{AB} - [4.5]_{AB} > -0.1$ to select sources with $z > 1.3$ (Papovich, 2008). We present the results of the color cut in Figure 2.1. We calculate the

¹<http://dx.doi.org/10.17909/czbk-dw64>

number density of such sources around 3C9 in a 1 arcmin radius to be $\Sigma_{3C9} = 16.5 \text{ arcmin}^{-2}$ which compared to the Spitzer UKIDSS Ultra Deep Survey (SpUDS) blank field ($\Sigma_{\text{SpUDS}} = 8.3 \text{ arcmin}^{-2}$; $\sigma_{\text{SpUDS}} = 1.6 \text{ arcmin}^{-2}$) in Wylezalek et al. (2013) implies an overdensity of 5.1σ . Similarly, we obtain $\Sigma_{4C0584} = 16.8 \text{ arcmin}^{-2}$ which implies an overdensity of 5.3σ . The exposure times for archival data were shorter than those used by Wylezalek et al. (2013) and therefore result in relatively higher errors for IRAC fluxes obtained from Spitzer. We note that these errors propagate into our color calculations, which could increase the number of outliers.

2.2 Observations & Data Reduction

2.2.1 NIRC2

We have archival NIRC2 observations of the quasar 4C 05.84 (PI: Stockton), observed on September 1st, 2006 and August 21st, 2007 which we have reduced using in house code to obtain the RGB composite shown in Figure 2.2. Our observations consist of AO Laser Guide Star (LGS) assisted imaging of the quasar in the J, H and Kp bands on NIRC2, using the wide camera at a plate scale of $0.04''/\text{pixel}$. The total exposure times were 25 minutes in Kp, 25 minutes in H and 54 minutes in the J band. Our data reduction follows the procedure outlined in Melbourne et al. (2005) using the distortion solution from Yelda et al. (2010). We calculate sky residual brightness to be $22.2 \text{ mag arcsec}^{-2}$ for J band, $21.2 \text{ mag arcsec}^{-2}$ for H band and $20.3 \text{ mag arcsec}^{-2}$ for Kp band. We have combined the data into an RGB using the Astropy implementation of the method outlined by Lupton et al. (2004).

2.2.2 KCWI

We observed 3C9 using KCWI on October 3/4, 2018 and followed up on August 17, 2020. The total time spent on 3C 9 was 6.5 hours. We observed 4C 05.84 with KCWI on November 22/23, 2017, July 8-10 2018 and October 2, 2018, for a total of 9.3 hours. We observed with an

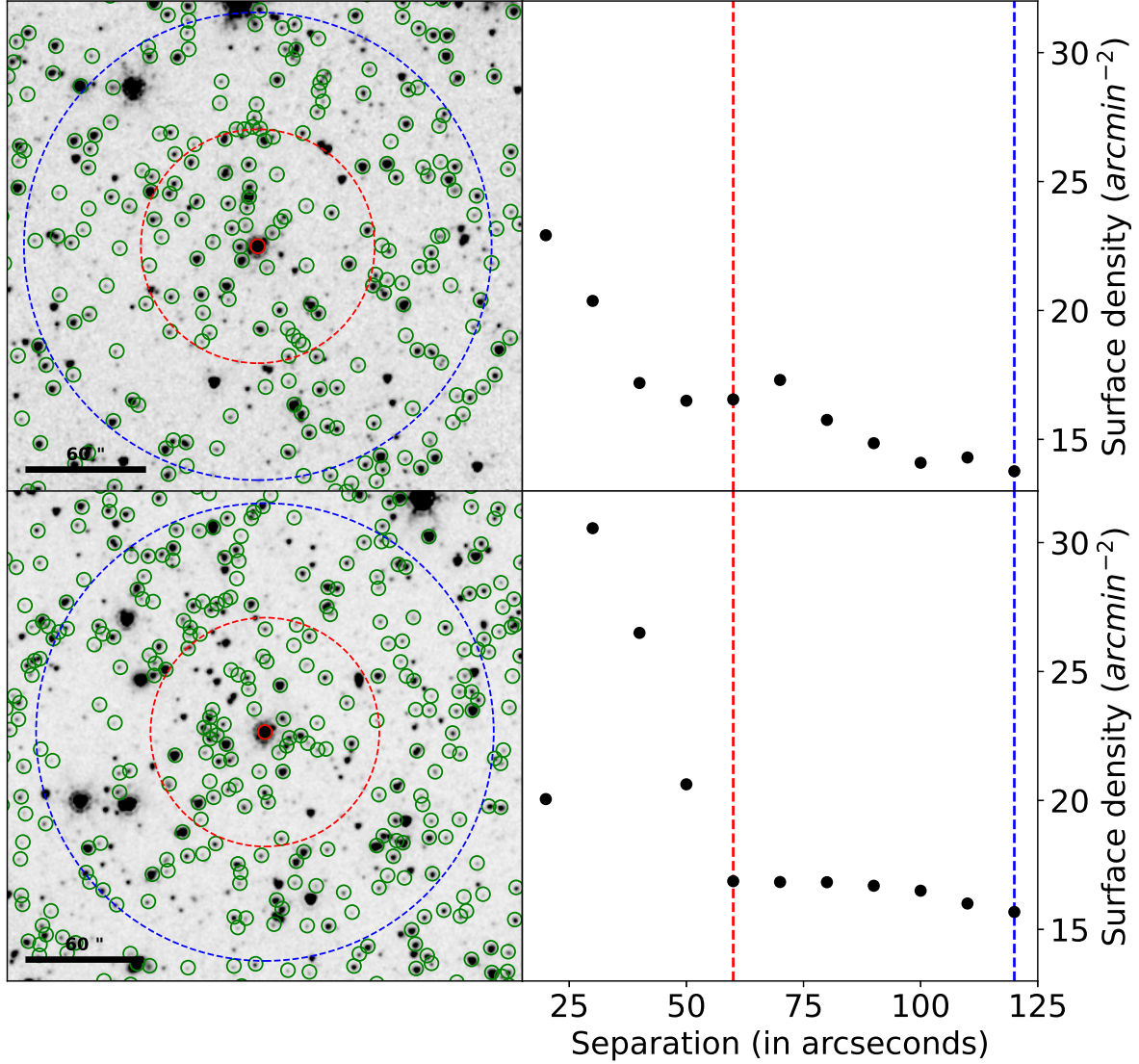


Figure 2.1. (LEFT) Overdensities measured around the quasars 3C 9 (Top) and 4C 05.84 (Bottom) from archival Spitzer data. The $4.5 \mu\text{m}$ IRAC image centered on the quasar (circled in red) is shown in both cases. We perform a color cut $[3.6]_{AB} - [4.5]_{AB} > -0.1$ (Papovich, 2008) to select sources with $z > 1.3$ (circled in green). We plot 1 arcmin and 2 arcmin circles centered on the quasar in dashed red and blue lines respectively. (RIGHT) The surface density of sources (in sources arcmin^{-2}) against separation from the quasar (in arcseconds). The vertical dashed red line at $60''$ is shown to indicate the number density of sources used for comparison against the SpUDS blank field number density $\Sigma_{\text{SpUDS}} = 8.3 \text{ arcmin}^{-2}$ in Wylezalek et al. (2013). Both quasars show a factor of ~ 2 increase in the number of sources at this radius compared to the field.

ABAAB pattern where the A frame targets the quasars and the B frames are “pure” sky frames, ensuring we have at least one neighboring sky frame for each object frame. For both quasars, we used the medium slicer with the BL grating and KBlue filter with the wavelength centered at 4500 Å. For the final reduced data, our wavelength coverage was 3532 Å to 5527 Å, at a spectral resolution of 1,800. The field of view for this KCWI configuration is $16.5'' \times 20.4''$, which was spatially dithered in units of $0.3''$. The total number of dithers for each object vary, depending on the total exposure time. We observed standard stars at the beginning and end of the night.

Primary data reduction was carried out using the KCWI Data Reduction Pipeline v1.1 (Neill et al., 2018). The pipeline performs cosmic ray removal, wavelength solution, flat-fielding and dark corrections, differential atmospheric refraction corrections and flux calibration. We skipped the pipeline sky subtraction and performed sky subtraction using our own routine. Sky subtraction was carried out by comparing the observed average flux in a sky patch on the object frame with a pure sky frame to obtain a scaling factor. Since this scaling factor may vary with wavelength, we performed this piece-wise along the wavelength axis to get the best residuals post sky subtraction. To correct the WCS information in the sky subtracted frames, we performed a 2D Gaussian fit using the photutils package to determine the quasar centroid. This Gaussian fit was performed at a wavelength slice far from the quasar expected emission lines to sample the point spread function (PSF). We assigned this centroid the coordinates from GAIA (Gaia Collaboration et al., 2018). These WCS corrected, sky subtracted cubes were co-added using CWITools (O’Sullivan & Chen, 2020) to give the final reduced datacube. The package also re-samples the datacubes from their native pixel scale of $0.69'' \times 0.29''$ to a grid with a pixel scale of $0.3'' \times 0.3''$ and combines individual data cubes using the Drizzle algorithm (Fruchter & Hook, 2002). After performing PSF Subtraction on this co-added datacube, we then used CWITools to obtain moment maps for Ly α , He II and C IV emissions lines, as well as subsequent surface brightness and moment maps for each emission line.

We performed PSF subtraction on the KCWI data as described in Vayner et al. (2016). To summarise the procedure, we construct a PSF image by using the continuum emission from

the quasar and the wings of the broadline emission lines at large velocity offset from systemic to avoid including any potential extended emission from the host galaxy or the CGM. This PSF image is then normalized to the peak flux and subtracted out at each wavelength channel while re-scaling the flux to the peak of the emission at that channel. To verify good spatial and spectral PSF subtraction, we proceed as follows. We analyse the radial profile of the resultant PSF subtracted data cube and compare it directly to the original data. For good PSF subtraction, we expect the flux to become comparable to sky residuals at a distance comparable to the size of the seeing disk, which for our nights was $0.5 - 0.7''$. The reconstructed PSF FWHM from KCWI data (with a slight wavelength dependence) is well-matched. There are wavelength dependencies to the PSF and spaxels close to the quasar show residual broad-line emission. PSF subtraction is good for all spaxels further than $0.6'' - 0.9''$ (2 - 3 pixels) of the quasar. To optimize PSF subtraction we have constrained our PSF to two critical wavelength regimes, those around the $\text{Ly}\alpha$ and C IV emission lines, constraining the broad line residual emission and over subtraction to within the expected sky residual noise. Surface brightness maps beyond $0.9''$ (3 pixels) should be minimally effected by PSF subtraction.

2.2.3 MOSFIRE

We observed 3C 9 using MOSFIRE on August 11/12, 2020 and 4C 05.84 on August 13, 2020 in H and K bands. The weather was clear with seeing estimated between $0.4''$ and $0.5''$. We aimed to detect $\text{H}\alpha$, [NII], [S II] in the K-band and [O III] and $\text{H}\beta$ in the H-band, given that 3C 9 is at a redshift of 2.019 and 4C 05.84 at 2.32. The slitmask configurations are described in Table 2.1. For each slitmask, we observed one continuum source with H magnitude less than 15 in a science slit to correct for instrumental drift during reductions. Other than Mask 1 which used the 3C 9 quasar as the continuum source itself, all other masks used stars from The Two Micron All Sky Survey (2MASS) (Skrutskie et al., 2006) as continuum sources. We used a slit width of $0.7''$ which gives $R = 3270$. The individual exposure time in H band was 120s whereas

for the K band it was 180s. We dithered using the ABBA observing mode. We observed the star HIP 116886 (spectral type A0V), selected from the ESO list for Spectrophotometric standards,² for telluric correction and flux calibration using the long2pos slitmask.

Table 2.1. MOSFIRE Slitmask configurations.

Quasar	Mask	PA degrees	Targets #	Exp Time min	Band
3C 9	1	-8.0	35	72	H
3C 9	1	-8.0	35	56	K
3C 9	2	53.0	32	36	H
3C 9	3	108.0	30	72	H
4C 05.84	1	7.0	30	38	H
4C 05.84	2	102.0	30	38	H
4C 05.84	2	102.0	30	36	K

We reduced the data using the MOSDEF pipeline (Kriek et al., 2015b). The pipeline carries out sky subtraction, masks bad pixels and cosmic rays, and combines individual frames. The pipeline also corrects for instrumental drift using the specified continuum source in a mask. We used the observed telluric star to perform our own flux calibration. We first perform a wavelength calibration for the telluric spectrum using arc lamps in K-band and atmospheric OH lines in H-band. We extracted the 1D spectrum of the star observed using the long2pos_specphot mask. The long2pos script obtains 4 spectra at the spectral resolution of the science exposure, two at the low end and two at the high end of wavelength coverage. We pick the higher throughput spectrum from each wavelength end. We fit a Gaussian to any hydrogen absorption lines in the stellar spectrum to subtract them out. We also detect and remove spurious spikes in the extracted spectrum that are from residual bad pixels. We then construct a blackbody emission model for the effective temperature of the spectral type, normalised to the 2MASS flux of the observed standard (Skrutskie et al., 2006). We divide the stellar spectrum by the blackbody spectrum to get the response curve for the instrument, which includes atmospheric and telescope-instrument response. We use the response spectrum to convert the extracted spectra from *Datanumbers/s* to

²www.eso.org/sci/observing/tools/standards/spectra/stanlis

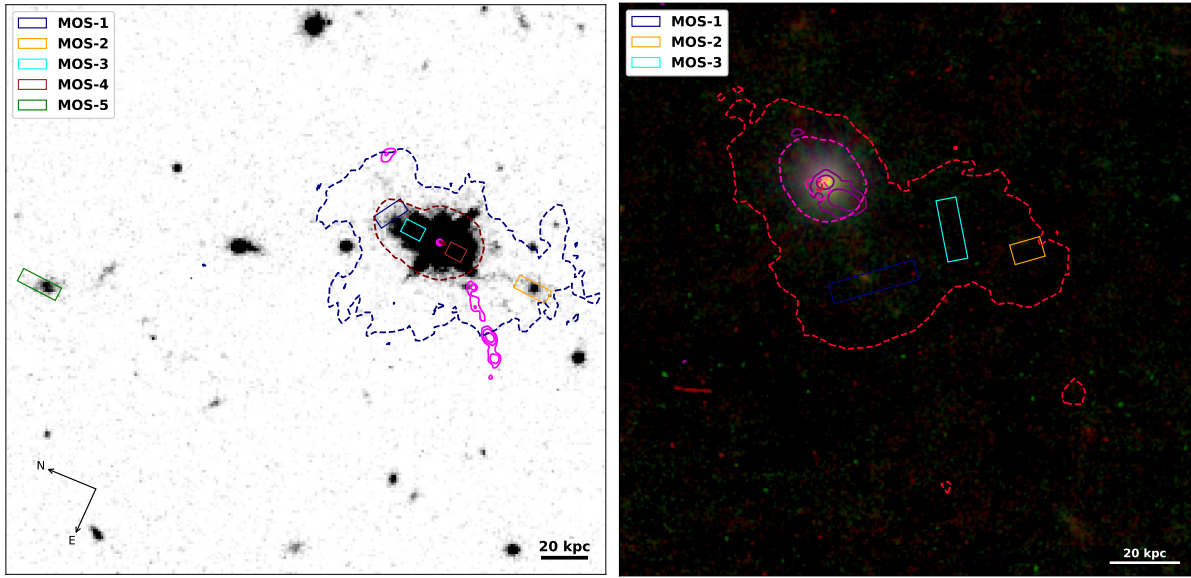


Figure 2.2. We show the $\text{Ly}\alpha$ nebulae as seen by KCWI, shown as dashed contours for both quasars. The inner and outer contours correspond to an observed flux density of 1.0 and $0.1 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$ respectively. For 3C 9, we overlay this on an HST WFC3 F160 image (Left) and for 4C 05.84 we overlay MOSFIRE slits on a NIRC2 RGB composite where the red, green and blue channels correspond to Kp, H and J band images of the quasar 4C 05.84 respectively (Right). We also display the spatial location of emission lines as detected with MOSFIRE and label the individual sources as shown in Table 2.2. We also overlay the contours of the radio jets coming out of the two quasars in magenta.

$\text{ergs cm}^{-2} \text{s}^{-1} / \text{\AA}$. Lastly, we independently checked the quality of flux calibration by checking the flux of continuum sources on science masks and comparing them to the expected 2MASS flux densities. We find that the MOSFIRE derived magnitudes are in agreement to within 0.2 mag for all H and K band masks, after correcting for slit loss and the differences between MOSFIRE and 2MASS bandpasses. Since $\text{H}\beta$ emission for 3C 9 falls close to the atmospheric window, the flux calibration for $\text{H}\beta$ has higher uncertainty. We also compare the response spectrum across different nights and find them to be qualitatively consistent with each other, i.e. the wavelengths for observed sky lines and any absorption lines in the telluric stars are consistent across different nights.

2.3 KCWI Results: Circumgalactic Medium

We extract flux and moment maps of each emission line for 3C 9 and 4C 05.84 using the CWITools package. We first perform a segmentation of the PSF-subtracted data cube for each emission line ($\text{Ly}\alpha$, C IV and He II), using a minimum threshold of 2σ , using the *cwisegment* routine. This gives us a resultant masked datacube where all pixels below the minimum threshold are masked. A zero-moment map is created by simply summing the flux from all the unmasked spaxels. The velocity (moment 1) and dispersion (moment 2) maps are created similarly by applying the respective moment equations to the unmasked spaxels in this datacube. The resultant moment maps for 3C 9 are in Figure 2.3 and 4C 05.84 are in Figure 2.4.

2.3.1 CGM Morphology & Kinematics

3C 9 CGM

The KCWI observations are sensitive to 2σ flux limits of $5 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. We detect $\text{Ly}\alpha$ emission extending throughout our field of view around 3C 9 with the most prominent emission seen as a nebulae with a diameter of 120 kpc centered on the quasar. The southern part of the nebula shows distinct clumps of $\text{Ly}\alpha$ with two faint peaks clearly identified southwest and southeast of the quasar. We also detect two distinct He II nebulae, the first around the quasar host galaxy with a spatial extent of $40 - 50 \text{ kpc}$ and a second about 30 kpc away, with a spatial extent of $\sim 30 - 40 \text{ kpc}$. Both He II and C IV emission around the quasar appears to have a biconical morphology. The radial profile of the three emission lines for the two quasars are in Figure 2.5. For purposes of discussion, we can demarcate different regions in the CGM around the quasars as shown in Figure 2.6. We have region 3C9-*a* (Northern cone), region 3C9-*b* (Southern cone) and region 3C9-*c* (Southern cloud further away from the quasar). We detect a C IV emission nebula coincident with the He II emission closer to the quasar in 3C9-*a* and 3C9-*b*, but do not detect any spatially resolved C IV emission coincident with the He II nebula in 3C9-*c*. We note that He II emission does not necessarily coincide with peaks in

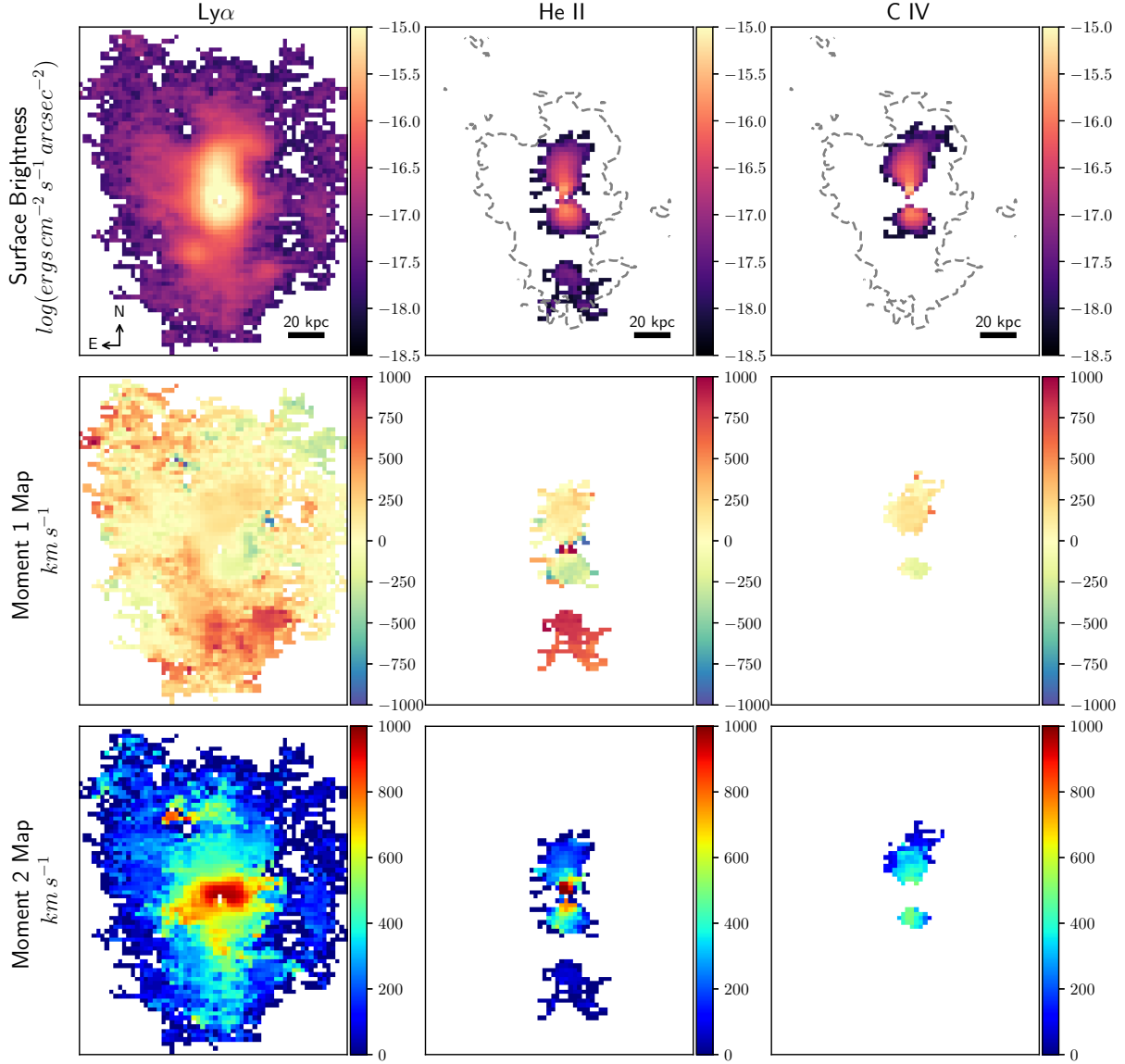


Figure 2.3. A PSF-subtracted image of the Ly α (Left column), He II (Middle column) and C IV (Right Column) derived properties for 3C 9. The top row is the surface brightness, middle row is the moment 1 map, and bottom row is the moment 2 map. All figures have an on-sky position angle of 0. The systemic redshift used to calculate the moment maps is used from OSIRIS measurements in Vayner et al. (2016). The grey dashed contour in He II and C IV Surface Brightness figures denotes a Ly α isophote at a surface brightness of $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$.

Ly α surface brightness, in fact, we detect no He II for the bright south-east Ly α peak or the fainter south-west Ly α peak.

As discussed in section 2.2, we have residual emission from the broad line region in

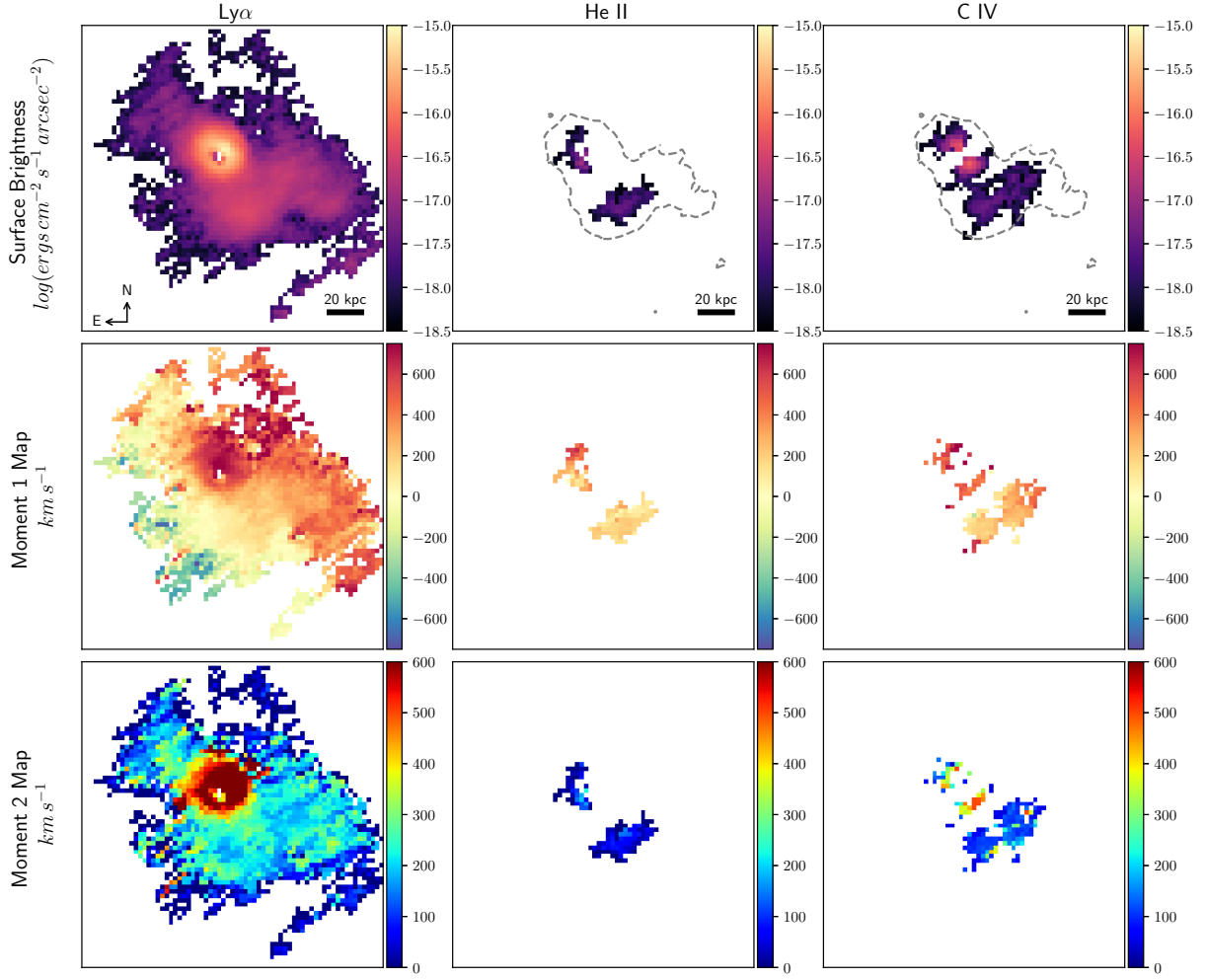


Figure 2.4. A PSF-subtracted image of the Ly α (Left column), He II (Middle column) and C IV (Right Column) derived properties for 4C 05.84. Same units and PA configuration as Figure 2.3.

the innermost 2-3 pixels, which translates to ~ 7 kpc from the center. As a result, we treat the innermost radial profile as an upper limit and discuss the features seen greater than 7 kpc away, which corresponds to 3 pixels. The radial profiles for 3C 9 similarly indicate that the He II emission seen in region 3C9-c is a distinct component, showing no spatially resolved C IV emission, however this may be due to observational sensitivity.

We detect a smooth velocity gradient across the nebula with velocity ranging from -800 km s^{-1} to 1000 km s^{-1} relative to the systemic redshift of the system ($z_{3C9} = 2.02$). region 3C9-c has a velocity greater than 800 km s^{-1} with respect to the quasar, seen both in He II and

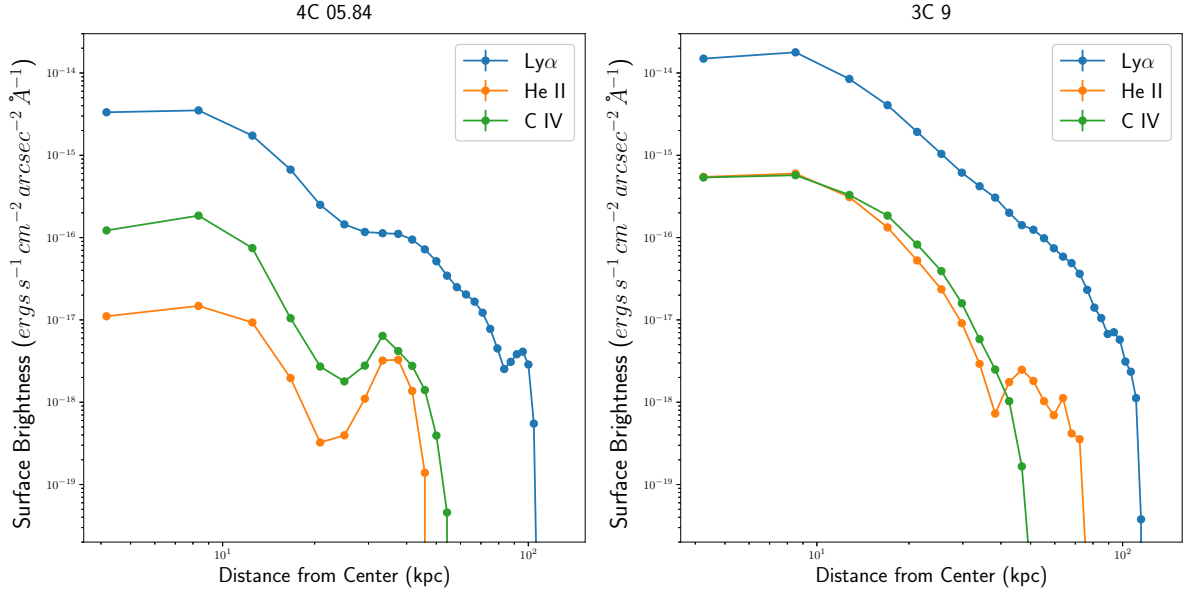


Figure 2.5. Radial surface brightness profiles of Ly α , C IV and He II derived from 2d surface brightness maps: see Figures 2.3 and 2.4 for 4C 05.84 (Left) and 3C 9 (Right). We center the surfaces on the quasar and construct successively larger annular regions to extract the azimuthally averaged surface brightness. We omitted the innermost 2 pixels, which corresponds to $0.6''$ corresponding or approximately 5 comoving kpc to avoid any contamination from PSF subtracted residuals.

Ly α . We can also see a region of high dispersion south of the quasar, with dispersion values measured to be in excess of 500 km s^{-1} in Ly α as seen in the moment 2 map in Figure 2.3. The He II nebula around the quasar host galaxy shows a smooth velocity gradient from 3C9-*b* to 3C9-*a*, with a velocity gradient between -400 km s^{-1} to 250 km s^{-1} . On the other hand, region 3C9-*c* shows a relative velocity gradient from $\sim 400 \text{ km s}^{-1}$ to 800 km s^{-1} , with the brightest part of the emission in a narrow $\sim 15 \text{ kpc}$ clump of gas at a velocity of 800 km s^{-1} with respect to the quasar. The southern He II emission has very low velocity dispersion across the nebula with values $< 100 \text{ km s}^{-1}$. The emission of He II in 3C9-*c* seems kinematically consistent with the Ly α emission in the region, even though the Ly α emission shows a gradient around the region.

4C 05.84 CGM

We detect Ly α emission for 4C 05.84 extending throughout our field of view up to a scale of 120 kpc in diameter in the immediate vicinity of the quasar and in faint but spatially resolved peaks southwest of the quasar. The presence of substructure can further be seen in the radial profile of the Ly α emission in Figure 2.5. We detect two distinct He II nebulae, the first immediately around the quasar, with an extent of 20 kpc and a second about 20 kpc southeast of the quasar, with an extent of 30 kpc. Similar to 3C 9, we denote different regions around the CGM as region *4C0584-a* (North Eastern cone), region *4C0584-b* (South Western cone) and the region *4C0584-c* (South West cloud further away from the quasar) as seen in Figure 2.6. The He II emission in the immediate vicinity of the quasar in regions *4C0584-a* and *4C0584-b* is markedly fainter than that in *4C0584-c*, which is also larger in size. This is surprising since we a priori expect both nebulae to be photoionized by the quasar. We detect slightly larger C IV emission nebulae around both He II nebulae. The C IV emission around the He II in *4C0584-c* also appears to have a biconical morphology. From the radial profile in Figure 2.5, we see that He II emission follows that of C IV for 4C 05.84, including that in *4C0584-c*.

The Ly α moment 1 map for 4C 05.84 shows a smooth gradient across the nebula ranging from -600 km s^{-1} to 800 km s^{-1} with dispersion $< 400 \text{ km s}^{-1}$ for the bulk of the nebula beyond the immediate vicinity of the quasar. The He II emission in *4C0584-c* lies within a velocity gradient of 100 km s^{-1} to 300 km s^{-1} with dispersion $< 150 \text{ km s}^{-1}$. Similar to 3C 9, the He II emission velocity gradient seems to match the corresponding Ly α velocity gradient in the region indicating the emission originates from the same region of gas with similar sources of ionization.

The moment 1 map for *4C0584-c* indicates a gradual velocity change in the observed C IV emission from southeast to northwest. However, we do not see clear evidence of a radially decreasing dispersion profile, as seen around the quasar in C IV. If the apparent biconical nature of C IV is due to the presence of an obscured AGN, we would expect to see higher values for

velocity dispersion in the center of the nebula as a result of outflows from the AGN. Since we do not see any evidence of outflows, the apparent biconical nature of the observed C IV emission is likely due to the complex geometry of the nebulae and the presence of dust between the quasar and the nebula illuminating certain parts of the nebula more than others.

2.3.2 C IV/Ly α and He II/Ly α ratio maps

Previous works in the literature have indicated that C IV/Ly α and He II/Ly α ratios can be used to probe the metallicity and ionization in the CGM around a quasar (Feltre et al., 2016; Guo et al., 2020; Lau et al., 2022). In this section, we use the surface brightness maps in Figures 2.3 and 2.4 to construct spatial maps for C IV/Ly α and He II/Ly α . We use these maps to explore the ionizing source and metallicity of the CGM around these two quasars in Section 2.5.4. These maps are presented in Figure 2.6. Both quasars show biconical morphologies in C IV emission immediately around the quasar, and significant He II emission around 20 kpc from the quasar. However, while we see C IV emission far away from the quasar for 4C 05.84 in *4C0584-c*, this is not the case for 3C 9. A comparison with the moment 1 maps indicates that in both quasars, the surface brightness ratio is higher in the region with the relatively blueshifted velocity. Both the *4C0584-c* and *3C9-a* show a slightly larger extent for C IV emission than He II.

Using these maps, we construct a He II/Ly α ratio vs. C IV/Ly α ratio plot for each spaxel, as shown in Figure 2.7. We indicate points where no He II or C IV is detected with limiting arrows. Limits are calculated using 1σ errors obtained from the Moment 0 error maps obtained from CWITools. Based on the morphology and kinematics of the two quasars, we identify three distinct components defined previously in this plot, the regions *3C9-a*, *3C9-b*, *3C9-c*, *4C0584-a*, *4C0584-b* and *4C0584-c*. He II emission in region *3C9-c* shows no counterpart in C IV. We observe a clear trend in 3C 9 with higher He II/Ly α ratio seen in *3C9-b*.

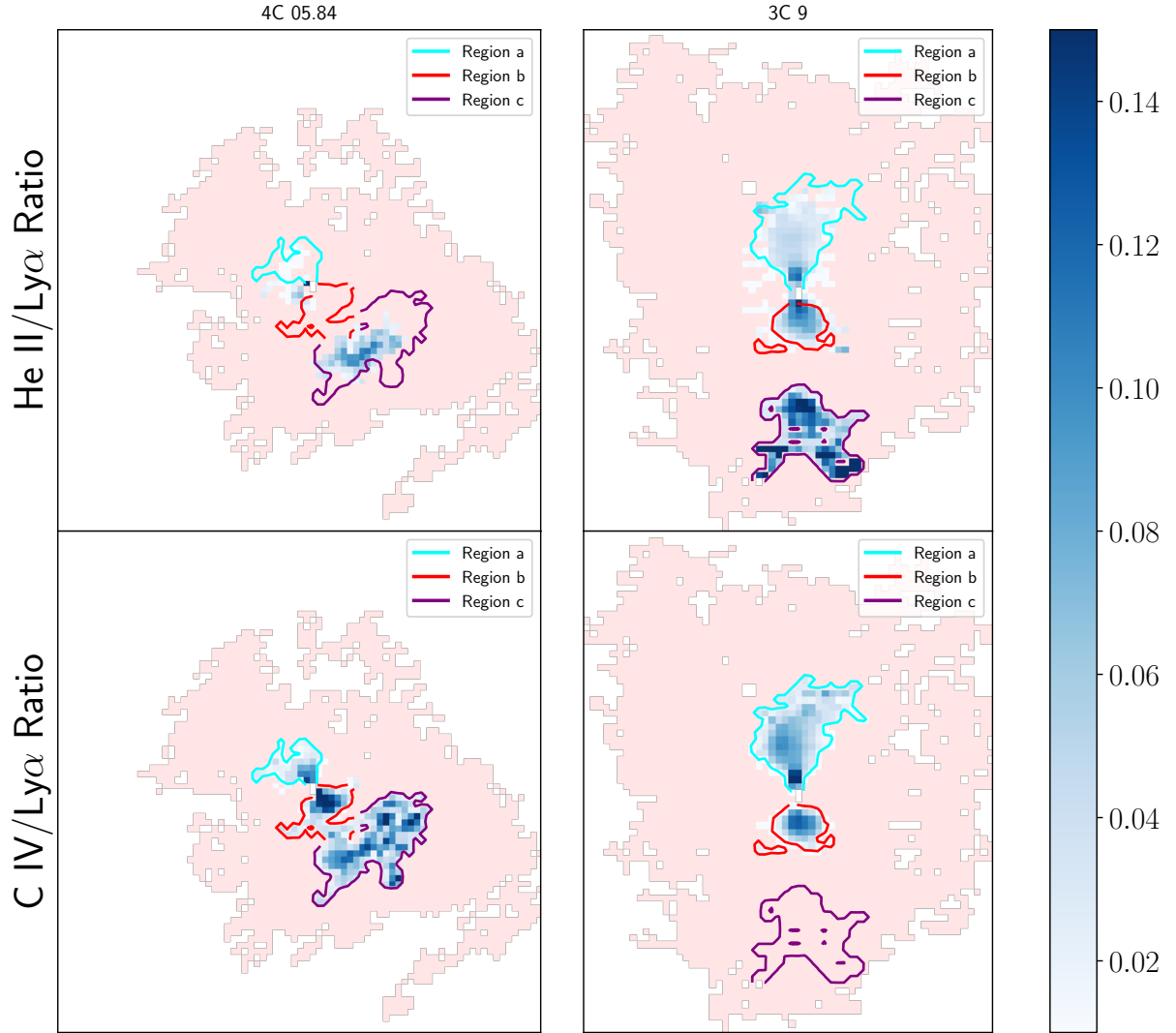


Figure 2.6. Emission line ratios constructed from Figures 2.3 and 2.4. We divide C IV and He II surface brightness maps by the $\text{Ly}\alpha$ maps to obtain the surface brightness ratios presented here. Three distinct regions are identified based on their spatial locations. 3C 9 shows a biconical outflow in C IV and He II with the northern cone denoted as region 3C9-a (outlined in cyan) and a southern cone denoted as region 3C9-b (outlined in red). We also see a large Southern cloud in He II (outlined in purple) denoted as region 3C9-c. For 4C 05.84, we see the biconical shape in C IV emission showing a Northeastern cone denoted as region 4C0584-a (outlined in cyan) and a southwestern cone (outlined in red) denoted as region 4C0584-b. We don't detect significant He II emission in this region. We also see evidence of a larger southeastern cloud denoted as region 4C0584-c (outlined in purple) seen both in C IV and He II.

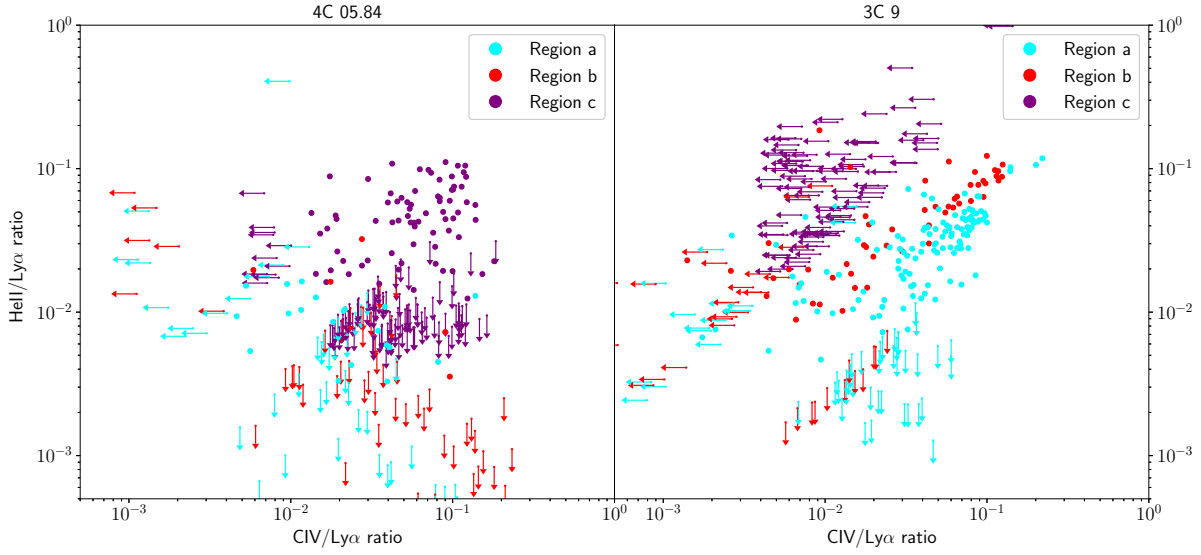


Figure 2.7. We used the surface brightness ratio maps in Figure 2.6 and plot the He II/Ly α ratio against the C IV/Ly α ratio for individual spaxels for 4C 05.84 (Left) and 3C 9 (Right). We further distinguish pixels belonging to the three different regions of the CGM as discussed in text for each quasar. For 4C 05.84, we have region 4C0584-a (Cyan), region 4C0584-b (Red) and the region 4C0584-c (Purple) for 4C 05.84. Similarly, we have region 3C9-a (Cyan), region 3C9-b (Red) and region 3C9-c (Purple) for 3C 9.

2.3.3 Asymmetry of Ly α halos

We calculate the asymmetry of the Ly α nebulae by calculating the second order moment of the flux (Stoughton et al., 2002). These moments are defined as

$$M_{xx} = \left\langle \frac{(x - x_{Neb})^2}{r^2} \right\rangle_f; M_{yy} = \left\langle \frac{(y - y_{Neb})^2}{r^2} \right\rangle_f \quad (2.1)$$

$$M_{xy} = \left\langle \frac{(x - x_{Neb})(y - y_{Neb})}{r^2} \right\rangle_f \quad (2.2)$$

Where x_{Neb} and y_{Neb} are flux weighted centroids for the 2σ isophotes of the nebulae and r is the distance of a given pixel from the centroid. We can then calculate the Stokes parameters

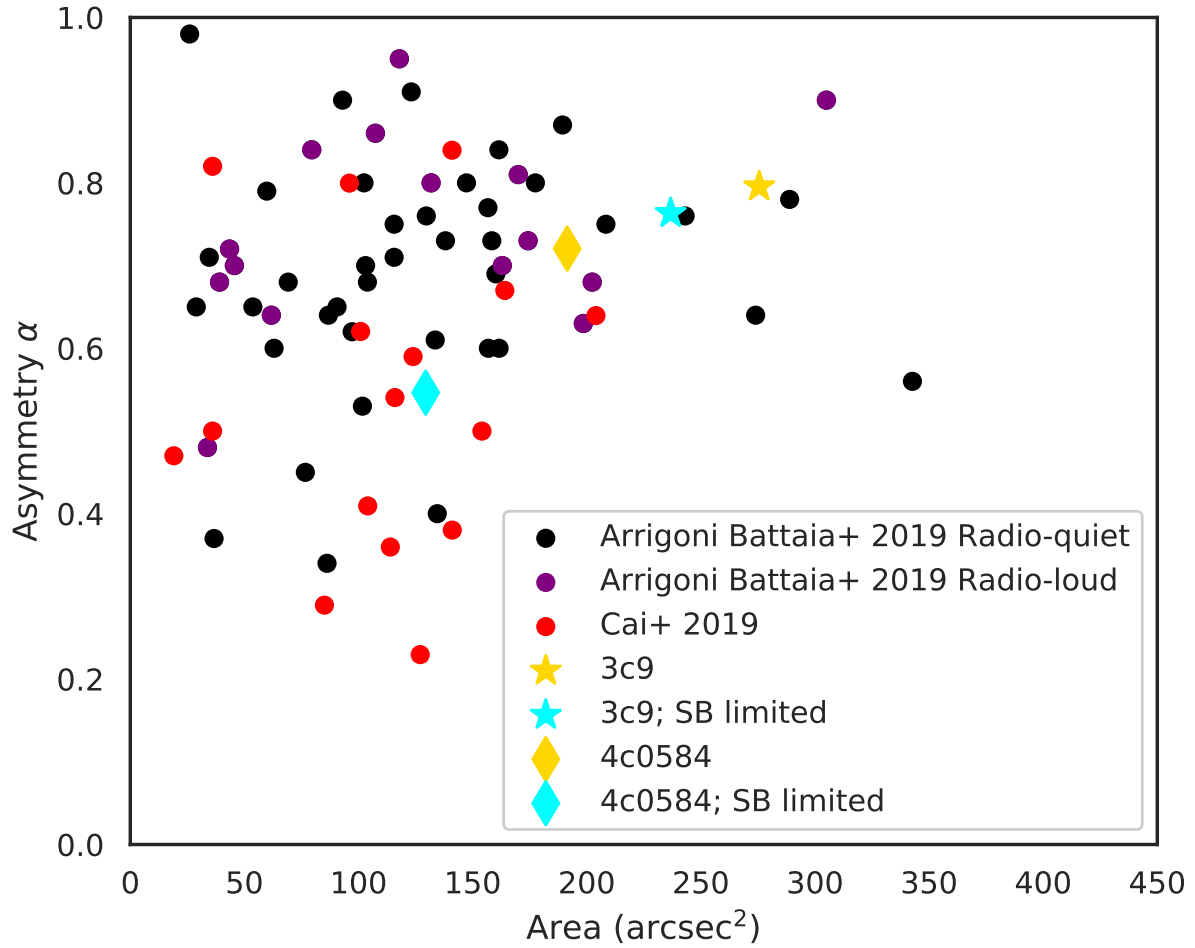


Figure 2.8. We plot the asymmetry α against the total area of the 2σ isophote for the two quasars 3C 9 and 4C 05.84. For comparison we plot these against the radio-loud and radio-quiet quasars from Arrighi Battaia et al. (2019) at $z \sim 3$ and from the $z \sim 2$ quasars in Cai et al. (2019). The cyan markers for 3C 9 and 4C 05.84 represent datapoints if we only consider pixels with a minimum surface brightness limit of $2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$.

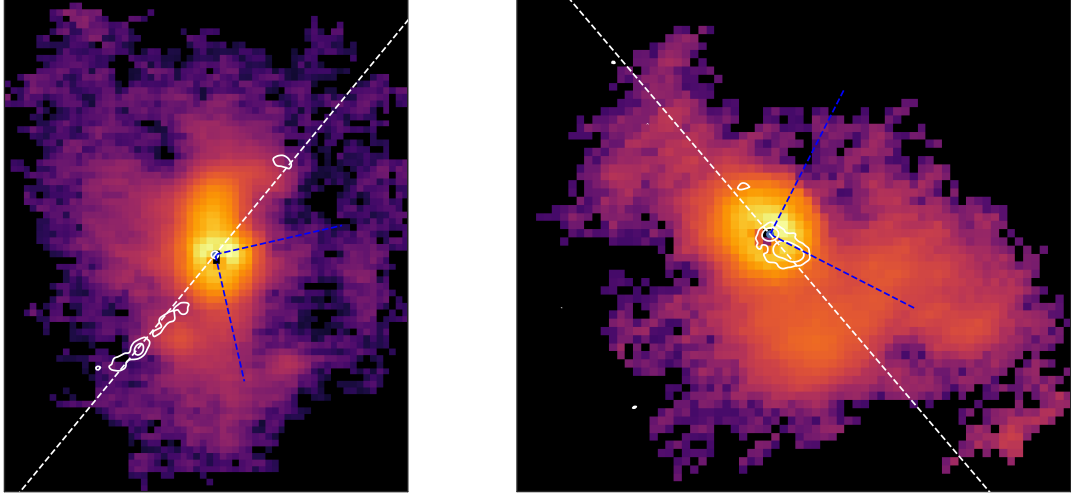


Figure 2.9. We use the angle ϕ determined using equation 2.5 and determine the major and minor axes (blue dashed line) for the Ly α nebula for 3C 9 (left) and 4C 05.84 (right). Using the right hand rule, the major axis is the X axis and the minor axis is the Y axis here. We also plot the radio jet contours and the jet axis and plot it on the same image (white dashed line).

using the moments

$$Q = M_{xx} - M_{yy}; U = 2M_{xy} \quad (2.3)$$

and derive the ratio between the minor and major axes of the nebula as the asymmetry α and the angle ϕ by using

$$\alpha = \frac{b}{a} = \frac{1 - \sqrt{Q^2 + U^2}}{1 + \sqrt{Q^2 + U^2}} \quad (2.4)$$

$$\phi = \arctan\left(\frac{U}{Q}\right) \quad (2.5)$$

Here, the angle ϕ is the angle between the major axis and the nearest X or Y axis. The results are shown in Figure 2.8. We also plot the major axis for the Ly α nebulae and the radio jets in Figure 2.9 We show the results from the $z \sim 3$ radio-loud and radio-quiet quasars from Arrigoni Battaia et al. (2019) and $z \sim 2$ quasars from Cai et al. (2019). To provide a comparison at a similar surface brightness limit to previous studies (i.e., 1σ limit in Cai et al. (2019) is 9×10^{-19} erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$ and 2σ in Arrigoni Battaia et al. (2019) is 4×10^{-18} erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$) we provide an asymmetry figure where we have considered a surface brightness limit

of $2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. The median projected areas at $z \sim 2$ and $z \sim 3$ are 63 arcsec^2 and 123 arcsec^2 respectively whereas the median asymmetries at these redshifts are 0.71 and 0.54 respectively. Once we take observational sensitivities into account, we find that 3C 9 is larger than the median Ly α nebula at $z \sim 2$ and $z \sim 3$, but 4C 05.84 is very similar in area to nebulae at $z \sim 3$ but significantly larger than median area at $z \sim 2$. While 3C 9 is more symmetric than the $z = 2$ Ly α 4C 05.84 is again comparable to median asymmetry of $z \sim 2$ nebulae. While longer exposure times increased the detection area only modestly for 3C 9, with no notable change in the calculated asymmetry α value, the changes for 4C 05.84 are statistically significant. We conclude that 4C 05.84 is largely consistent with the expected asymmetry for nebulae at this redshift, whereas 3C 9 is more axi-symmetric than other samples. Both nebulae are larger than expected for $z \sim 2$ sources projected on-sky area.

We also determine the axis of the radio jet and compare this angle with that of the Ly α nebula. We measure the angle between the radio and CGM axes to be 52.3 degrees for 3C 9 and 22.5 degrees for 4C 05.84.

2.4 MOSFIRE Results: Group/cluster Member Properties

Table 2.2. Redshift and Velocities of spectroscopically-confirmed group/cluster members.

Quasar	Source	Redshift	RA HMS	Dec DMS	Quasar Distance kpc	Line Used
3C 9	MOS-1	2.0221 ± 0.0001	00:20:25.198	+15:40:57.602	24	[OIII]
3C 9	MOS-2	2.03002 ± 0.00004	00:20:25.244	+15:40:49.409	44	H α
3C 9	MOS-3	2.0213 ± 0.0001	00:20:25.238	+15:40:53.522	12	[OIII]
3C 9	MOS-4	2.0294 ± 0.0000	00:20:25.598	+15:40:45.527	61	[OIII]
3C 9	MOS-5	2.02614 ± 0.00006	00:20:25.914	+15:41:12.48	172	H α
4C 05.84	MOS-1	2.3239 ± 0.0001	22:25:14.568	+05:27:05.673	32	H α
4C 05.84	MOS-2	2.3241 ± 0.0000	22:25:14.292	+05:27:06.406	61	H α
4C 05.84	MOS-3	2.3246 ± 0.0000	22:25:14.336	+05:27:01.162	38	[OIII]

We use MOSFIRE to target potential group/cluster members around both quasars up to an angular separation of 3 arcminutes, which translates to a comoving distance of approximately

Table 2.3. Line Fluxes^g of spectroscopically confirmed proto group/cluster members.

Source Name	[O III]	H β	H α	[NII]	Ly α	He II	C IV
3C9-MOS-1 ^a	11.7 $\pm$ 0.5	^b	^d	^d	369.1 $\pm$ 0.01	12.5 $\pm$ 0.01	1.66 $\pm$ 0.002
3C9-MOS-2	18.3 $\pm$ 0.3	2.0 $\pm$ 0.2	5.8 $\pm$ 0.3	0.32 $\pm$ 0.06	44.74 $\pm$ 0.05	1.73 $\pm$ 0.01	^c
3C9-MOS-3	47.3 $\pm$ 0.5	5.1 $\pm$ 0.3	30.6 $\pm$ 0.3 ^f	^e	^e	^e	^e
3C9-MOS-4	7.5 $\pm$ 0.3	0.36 $\pm$ 0.09	^e	^e	^e	^e	^e
3C9-MOS-5	^c	1.2 $\pm$ 0.5	5.8 $\pm$ 2.0	2.5 $\pm$ 0.3	^d	^d	^d
4C05.84-MOS-1	15.0 $\pm$ 0.3	< 0.4 ^c	^d	^d	37.72 $\pm$ 0.01	2.7 $\pm$ 0.005	0.277 $\pm$ 0.005
4C05.84-MOS-2	0.78 $\pm$ 0.09	0.17 $\pm$ 0.05	0.75 $\pm$ 0.2	< 0.24	19.09 $\pm$ 0.01	^c	^c
4C05.84-MOS-3	6.0 $\pm$ 0.2	< 0.26 ^c	^d	^d	23.89 $\pm$ 0.02	0.016 $\pm$ 0.0005	0.139 $\pm$ 0.005

^a Redshift confirmed by using [O III 5007] and [O III 4959]^b Emission line falls on top of a sky line and no flux could be extracted.^c No flux detected.^d No data available.^e Flux Extraction affected by Quasar residuals.^f H α flux extraction likely contaminated by [NII] and must be treated as an upper limit.^g All line fluxes in units of 10⁻¹⁷ erg cm⁻² s⁻¹**Table 2.4.** NIRC2 Magnitudes for identified sources

Source	J mag	H mag	Kp mag	
4C0584-MOS-1	- ^a	22.8	22.0	^a No source could be detected
4C0584-MOS-2	- ^a	- ^a	- ^a	^b Magnitude extracted as a 1.1 σ detection
4C0584-MOS-3	- ^a	24.6 ^b	24.6 ^b	

1.4 Mpc at the redshift of the quasars. The number of science targets we have for each mask are detailed in Table 2.1. At the quasar redshifts, we detect H α in the K band and H β , O[III] 5007 and O[III] 4959 in the H band. Our target selection relies on a Spitzer color cut as described in Section 2.1. Table 2.2 lists spectroscopically identified MOSFIRE sources around the two quasars. We also list the extracted line fluxes for all spectroscopically detected members in Table 2.3. Lastly, we show the extracted NIRC2 magnitudes for MOSFIRE confirmed sources in Table 2.4. We spectroscopically confirmed sources at $z > 1.3$ for 15 out of 62 targets in the 4C 05.84 field, and 19 out of 94 targets in the 3C 9 field. For identification of group/cluster members, we chose a redshift range of $z_{quasar} \pm 0.01$. We only confirm sources that have multiple emission lines detection, which leads to a lower confirmation rate. Given telescope time and weather

conditions we were only able to complete K-band observations on only 1 mask for each quasar, to target $H\alpha$, which is expected to be prominent for these galaxies, can only be observed for a fraction of sources around each quasar. For 3C 9, $H\beta$ falls close to the edge of the atmospheric transmission, making it difficult to confirm any galaxies with faint $H\beta$ and [O III] emission at other redshifts. Identified redshifts, locations and properties of the extended dataset will be discussed in a future work.

To calculate the redshift of the group/cluster members, we first visually inspect each source's spectrum and define a boxcar region to extract a 1D spectrum. We fit each spectrum with a Gaussian to determine the centroid and σ for each emission line to determine the redshift z_i of the member. For all cases, we have detection of multiple lines for the same source, and as such, the redshift is calculated using the line with the highest Signal-to-noise ratio. We then use the redshift of the quasar ($z = 2.019$ for 3C 9 and $z = 2.32$ for 4C 05.84 (Vayner et al., 2016)) to determine the velocity offset of the companion source from the systemic redshift using $v_i = c \frac{z_i - z}{1 + z}$. The fitted σ gives us the resultant velocity dispersion of each source.

We determine the astrometry for each MOSFIRE spectroscopically-confirmed source to extract a spatially-coincident spectrum in the KCWI data. We verify the MOSFIRE astrometry accuracy using the RA and Dec of the continuum source used in the science slit for each mask from the MOSFIRE pipeline header parameters. We additionally check for any optical distortions between the KCWI and MOSFIRE slitmasks by checking the pointing of the MOSFIRE slitmask on the quasar. We then calculated slit offsets for nearby objects from the quasar in MOSFIRE and KCWI WCS coordinates and found them to be in good agreement. We found that the distortion between the two instruments does not cause a significant offset in the astrometry (< 0.1 arcsecond). We show the locations of the MOSFIRE slits indicating the spatial extent of detected emission lines in Figure 2.2.

2.4.1 KCWI and MOSFIRE Spectra for all sources

We plot all extracted 1D MOSFIRE spectra for all identified sources in this section. All the spectra are available in the online version of this journal for 4C 05.84 (3 Figures) and 3C 9 (5 Figures). We show all extracted spectra for 4C0584-MOS-1 in Figure 2.10 and 3C9-MOS-2 in Figure 2.11 as examples for the two Figure Sets. Wherever possible, we have fitted identified lines with a Gaussian function. In some cases, the best fit requires us to fit a broad and narrow Gaussian component. In the case of 3C9-MOS-3 and 3C9-MOS-4, we have added a continuum fit to take into account any flux contamination from the quasar. Since $H\alpha$ can contaminate flux extraction from [NII] and vice versa, we always fit two Gaussians when extracting flux. For most sources where $H\alpha$ and [NII] 6583.46 is observed, we observe no contamination as the two lines can be visually distinguished. The only exceptions are 3C9-MOS-3 and 3C9-MOS-4 spectra, where we do see a blending between the two lines. In these cases, we were unable to distinguish the fluxes from $H\alpha$ and [NII] emission lines. Thus, for 3C9-MOS-3, we considered the extracted flux for the [O III] and consider the same velocity and spatial extent to be true for $H\alpha$ and report this as the $H\alpha$ flux. We do not report any flux for [NII] for this object. We are unable to apply the same process to 3C9-MOS-4, so no $H\alpha$ or [NII] flux is reported for this object. We note in Table 2.3 that this $H\alpha$ flux could be affected by [NII] and must be treated as an upper limit.

We overlay the MOSFIRE slit aperture on the KCWI emission line maps and extract a 1D spectrum for $Ly\alpha$, He II and C IV corresponding to the location of the MOSFIRE slit for comparison. We plot 1 source here from each quasar for reference. The complete figure set (3 images for 4C 05.84 and 6 images for 3C 9) is shown in the appendix.

We show in Table 2.5 the spectroscopically identified MOSFIRE galaxies and the kinematically distinct regions of CGM they are associated with as seen with KCWI. This will be useful to keep in mind particularly when we discuss our results in section 2.5. Whenever we refer to the MOSFIRE identified galaxies and any properties associated with the ISM of that

galaxy (e.g. star formation rate), we use the MOSFIRE identifier for that galaxy. Whenever we discuss the CGM properties of distinct regions around the quasar, we use the region identifiers established in Figure 2.6.

Table 2.5. CGM regions around the two quasars and the associated MOSFIRE galaxies.

Quasar System	CGM Region	MOSFIRE Identified Galaxies	Transition used for Definition
3C 9	3C9-a	3C9-MOS1, MOS 3C9-MOS-3	C IV
3C 9	3C9-b	3C9-MOS-4	He II
3C 9	3C9-c	3C9-MOS-2	He II
4C 05.84	4C0584-a	-	C IV
4C 05.84	4C0584-b	-	C IV
4C 05.84	4C0584-c	4C0584-MOS-1, 4C0584-MOS-3	C IV

2.4.2 Star Formation Rates & Metallicities

We convert $H\alpha$ fluxes into an estimation of star formation rates (SFR) from Murphy et al. (2011). We use the expression -

$$\frac{\text{SFR}_{H\alpha}}{M_{\odot}\text{yr}^{-1}} = 5.37 \times 10^{42} \frac{L_{H\alpha}}{\text{ergs s}^{-1}} \quad (2.6)$$

Wherever possible, we have corrected the $H\alpha$ flux based on a calculation of the Balmer decrement. Using the attenuated to intrinsic line ratio $R_{\alpha\beta}$ assuming Case B Recombination at a temperature of 10,000 K, we calculate the value of $E(B - V)_{\text{nebular}}$ using results from Calzetti (2001). We then convert this into $E(B - V)_{\text{continuum}}$ using the conversion (Calzetti et al., 2000) -

$$E(B - V)_{\text{nebular}} = (0.44 \pm 0.03) \times E(B - V)_{\text{continuum}} \quad (2.7)$$

We then follow Steidel et al. (2014) to assume either the Galactic or the Small Magellenic Cloud (SMC) Extinction curve depending on the measured $E(B - V)$, to obtain the $H\alpha$ attenuation in

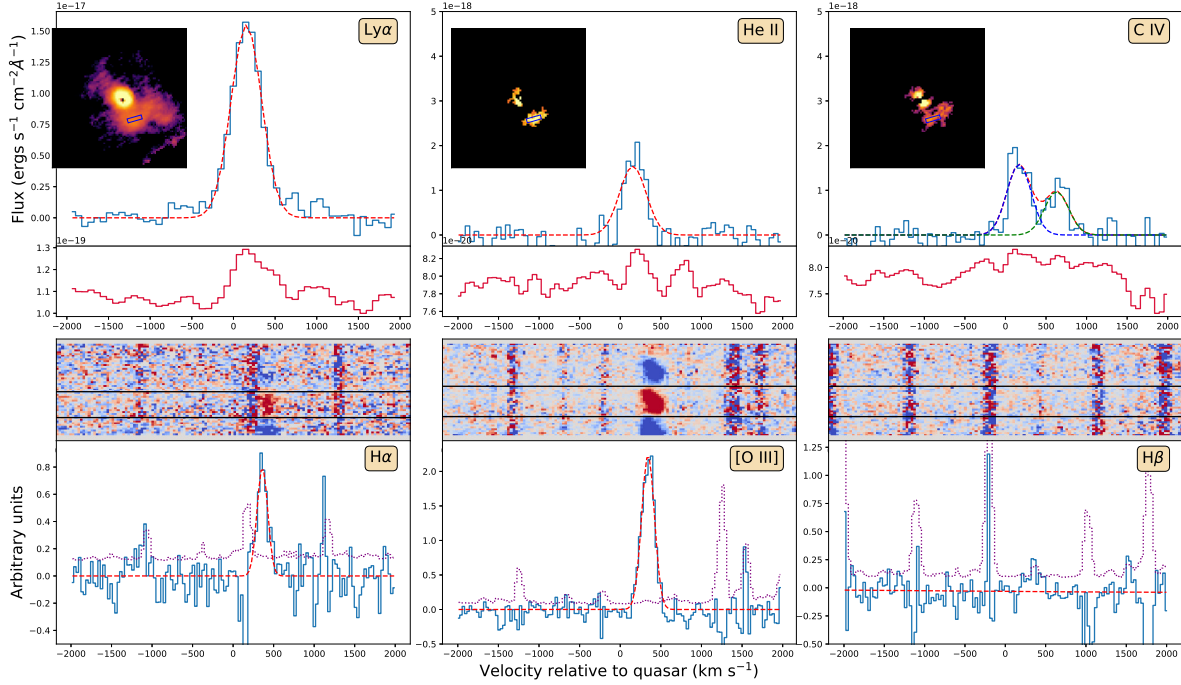


Figure 2.10. Figure showing all spectra for the source 4C 05.84 - MOS-1 from KCWI and MOSFIRE data. The X-axis for all spectra shows the velocity with respect to the quasar's redshift in km s^{-1} . For the top row, the Y-axis shows the extracted 1D spectrum in $\text{erg s}^{-1} \text{cm}^{-2}$, whereas for the bottom row, the Y-axis is in relative units. The top row contains 1D spectra extracted from KCWI Surface Brightness plots as shown in Figure 2.4. The red dashed line indicates the best fit Gaussian for each emission line whereas the propagated scaled uncertainties for the measurements are shown in the y axis split plot shown in red. Each emission line shows an inset of the KCWI Surface brightness image with a rectangular slit (blue) corresponding to MOSFIRE emission line detection showing the location where the KCWI 1D spectrum was extracted from. The bottom row consists of MOSFIRE detected $H\alpha$, $H\beta$ and $[O III]$ emission lines with the 2D spectra on top and the extracted 1D spectrum between the horizontal boxcar region (shown with solid black horizontal lines in the 2D spectrum) on the bottom. The red dashed line indicates the best fit Gaussian whereas the purple dotted line indicates the peak sky noise. The complete figure set (3 images) is presented in the Appendix.

magnitudes as given by -

$$A(H\alpha) = 4.54 E(B - V)_{\text{cont}}; E(B - V) \leq 0.20 \quad (2.8)$$

$$A(H\alpha) = 5.72 E(B - V)_{\text{cont}}; E(B - V) > 0.20 \quad (2.9)$$

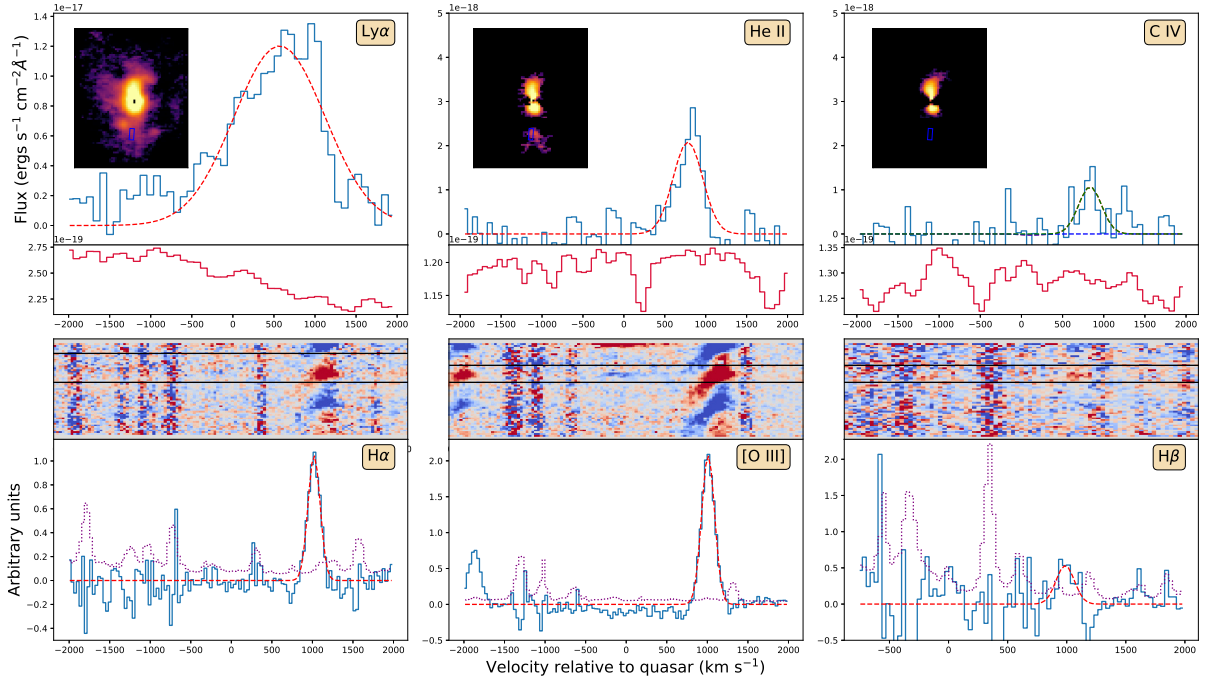


Figure 2.11. Figure showing all spectra for the source 3C 9 - MOS-2 from KCWI and MOSFIRE data with all axes and labels similar to Figure 2.10. The complete figure set (5 images) is presented in the Appendix.

For sources where we do not have $H\alpha$ data but only $H\beta$, we assume Case B Recombination nebular conditions with $T=10,000$ K giving an $H\alpha/H\beta$ ratio of 2.86 to calculate $H\alpha$ flux, which we then use to compute the SFR for each source. Since the $H\beta$ line falls particularly close to low atmospheric transmission window for 3C 9 and close to sky lines in the H band for both quasar, we find that the calculated $H\alpha/H\beta$ ratios can be as high as ~ 6 . These should not be taken to imply dust extinction but are likely due to a combination of relatively low SNR for the $H\beta$ line and the difficulty in carrying out accurate telluric calibration on the edge of the atmospheric transmission window.

For each source we calculate metallicities using $O3N2 = \log([O III]/H\beta)/([N II]\lambda 6584/H\alpha)$ and $N2 = \log([N II]\lambda 6583/H\alpha)$ to calculate metallicities where data is available using calibration from Pettini & Pagel (2004). In cases where we do not detect $[N II]$ at a 2σ limit, we have instead provided a limit. For objects where we do not have any $H\alpha$ and $[N II]\lambda 6584$ data, we instead use results from Nagao et al. (2006a) to provide an upper limit on the $12 + \log(O/H)$ values

using $[\text{O III}]/\text{H}\beta$. We estimate virial masses for detected MOSFIRE sources that are spatially resolved. We choose the extent of the object as detected with MOSFIRE to be the total radius and the velocity dispersion measured by MOSFIRE to be the line-of-sight velocity. We then calculate the total mass by converting the line-of-sight velocity into 3d velocity for the source, assuming an isotropic velocity distribution. The extracted metallicities, SFRs and an estimation of the virial mass for each source is listed in Table 2.6.

Table 2.6. Group/cluster Member properties.

Source	$12 + \log(\text{O}/\text{H})$ (O3H β)	$12 + \log(\text{O}/\text{H})$ (N2)	$12 + \log(\text{O}/\text{H})$ (O3N2)	$\text{SFR}_{\text{H}\alpha}$ $M_{\odot} \text{ yr}^{-1}$	Virial Mass $\times 10^{10} M_{\odot}$	Line Used
3C9-MOS-1	-	-	-	19.8 ^a	16.7	[O III]
3C9-MOS-2	< 8.42	8.47	8.34	10.0	1.2	[O III]
3C9-MOS-3	-	-	-	257	-	[O III]
3C9-MOS-4	-	-	-	1.7 ^b	3.4	[O III]
3C9-MOS-5	< 9.3	8.80	-	30.4	5.7	H α
4C0584-MOS-1	-	-	-	6.4	1.6	H α
4C0584-MOS-2	< 8.64	8.61	8.50	3.73	0.56	H α
4C0584-MOS-3	-	-	-	14.2 ^a	2.3	[O III]

^a Calculated assuming H α flux equal to the [O III] flux.

^b Calculated using H β and assuming Case B Nebular conditions.

2.4.3 Nebular Diagnostic Diagrams

We construct Baldwin, Phillips and Terlevich (BPT) diagrams (Baldwin et al., 1981) for the companion galaxies using MOSFIRE fluxes. We plot these values against star forming sequences indicated in Kewley et al. (2001) and Kauffmann et al. (2003), and the Seyfert-LINER separation as defined in Schawinski et al. (2007). We include the results from Kewley et al. (2013) for the evolution of the star forming sequence as a function of redshift, highlighting the sequences at the redshifts of our quasars.

To calculate the emission line ratios, we extract flux for an aperture size that fits all four emission lines spatially and spectrally with flux greater than 2σ . We then propagate measurement

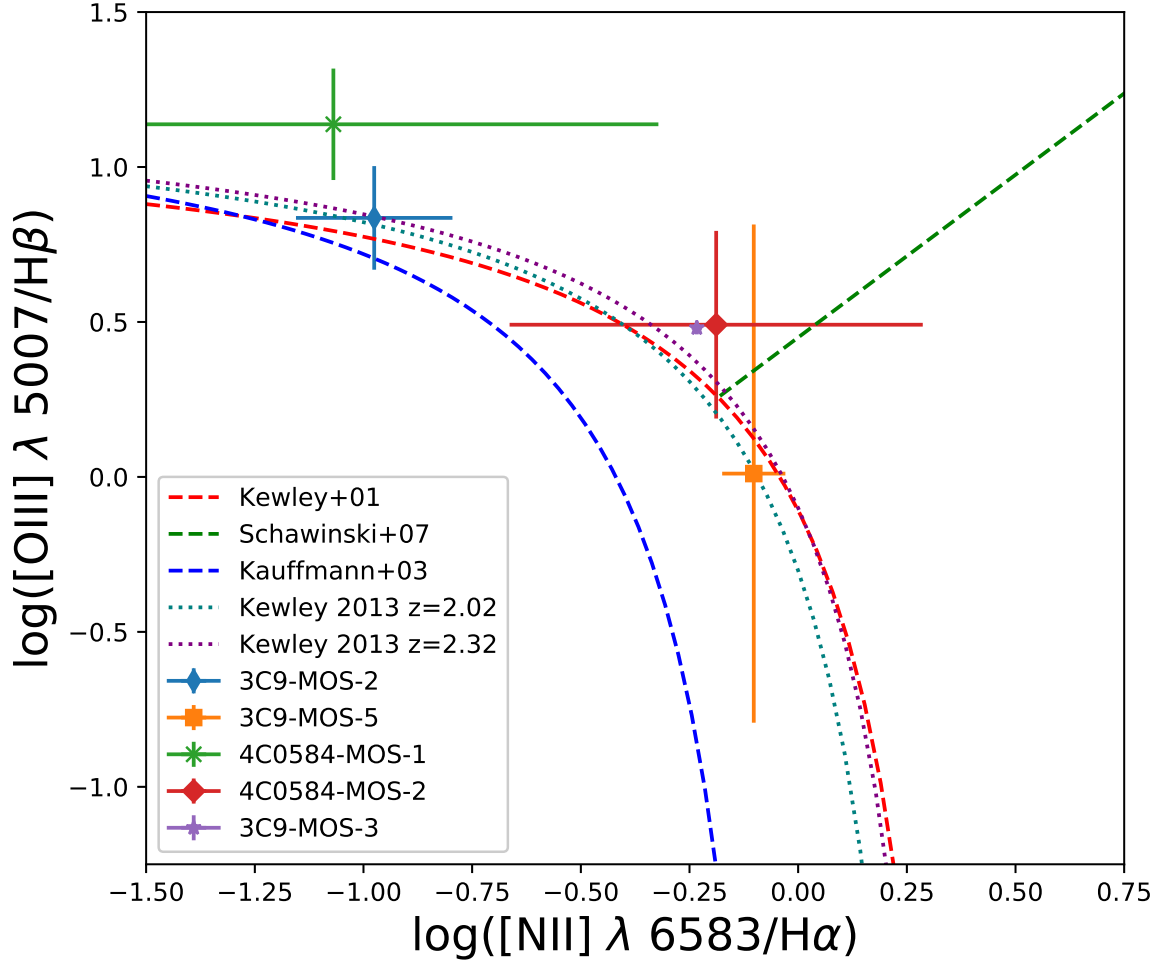


Figure 2.12. Diagnostic diagram ($\log([\text{O III}]/\text{H}\beta)$ vs. $\log([\text{N II}]/\text{H}\alpha)$) (Baldwin et al., 1981) for all sources detected at the redshift of the respective quasars using MOSFIRE. The star forming sequences from Kewley et al. (2001) and Kauffmann et al. (2003) are plotted to demarcate the star forming sequence. We include the sequence with redshift dependence for the two quasars as taken from Kewley et al. (2013), including the line demarcating AGNs from LINERs as taken from Schawinski et al. (2007).

uncertainties in our calculation of the ratio. The results are plotted in Figure 2.12.

We had sufficient spectral coverage to investigate line ratios for 5 MOSFIRE sources. We now address all 5 sources individually. Firstly, we notice that 3C9-MOS-3, which is the quasar host galaxy, is the only source where the observational uncertainties are small enough that we can definitively categorize it as an AGN. This is not surprising. However, all other sources have significant uncertainties in the calculated line ratios.

Firstly, we consider the sources around 3C9, i.e. 3C9-MOS-2 and 3C9-MOS-5. Both of these sources lie on the star forming sequence. The question to consider is whether these can be ionized by an AGN given the large uncertainties. For 3C9-MOS-2, which is closer to the quasar, this is certainly a possibility. However, given that we see the stellar continuum from the galaxy in HST imaging, it is equally plausible that this galaxy is indeed on the star forming sequence. The same argument is even stronger for 3C9-MOS-5, as it is significantly further away from the quasar and detected independently with Spitzer and HST. We conclude that these galaxies are likely on the star forming sequence.

For 4C0584, the picture is less clear. We detect a strong continuum in NIRC2 imaging for 4C0584-MOS-1 but a much weaker component for 4C0584-MOS-2. While it does appear that both these sources are likely ionized by an AGN, there are important considerations here. Firstly, for 4C0584-MOS-1, the strong stellar continuum detection implies that it is possible that there is at least a combination of AGN and star forming activity that is causing the ionization of the galaxy. This seems less likely for 4C0584-MOS-2, which on sky appears to be further away from the quasar than 4C0584-MOS-1, but this could be due to on sky projection. The other complicating factor is that for 4C0584-MOS-1, the [NII] line flux is contaminated by a sky line. This explains the particularly large uncertainty in the [NII]/H α ratio calculation which would bring it in line with 4C0584-MOS-2, if the [NII] flux was strong. Given the emission line fluxes and their uncertainties, it seems likely that at least some part of the emission is powered by AGN photoionization. Since our calculated star formation rates for these galaxies have been derived using the nebular line fluxes, these rates should be treated as upper limits for these galaxies,

as the true nebular emission due to star formation is a fraction of the observed flux. However, this interpretation does not affect our mass calculation of the system, which only relies on the observed positions and velocities of the companion galaxies.

2.4.4 Calculating the Dark Matter mass of the two systems

The identification of companion galaxies allows us to calculate the dynamical mass of the dark matter halo. There are different approaches in the literature that calculate dark matter halo masses for a group/cluster of galaxies at comparable redshifts. Firstly, clustering strengths of galaxies in a group/cluster environment can be compared to simulated population of dark matter halos to estimate the halo mass. This is usually carried out by calculating galaxy-galaxy autocorrelation lengths, given a group of galaxies (Trainor & Steidel, 2012; White et al., 2012). The drawback to this approach is that the robustness of the autocorrelation length calculation improves with the number of galaxies, and thus this method yields reliable results only with large number of galaxies. Secondly, one can use halo mass (M_{DM}) - stellar mass ($M_{stellar}$) relations to calculate the DM halo mass (Moster et al., 2010; Moster et al., 2018). This method has been validated by comparison with characteristic group luminosities using SDSS (Yang et al., 2007) and has subsequently used to calculate group masses at lower redshifts (Fossati et al., 2019). However, this method relies on accurate SED modelling, thus works best when the galaxies in question have imaging across a wide range of optical and infrared bands. Other works have utilized this technique to estimate DM halo masses at higher redshifts. Arrigoni Battaia et al. (2022) use this method to estimate the DM halo mass of a $z \sim 3$ QSO environment and find a halo mass of $8.6 \times 10^{12} M_{\odot}$, the bulk of which comes from the QSO host galaxy DM mass. Similarly, Chen et al. (2021) find a DM halo mass of $6.4 \times 10^{12} M_{\odot}$ for the Slug nebula around the radio quiet quasar UM 287 at $z = 2.23$. In both of these cases, the authors recognize the uncertainty in the calculations come largely from the estimation of the stellar masses of the galaxies in the environment.

In this work, we follow the procedure laid out by Tempel, E. et al. (2014) to calculate the dynamical mass of the environments. Chen et al. (2021) and Arrigoni Battaia et al. (2022) use this as an alternate method for their DM mass calculations and find good agreement with the estimates from $M_{DM} - M_{stellar}$ relations. Given the velocity dispersion along line of sight to be σ_{LOS} and assuming a virialized system, the three dimensional velocity dispersion is given by $\sigma_{3D} = \sqrt{3} \sigma_{LOS}$. Then, assuming an NFW profile (Navarro et al., 1997) for the dark matter halo, we can iteratively calculate the projected radius on sky and the corresponding M_{200} . Having calculated the projected radius, the enclosed mass is given by -

$$M_{tot} = 2.325 \times 10^{12} \frac{R_g}{Mpc} \left(\frac{\sigma_{3D}}{100 km s^{-1}} \right)^2 M_{\odot} \quad (2.10)$$

We obtain a projected radius of 123 kpc for 4C 05.84 using this method and a velocity dispersion of $352 km s^{-1}$ which gives a total mass of $3.5 \times 10^{12} M_{\odot}$. For 3C 9, we get a projected radius of 263 kpc and a velocity dispersion of $673 km s^{-1}$ which gives us a total mass of $2.77 \times 10^{13} M_{\odot}$. We now address a concern regarding the mass calculation for 4C 05.84. For both quasars, we have calculated the mass of the dark matter halos under the assumption that the emission lines traced by MOSFIRE are tracing emission from companion galaxies and not simply emission from the CGM or any gas blobs in the vicinity of the quasar host galaxies. We believe we are indeed tracing the velocities and locations of galaxies since these sources were selected based on imaging of their stellar continuum using either HST F160W or as seen with Spitzer. However, for 4C0584-MOS-3, while the source was identified on the basis of continuum emission with Spitzer IRAC imaging, the source was close enough to the quasar such that the PSF from the quasar blended with the source. NIRC2 imaging of the quasar does not show a stellar continuum at the location of 4C0584-MOS-3. While it is possible that this is due to the sensitivity of the NIRC2 exposures, we consider the consequences if 4C0584-MOS-3 is indeed tracing the CGM and not stellar emission from a companion galaxy. When we remove 4C0584-MOS-3 from our mass calculation, we calculate the dark matter halo mass of the system to be $5 \times 10^{12} M_{\odot}$,

larger than our original estimate. This is because MOS-3 does not serve as an outlier in physical separation from the rest of the group members, and has a velocity relatively close to the mean velocity of the system. As a result, when excluded from the calculation, it does not greatly affect the extent of the dark matter virial radius, but the expected velocity dispersion does increase, resulting in a net increase dark matter halo mass. However, since a virial mass calculation of the source 4C0584-MOS-3 indicates a mass $\sim 10^{10}M_{\odot}$, it is reasonable to assume this compact area could originate from star formation within a galaxy. Thus, for purposes of estimation of growth of these dark matter halos as discussed in Section 2.5.2, we assume the originally calculated mass as a conservative estimate with the caveat that the calculated mass growth must be seen as a lower limit.

2.5 Discussion

2.5.1 CGM and companion galaxies

$\text{Ly}\alpha$ is a resonant emission line with a large optical depth. Thus the observed spatial profile does not necessarily coincide with the ionizing region. He II emission, on the other hand, arises from a much more localized environment. We detect multiple He II and C IV clouds with either a high-velocity offset or a large radial separation from the quasar — or both — using KCWI, which indicates the presence of other galaxies in the environment. With MOSFIRE follow up we confirmed the presence of the companion galaxies by identifying $\text{H}\alpha$, $\text{H}\beta$ and [O III] emission lines. Knowing the locations of the companion galaxies, we can also confirm that the peak in surface brightness in He II away from the quasar host galaxy as seen in Figure 2.5 for both 3C 9 and 4C 05.84 in He II originates from companion galaxies. The case of $\text{Ly}\alpha$ however, is more complicated. While we do detect a peak in $\text{Ly}\alpha$ emission indicative of substructure at the radial distance of companion galaxies around 3C 9 and 4C 05.84, in the case of 3C 9 at least, it is clear from Figure 2.3 surface brightness profile that the $\text{Ly}\alpha$ emission peak does not necessarily coincide with the emission from the companion galaxies. In fact, by plotting the

$\text{Ly}\alpha$ emission, locations of companion galaxies and the locations of radio jets together as seen in Figure 2.2, we see that for 4C 05.84, the $\text{Ly}\alpha$ surface brightness peak in the region *4C0584-c* happens to coincide with the direction of the radio jet and the companion galaxies. However, for 3C 9, the $\text{Ly}\alpha$ emission seems to be coincident with the radio jets rather than companion galaxies.

For 4C 05.84, the He II emission in *4C0584-c* coincides with C IV emission as well as $\text{H}\alpha$, $\text{H}\beta$ and [O III] emission observed using MOSFIRE. The large spatially resolved extent of the He II and C IV in *4C0584-c* indicates that these are part of the companion galaxies 4C0584-MOS-1 and 4C0584-MOS-2.

Regarding 3C 9, we observed He II emission away from the quasar in region *3C9-c* but no spatially resolved C IV emission in that region. But we detect $\text{H}\alpha$, $\text{H}\beta$ and [O III] coincident with the He II emission. If we assume that the quasar is responsible for photoionizing regions *3C9-a* and *3C9-b*, this implies the ionizing luminosity must be sufficient to cause C IV emission in *3C9-c*. The absence of C IV emission thus indicates the presence of lower gas metallicity in region *3C9-c*. This finding is supported by Figure 2.7, which shows the He II/ $\text{Ly}\alpha$ ratio against the C IV/ $\text{Ly}\alpha$ ratio for all spaxels in the KCWI field of view. The figure demonstrates that the absence of C IV detection in *3C9-c* is not due to observational sensitivity. This is particularly interesting as this is consistent with the observed [NII]/ $\text{H}\alpha$ ratio for the galaxy which indicates a low metallicity.

2.5.2 Proto group/cluster mass growth

To estimate the growth of these dark matter halos, we calculate the growth rate using two independent approaches. First, we use analytic relations derived using the extended Press-Schechter formalism to calculate the growth rate of the dark matter halos (Correa et al., 2015a,b,c). Second, we compare the dark matter masses to the merger trees constructed using the joint set from Millenium and Millenium-II simulations (Fakhouri et al., 2010).

Using the analytic Press-Schechter formalism, we use WMAP9 cosmological parameters to estimate the mass growth of the halos. We find that 4C 05.84 is accreting mass at a rate of approximately $2.3 \times 10^3 \text{ M}_\odot \text{ yr}^{-1}$ at $z = 2.32$ and will grow to a mass of $2.2 \times 10^{13} \text{ M}_\odot$ by present day. The same approach gives a mass accretion rate of $2 \times 10^4 \text{ M}_\odot \text{ yr}^{-1}$ for 3C 9 at $z = 2.02$. We calculate 3C 9 will grow to a mass of $2.35 \times 10^{14} \text{ M}_\odot$ by present day.

We compare these results to the halo merger trees constructed using the joint data set from the Millenium and Millenium-II simulations. Fakhouri et al. (2010) found an analytical fit to the mass accretion rate for the simulated halo merger trees given by -

$$\begin{aligned} \langle \dot{M} \rangle_{mean} = & 46.1 \text{ M}_\odot \text{ yr}^{-1} \left(\frac{M}{10^{12} \text{ M}_\odot} \right)^{1.1} \\ & \times (1 + 1.11z) \sqrt{\Omega_m (1 + z^3) + \Omega_\Lambda} \end{aligned} \quad (2.11)$$

Starting with a range of DM halo masses at present-day, we calculate the progenitor mass by integrating the mass accretion rate as a function of redshift. We find the DM halo mass at present-day matches the dynamical mass of the quasar systems as calculated in Section 2.4.4 at the redshift of the quasar. Using this approach, we calculate that 4C 05.84 will grow to a mass of $2.3 \times 10^{13} \text{ M}_\odot$ and 3C 9 will grow to a mass of $2.15 \times 10^{14} \text{ M}_\odot$ by present-day, in reasonable agreement with our extended Press-Schechter calculation. This implies that the 4C 05.84 system will grow to a mass 10 times more massive than the local group (Benisty et al., 2022), making it a large group. Whereas 3C 9 will grow to a mass comparable to the dynamical mass estimates of Abell 2495 ($2.8 \pm 0.7 \times 10^{14} \text{ M}_\odot$) or MKW3S ($2.3 \pm 0.6 \times 10^{14} \text{ M}_\odot$) clusters (Sifón et al., 2015). This implies the 3C 9 system is in fact a protocluster environment.

Fakhouri et al. (2010) also calculate and fit the mean number of mergers a DM halo of mass M is expected to undergo between redshift of z and present day, with progenitor mass ratios in the range of $\xi = 0.1$ and $\xi = 0.3$. Based on their results, DM halos with a mass of 4C 05.84 had

an average of 0.9 mergers between $z = 2.32$ and today, whereas for 3C 9 it was an average of 1 merger between $z = 2.02$ and now. Based on the virial mass estimates for the group/cluster members as listed in Table 2.6, all group/cluster members detected fall within the expected mass range to be merger candidates. If we treat the relative velocity between group/cluster members and the quasar as a velocity of approach, we can calculate the dynamical time for the galaxies to merge. The maximum time is ~ 140 Myrs for the 3C9-MOS-5 source to merge with 3C 9, assuming the true separation is equal to the projected on-sky separation. This is likely an underestimate of the distance and therefore the merger may occur later. However, even if the projected distance is underestimated by a factor of 10, all the companion sources detected have sufficient time compared to estimated dynamical time to merge with the quasar host. The number of mergers thus would be 2-3 for each quasar system, which is higher than the expected number of mergers seen with the Millenium halo merger trees. While these two estimates differ by a factor of 2 or 3, the simulations usually calculate these as an average across a large number of merging systems. Given the stochastic nature of individual merger systems combined with small number statistics means we do not consider this result significantly different from the simulations.

The mass growth estimates calculated here rely on the initial mass of the DM halo, which has been calculated using the observed companion galaxies' positions and relative velocities with respect to the quasar. However, since it is possible there are galaxies further away from the quasar which were not detected, the calculated dynamical mass should be seen as a lower limit, which implies the same is true for the calculated mass accretion rates and the present day masses of these systems. We would like to stress that these calculations are approximations and can change based on new or improved data and that these masses must be treated as lower limits. We also caution against a simple interpretation of these structures as a protogroup or protocluster. We have chosen to demarcate the definition of a cluster as a bound structure that evolves to $z = 0$ with a minimum mass of $10^{14} M_{\odot}$, consistent with literature (Overzier, 2016). However, galactic structures lie on a mass spectrum and we would like to emphasize that with

the aforementioned definition of a cluster and given our calculations, 4C 05.84 would be a large group whereas 3C 9 will be a small cluster by $z = 0$.

2.5.3 Inner and Outer CGM component model

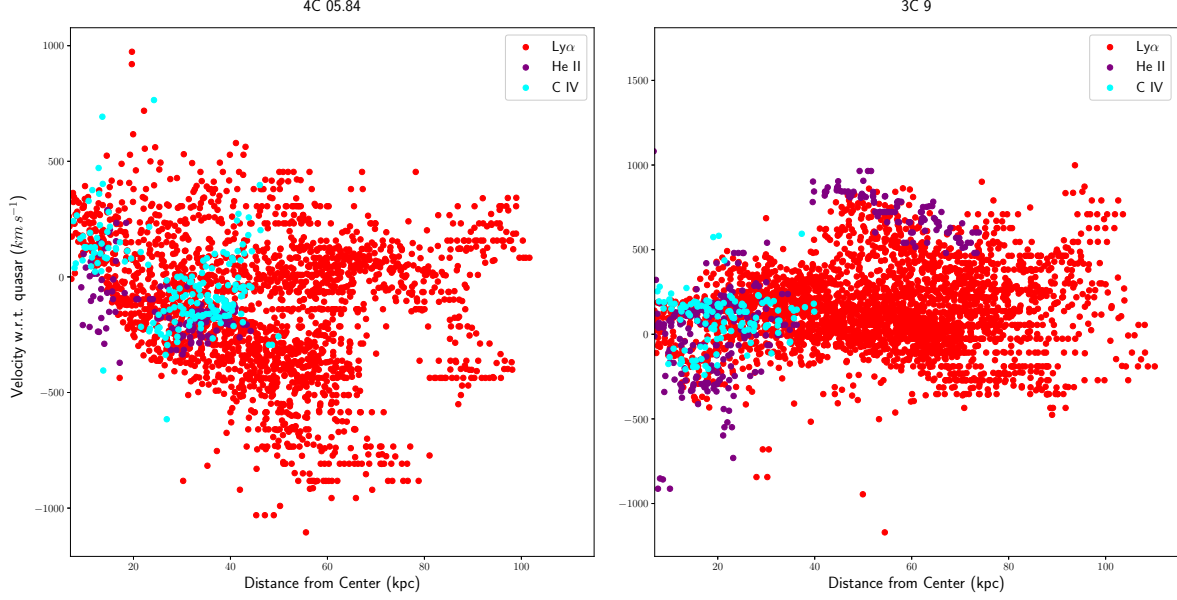


Figure 2.13. We construct the cylindrical projection of the CGM around the two quasars by plotting the velocity with respect to the quasar against the projected distance from the quasar using data from Moment maps in Figures 2.3 and 2.4. We only present datapoints at least 7 kpc away from the quasar since the moment maps obtained from the KCWI data may contain residuals from PSF Subtraction within this region. We can compare these plots to the cylindrical projection presented in Chen et al. (2020)

Recent observational models have shown distinct dynamical structures to individual CGMs that may be interesting to further explore observationally with KCWI. Chen et al. (2020) observed $\sim 200,000$ sightlines and absorption profiles through the intervening medium to study the CGM in aggregate and found a simple two component model worked best for their observations. This two component model has an inner and outer component. The inner CGM extends up to the inner 50 kpc and consists of outflows with velocities up to 600 km s^{-1} , whereas the outer CGM extends to 200 kpc with significantly lower velocities. Theoretically, the two component model implies that the inner CGM is the part of the CGM that is closer to the galaxy and directly

encounters any galactic scale outflows, whereas the outer CGM is a larger, more diffuse body of gas.

To study the signatures of a potential two component model with our data, we create a scatter plot of velocity vs. distance from quasar as shown in Figure 2.13 with the three emission lines we detect using KCWI, i.e. $\text{Ly}\alpha$, He II and C IV. To generate Figure 2.13 we use data in our moment 1 maps from Figures 2.3 and 2.4 with the calculated the on-sky projected distance of each spaxel from the quasar. We then exclude any spaxels that are within the inner 0.9 arcseconds for the quasars since these spaxels are susceptible to residuals from PSF subtraction. At the redshift of the quasars, this distance translates to about 7 kpc. We therefore are able to probe distances larger than 7 kpc and have the ability to resolve a potential inner CGM. Chen et al. (2020) created a similar plot but instead used the probed column densities to create a cylindrical projection of the CGM in the aggregate by combining all of their quasar sightlines. While they are able to probe the apparent optical depth of the hydrogen clouds, we do not have that information.

We find the $\text{Ly}\alpha$ emission velocity is centered around the quasar redshift for 3C 9, whereas for 4C 05.84 the velocity is offset from the quasar center. Yet, given the resonant nature of $\text{Ly}\alpha$, it is difficult to deduce any evidence of coherent outflows close to the quasar, so we are only able to observe the "Outer" CGM using $\text{Ly}\alpha$. However, He II and C IV provide further information about the kinematic structure of the CGM, including signatures of outflows in the inner CGM.

For 3C 9, we detect traces of outflows within the inner 50 kpc with velocities exceeding 500 km s^{-1} and approaching approximately 900 km s^{-1} . The C IV and He II emission coincident within the inner 40 kpc are associated with the CGM of the quasar host galaxy. For 3C 9, the He II emission between 40 and 80 kpc from the quasar is associated with the fringes of

the detected Ly α "Outer" CGM velocity structure as seen in Figure 2.13. We know from our MOSFIRE observations that the He II in region 3C9-*c* is associated with companion galaxy 3C9-MOS-2. The fact that the He II kinematics are on the fringes of the outer CGM highlights the stark velocity difference between the CGM around the quasar host galaxy and 3C9-MOS-2. We note that this may be the signature of the CGM from the infalling galaxy (3C9-MOS-2) starting to align with the larger CGM of the quasar host galaxy.

For 4C 05.84, we detect He II and C IV coexisting with two distinct regions within the inner 40 kpc. The inner 20 kpc of 4C 05.84 C IV and He II correspond to the quasar host galaxy, whereas the secondary structure from 20 to 40 kpc corresponds to the companion galaxies MOS-1, MOS-2 and MOS-3. We note that the observed Ly α emission profile for 4C 05.84 in Figure 2.13 has some peculiar features. Firstly, the observed Ly α emission close to the quasar actually does not converge upon the redshift of the quasar but at a redshifted velocity of $\sim 600 \text{ km s}^{-1}$ for $z = 2.32$. While we have used the value of $z = 2.32$ throughout this paper from Vayner et al. (2021c), 4C 05.84 has earlier been reported to have $z = 2.323$ (Barthel et al., 1990). If taken to be the redshift of the quasar, the observed CGM emission would change the velocity offset to $\sim 300 \text{ km s}^{-1}$. The other noteworthy observation is the large difference in velocities between the "inner" CGM and the Ly α emission 40-80 kpc away where we see a systematic blueshift in Ly α emission, offset by as much as 1000 km s^{-1} compared to the inner CGM velocity.

We now compare the observed two component structure for the two quasars 3C 9 and 4C 05.84. We notice that while for 3C 9, the larger Ly α emission neatly converges towards the redshift of the quasar, for 4C 05.84, the emission close to the quasar seems to be offset from the mean velocity of Ly α emission for distances larger than 20 kpc. This indicates the host galaxy may have experienced a shift in velocity compared to the larger CGM around it in the past. This is interesting since Vayner et al. (2021c) did not detect any signatures of a merger

in diffraction limited observations of the host galaxy ISM kinematics. Additionally, the large velocity offset between the innermost and outer parts of the CGM in 4C 05.84 is reminiscent of the He II emission joining the outer CGM in 3C 9 between 40-80 kpc as seen in Figure 2.13. If the CGM is indeed a two component model where the outer halo is largely confined to $\pm 500 \text{ km s}^{-1}$ for distances larger than 10-20 kpc, then this Ly α emission could be indicative of gas accreting on to the outer CGM from the cosmic web.

In summary, we detect signatures of outflow consistent with those expected from the inner and outer CGM for both 3C 9 and 4C 05.84. We detect potential outflows from the inner CGM using He II emission, whereas the outer CGM is detected and studied using Ly α , He II and C IV.

2.5.4 Source of CGM ionization

We use the observed Ly α , He II and C IV emission profiles to discuss the source of ionization powering the CGM emission. Figure 2.14 shows the He II/Ly α , C IV/Ly α and C IV/He II ratios as a function of radial on-sky separation from the quasar. We have only plotted spaxels at a distance greater than 8 kpc to remove any spaxels with PSF subtraction residuals. While He II and C IV have been used to distinguish AGN ionization from shocks in the ISM, they require the C III] line (Villar-Martin et al., 1997; Nagao et al., 2006b; Feltre et al., 2016; Humphrey et al., 2019). Instead, we use the observed He II/Ly α and C IV/Ly α ratios to consider the source of ionization for the observed CGM profiles around these two quasars.

Firstly, we note that the observed He II/Ly α ratios for both quasars are less than 0.15 for all observed spaxels with significant detection. Cantalupo et al. (2019) obtained theoretical limits on He II/Ly α ratios of 0.23 and 0.30 for Case A and Case B recombination respectively at $T = 2 \times 10^4 \text{ K}$, for fully ionized He II, suggesting that the He II is not fully ionized.

Secondly, we note that for Regions 3C9-*a*, 3C9-*b*, 4C0584-*a* and 4C0584-*b*, corresponding to CGM gas directly associated with the quasar host galaxy, the observed He II/Ly α and C

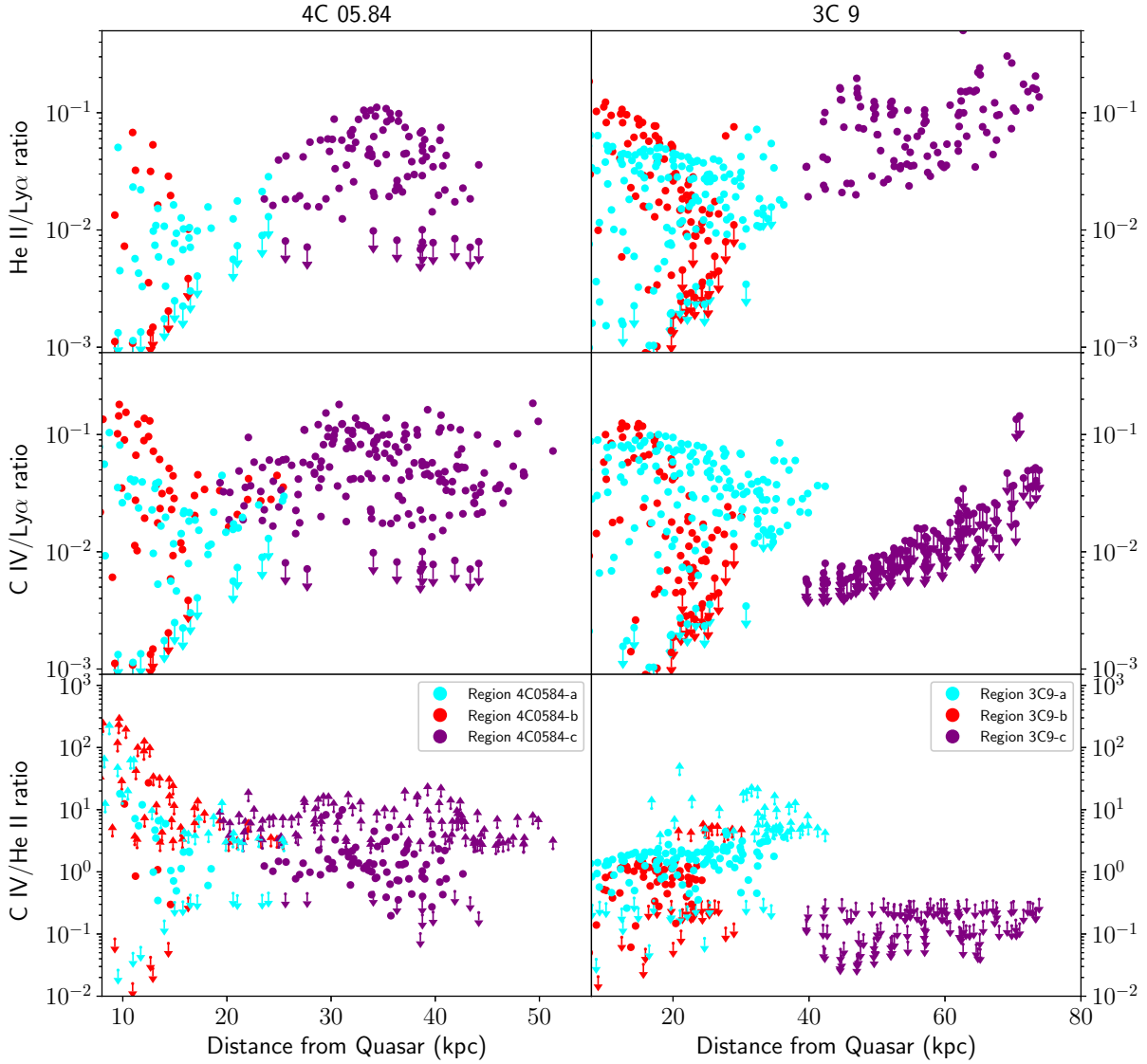


Figure 2.14. We investigate sources of ionization in the CGM by looking at He II/Ly α , C IV/Ly α and C IV/He II ratios as a function of distance from the quasar. The 4 inner regions 3C9-a, 3C9-b, 4C0584-a and 4C0584-b all have radially decreasing He II/Ly α and C IV/Ly α ratios, consistent with quasar photoionization. Regions 3C9-c and 4C0584-c do not show such a radial trend, with the He II/Ly α ratio for 4C0584-c peaking at a distance of 32 kpc from the quasar, whereas for 3C9-c, it decreases and then increases. Regions 4C0584-a and 4C0584-b also show a radially decreasing C IV/He II ratio, whereas 3C 9 does not show such a trend. These trends are consistent with the picture that Regions 3C9-a, 3C9-b, 4C0584-a and 4C0584-b are part of the quasar host galaxy CGM and ionized by the quasar, whereas Regions 3C9-c and 4C0584-c are associated with the CGM surrounding companion galaxies.

IV/Ly α ratios, wherever data is available, decrease with greater on-sky separation from the quasar. Comparing our results to photoionization models in Humphrey et al. (2019), we find that the decreasing ratios are consistent with a decrease in $\log(U)$. A radially decreasing $\log(U)$ parameter is consistent with quasar photoionization. Regions *3C9-c* and *4C0584-c*, which are likely associated with companion galaxies, do not show radially declining ratios. Region *4C0584-c* shows a peak at ~ 32 kpc from the quasar for the He II/Ly α ratio, whereas *3C9-c* shows a radial decrease, followed by an increase. This could be explained by line of sight projection effects. If we assume that the CGM around the companion galaxies is ionized by the quasars and the CGM and companion galaxies are extended along the line of sight, then the radial distance from the quasar will change significantly, compared to the on-sky projected separation. For these regions, we require the C III] line to definitively identify the source of ionization.

Thirdly, we compare our results to those of Guo et al. (2020) obtained from stacking $z = 3$ CGM spectra from 80 quasars observed with MUSE. Since we do not have data for the C III] line, we consider two regimes, whether C IV/He II is greater than or less than 1. We consider the case where C IV/He II ratios are less than 1, relevant for the region *3C9-c*. Based on the photoionization modelling in Guo et al. (2020), this would suggest $\log(U) < 2.4$ in this region, whereas no constraints can be placed on the metallicity based on this line ratio alone. This is again consistent with quasar photoionization. However, since *4C0584-c* and *3C9-c* are at comparable on-sky projected distances from the quasar, the lack of C IV detected in *3C9-c* could indicate a significantly larger distance from the quasar along the line of sight, resulting in significantly lower $\log(U)$ parameter value. The other explanation for a lack of C IV detection is if the observed gas in Region *3C9-c* is an infalling subhalo around the companion galaxy, the companion galaxy has not undergone significant star formation prior to infall, and thus has not formed and ejected metals into the CGM, resulting in a low metallicity. However, confirmation of this scenario would require additional diagnostics for the CGM.

Lastly, we consider the biconical ionization around both quasars as seen in He II and C IV. Since these likely indicate quasar photoionization cones, we consider the implications for the larger

Ly α nebula. The presence of these biconical regions around both quasars, and the presence of the extended regions *4C0584-c* and *3C9-c* within the opening angles of these cones strongly indicate C IV and He II emission in these regions being powered by quasar photoionization. The question then arises: Is this also true for the Ly α emission? If only the inner CGM is directly photoionized by the quasar, this would suggest that recombination may not be the only significant mechanism powering Ly α emission. Further confirmation of this scenario would require C III] observations with additional radiative transfer modelling for these systems. We also note the important caveat that radio jets can affect the observed lines, since they can modify the gas densities and kinematics in these systems.

2.6 Summary

We have presented results for two radio-loud quasars, 3C 9 and 4C 05.84. By combining optical observations of the CGM with near-infrared spectroscopy of companion sources, we have comprehensive picture of the environment around these quasars. While previous studies have investigated diffuse gas around radio-loud quasars at $z \sim 2$ using long slit spectroscopy (Shukla et al., 2022), or explored Ly α nebulae around radio-loud quasars at $z = 3$ (Borisova et al., 2016; Arrigoni Battaia et al., 2019), our work stands out as one of the initial multi-wavelength analysis of Ly α nebulae $z = 2$ radio-loud quasars with IFU observations. We have uniquely identified companion galaxies that potentially contribute to observed Ly α nebulae emission and have conducted a comparative analysis of the nebulae's orientation in relation to the radio jets. We summarise our findings as follows:

1. For both quasars, we detect large Ly α nebulae, projected on sky to be 120 kpc across, with spatially resolved substructure down to a sensitivity of $5 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$.
2. We detect He II and C IV nebulae around these quasars about 40-50 kpc across as projected on sky. While we detect these nebulae immediately around the quasar, we also detect ~ 20 kpc diameter kinematically distinct regions 15-30 kpc away from both quasars.

3. The He II nebulae around both quasars show a biconical shape, indicating that they are being powered due to ionization by the quasar. The shape of the nebulae traces this ionization cone which further strengthens the fact that the detected Ly α and He II nebulae immediately around the quasar are aligned with their observed radio jets. Observed C IV/Ly α and He II/Ly α ratios additionally show that the CGM emission is predominantly powered by quasar photoionization. This assertion is strengthened by the biconical morphology of He II and C IV emission seen around both quasars, indicative of an ionization cone.
4. We detect H α , H β and [O III] emission from the companion galaxies in the environment around each quasar using MOSFIRE observations. For 3C 9, we detected H α and [O III] coincident with the kinematically distinct southern He II region 3C9-c indicating the presence of a companion galaxy. We also detect H α emission in a galaxy about 172 kpc away from the quasar.
5. The observed radial profile for Ly α emission around these two quasar host galaxies deviates from a smooth gradual decline. These surface brightness deviations align with the locations of Ly α , He II and C IV emission from the CGM likely associated with the companion galaxies. This association is confirmed by both the spatial and velocity match of the observed H α , [O III] and H β emission. Therefore, the observed substructure in Ly α , nebular emissions around high-redshift quasars may serve as an indicator of the presence of companion galaxies.
6. Confirmed companion galaxies around 3C 9 shows this source is in active cluster formation. The mass of the 3C 9 cluster progenitor is estimated to be $2.7 \times 10^{12} M_{\odot}$. Confirmed companion sources around the 4C 05.84 were similarly used to calculate the mass of the group progenitor to be $3.5 \times 10^{12} M_{\odot}$. We estimate that the total mass of the 4C 05.84 system will grow to about $2.3 \times 10^{13} M_{\odot}$ by present day whereas 3C 9 will grow to a mass of $2.15 \times 10^{14} M_{\odot}$ by present day. Assuming that these structures are not yet

gravitationally bound, this makes the detected structure around 4C 05.84 a protogroup and that around 3C 9 a protocluster.

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Appendix

MOSFIRE and KCWI 1D Spectra

1D spectra extracted from KCWI and MOSFIRE for all identified sources around the two quasars are presented here. The units and methodology for figure preparation is identical to those used for Figures 2.10 and 2.11.

2.6.1 3C 9

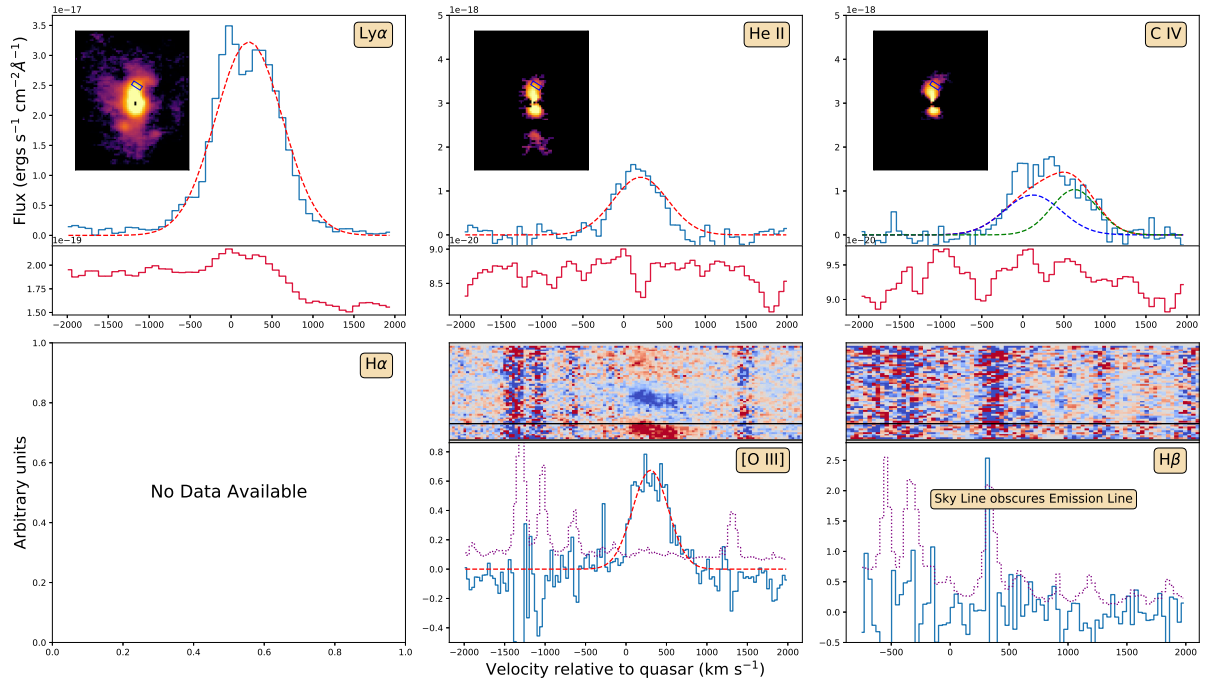


Figure 2.15. All spectra for 3C9-MOS-1

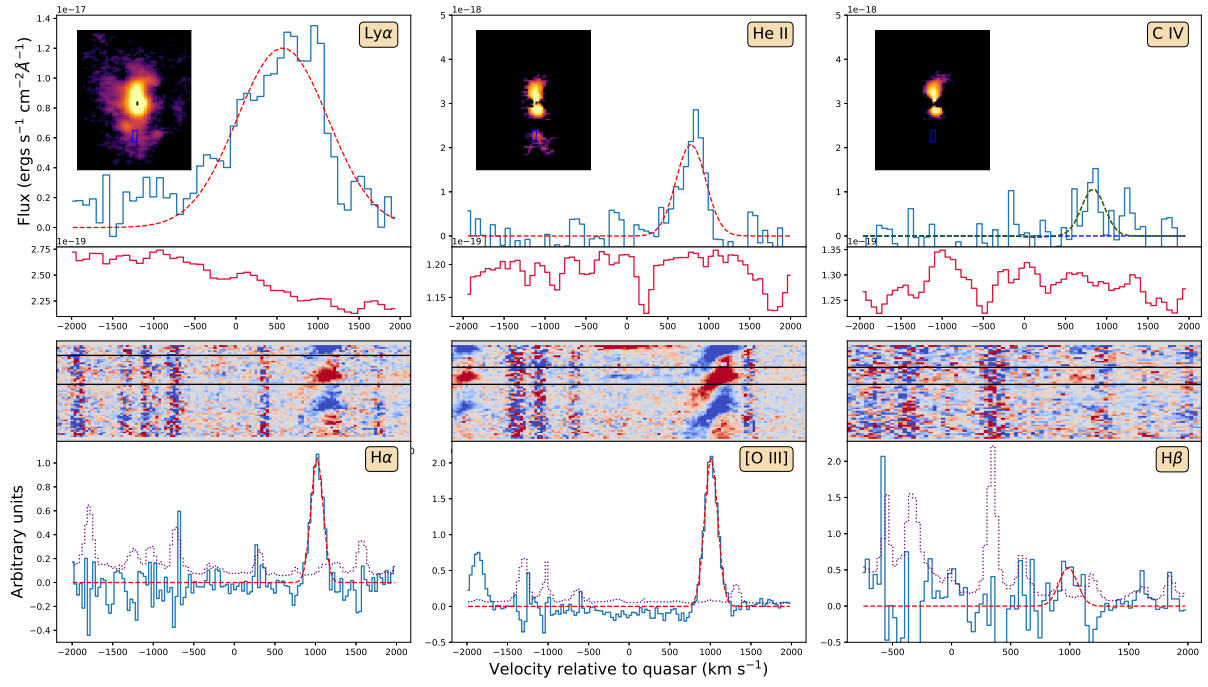


Figure 2.16. All spectra for 3C9-MOS-2

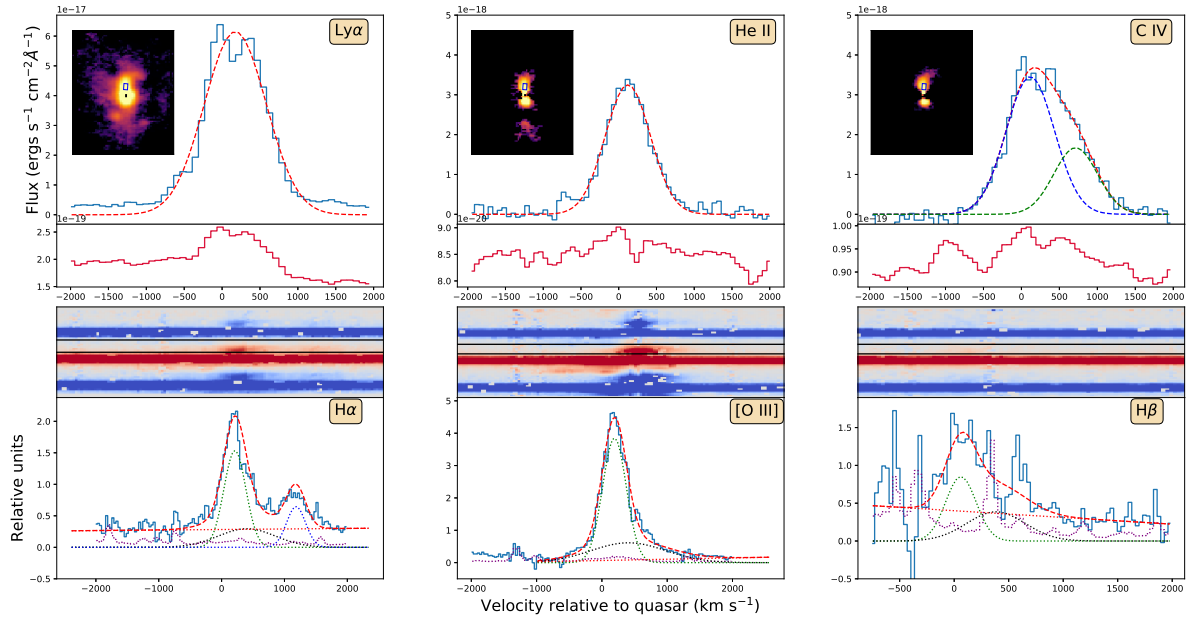


Figure 2.17. All spectra for 3C9-MOS-3

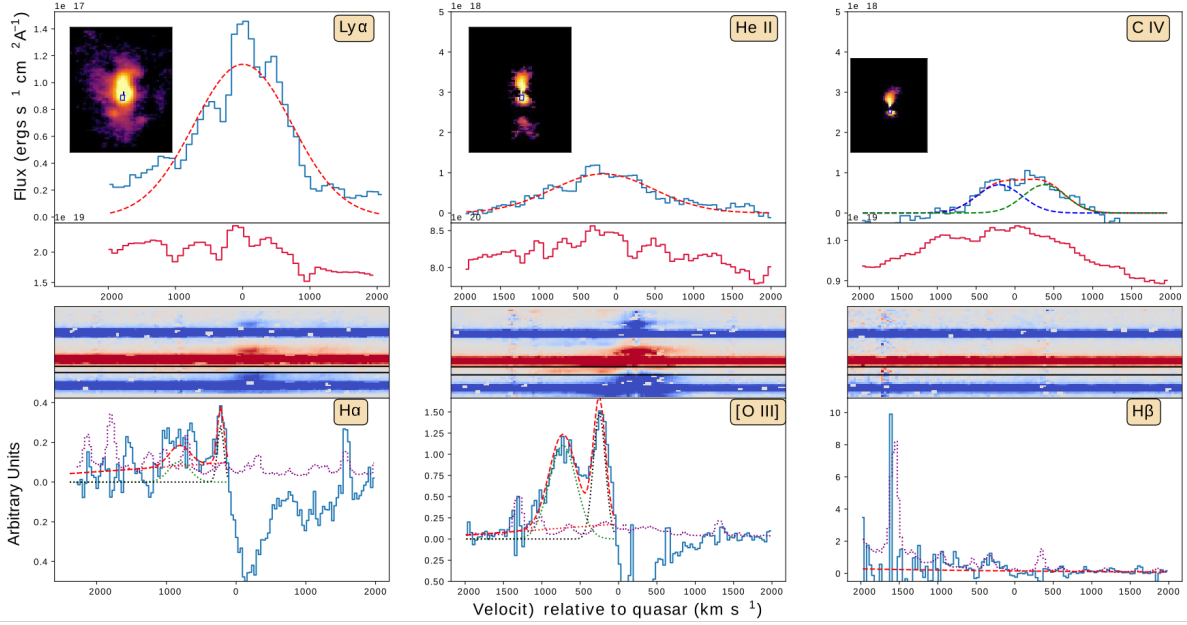


Figure 2.18. All spectra for 3C9-MOS-4

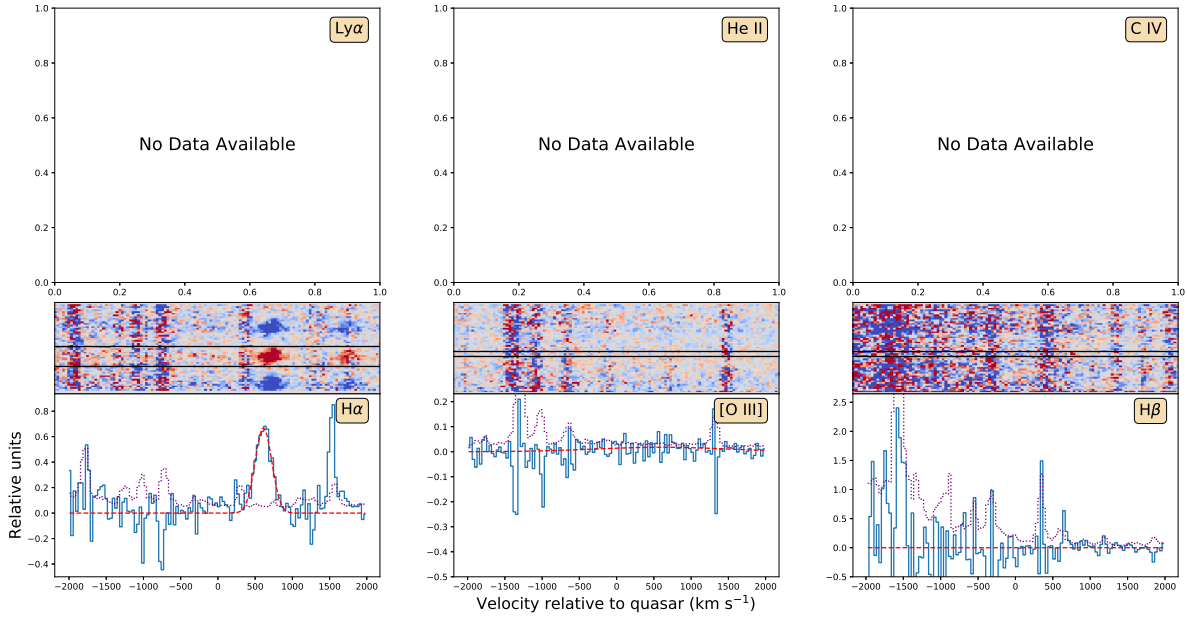


Figure 2.19. All spectra for 3C9-MOS-5

2.6.2 4C 05.84

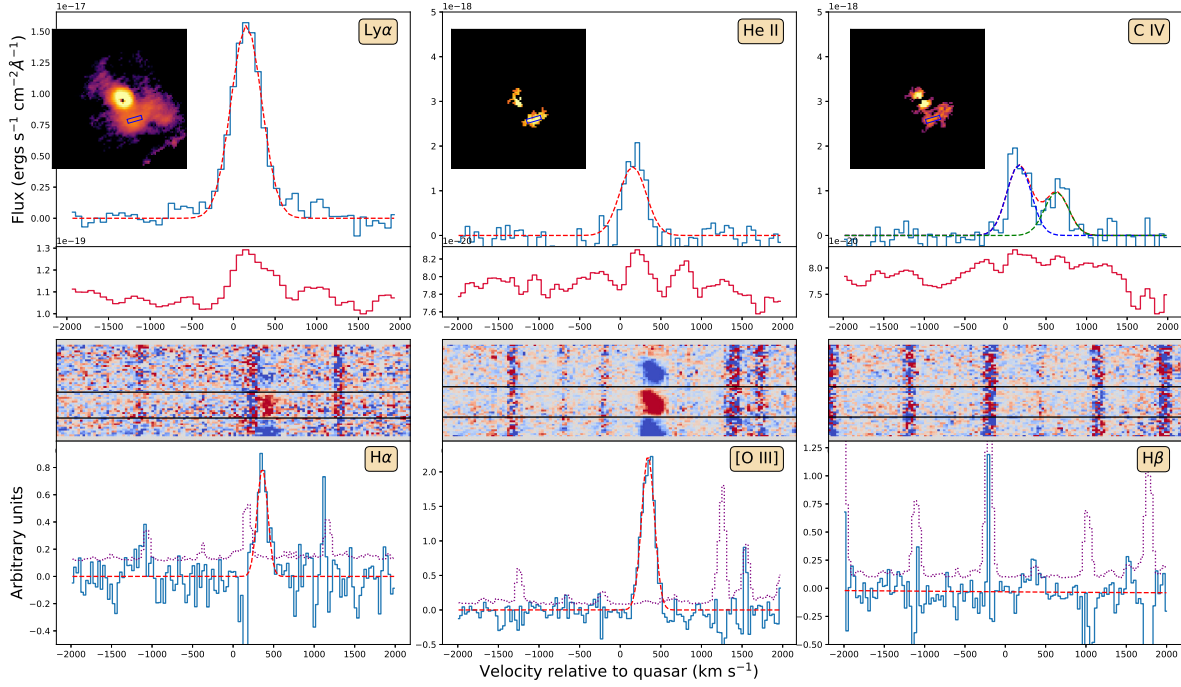


Figure 2.20. All spectra for 4C0584-MOS-1

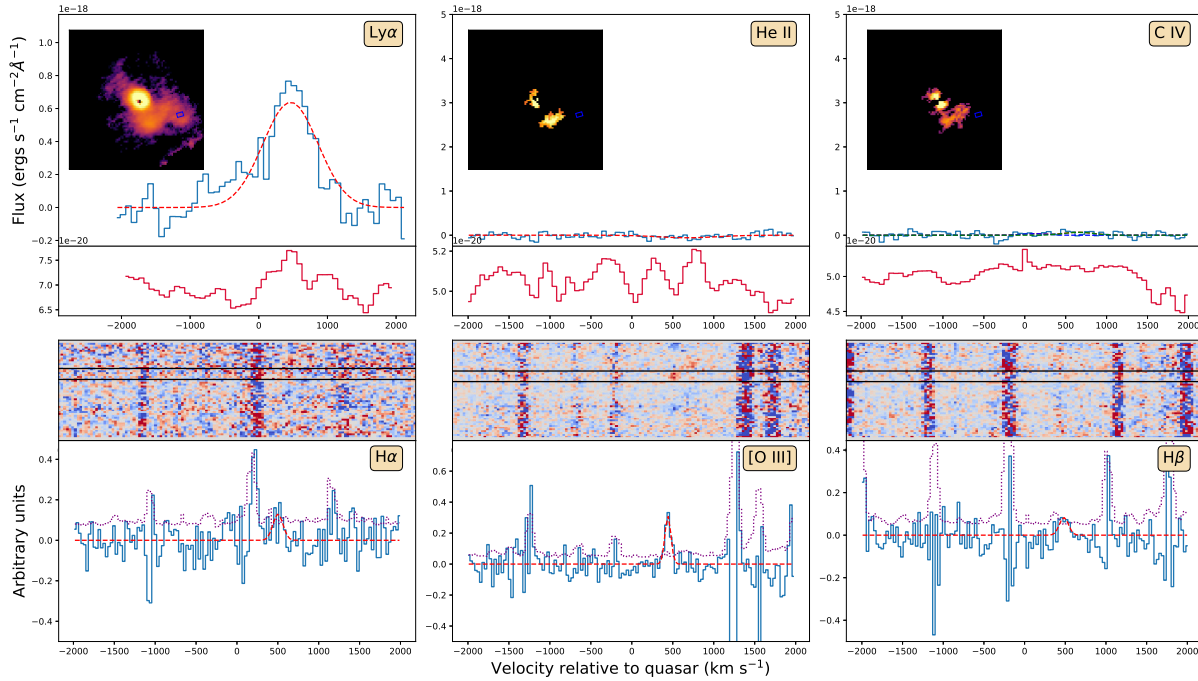


Figure 2.21. All spectra for 4C0584-MOS-2

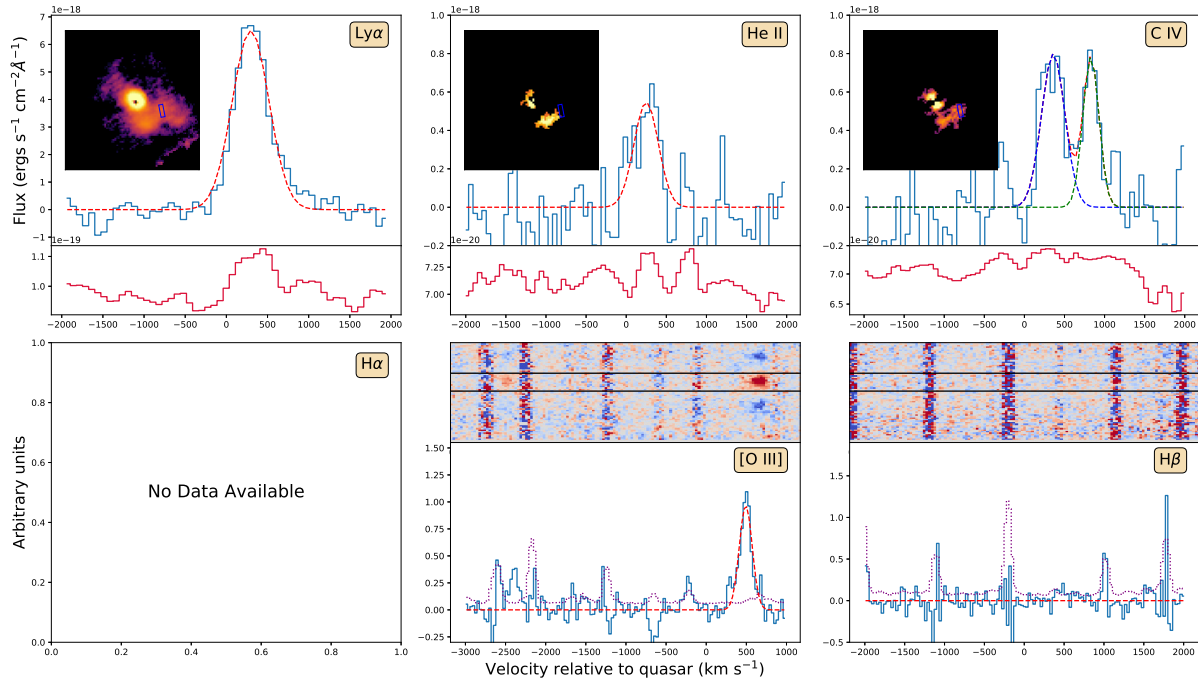


Figure 2.22. All spectra for 4C0584-MOS-3

Chapter 2, in part, is a reprint of the material as it appears in *Astrophys. J.*, Sabhlok, Sanchit; Wright, Shelley A.; Vayner, Andrey; Simonaitis-Boyd, Sonata; Murray, Norman; Armus, Lee; Cosens, Maren; Wiley, James; Kriek, Mariska 2024, *Astrophys. J.*, 964, 84. doi:10.3847/1538-4357/ad2350. The dissertation author was the primary investigator and author of this paper.

Chapter 3

Circumgalactic Environments around Radio-loud quasars at Redshift ~ 2

3.1 Observations

The sample consists of 7 radio-loud quasars with spatially resolved observations of the radio jet emissions. These quasars have been selected from the Sloan Digital Sky Survey and were originally identified in the Cambridge radio survey catalogs.

3.1.1 Strategy

The observations consist of 20 minute exposures on the source and 20 minute sky frames with an ABAAB pattern, dithered around the source, where the A frame targets the quasars and the B frames are “pure” sky frames, ensuring we have at least one neighboring sky frame for each object frame. We used the medium slicer with the BL grating and KBlue filter with the wavelength centered at 4500 . We observed standard stars at the beginning and end of the night selected from the ESO list for Spectrophotometric standards ¹ for flux calibration.

For both quasars, we used the medium slicer with the BL grating and KBlue filter with the wavelength centered at 4500 Å. For the final reduced data, our wavelength coverage was 3532 to 5527, at a spectral resolution of 1,800. The field of view for this KCWI configuration is $16.5'' \times 20.4''$, which was spatially dithered in units of $0.3''$, which refer to only the A frames,

¹<https://www.eso.org/sci/observing/tools/standards/spectra/stanlis.html>

i.e. when looking at the quasars. The total number of dithers varied per object depending on the total time observed. We observed standard stars at the beginning and end of the night. Primary data reduction was carried out using the KCWI Data Reduction Pipeline v1.1. The data reduction follows the procedure described in Section 3.2 from Sabhlok et al. (2024).

Table 3.1. Properties of the QUART sample.

Quasar	RA HMS	Dec DMS	Redshift	Exp. time minutes	Q_{bol} $10^{46} \text{ erg s}^{-1}$	W3 mag_{AB}	S_{5GHz} W Hz^{-1}
3C 9	00:20:25	+15:40:54	2.02	390	8.17 ± 0.31	15.40	443
4C 09.17	04:48:21	+09:50:51	2.1083	320	2.88 ± 0.14	15.54	443
4C 11.45	13:21:18	+11:06:50	2.178	100	-	16.52	793
7C +1354	13:57:06	+25:37:24	2.032	240	2.75 ± 0.11	16.86	120
4C 57.29	16:59:46	+57:31:32	2.173	160	2.1 ± 0.1	15.87	114
4C 05.84	22:25:14	+05:27:08	2.32	560	20.3 ± 1.0	15.18	253
4C 04.81	23:40:58	+04:31:16	2.589	340	0.62 ± 0.02	15.68	470

3.2 Results

3.2.1 Spatially mapping the emission around quasars

The emission around the quasars 3C 9 and 4C 05.84 is described in Sabhlok et al. (2024), while that around 7C +1354 and 4C 09.17 is described in Vayner et al. (2023). The emission around the other three quasars is described here. The Ly α , He II, and C IV Moment maps correspond to Figures 3.1, 3.2 and 3.3 respectively. All emission line moment maps are shown in the Appendix.

4C 57.29

4C 57.29 displays a Ly α nebula ~ 100 kpc in diameter, with the major axis extending from NE to SW of the quasar. The Ly α emission contains velocities ranging from -500 km s^{-1} to 600 km s^{-1} , but appears to be tracing the turbulent motion in the CGM based on the host galaxy mass from Vayner et al. (2021b), and does not show any signs of distinct kinematic components. The He II emission is detected very close to the quasar host galaxy and only a small fraction

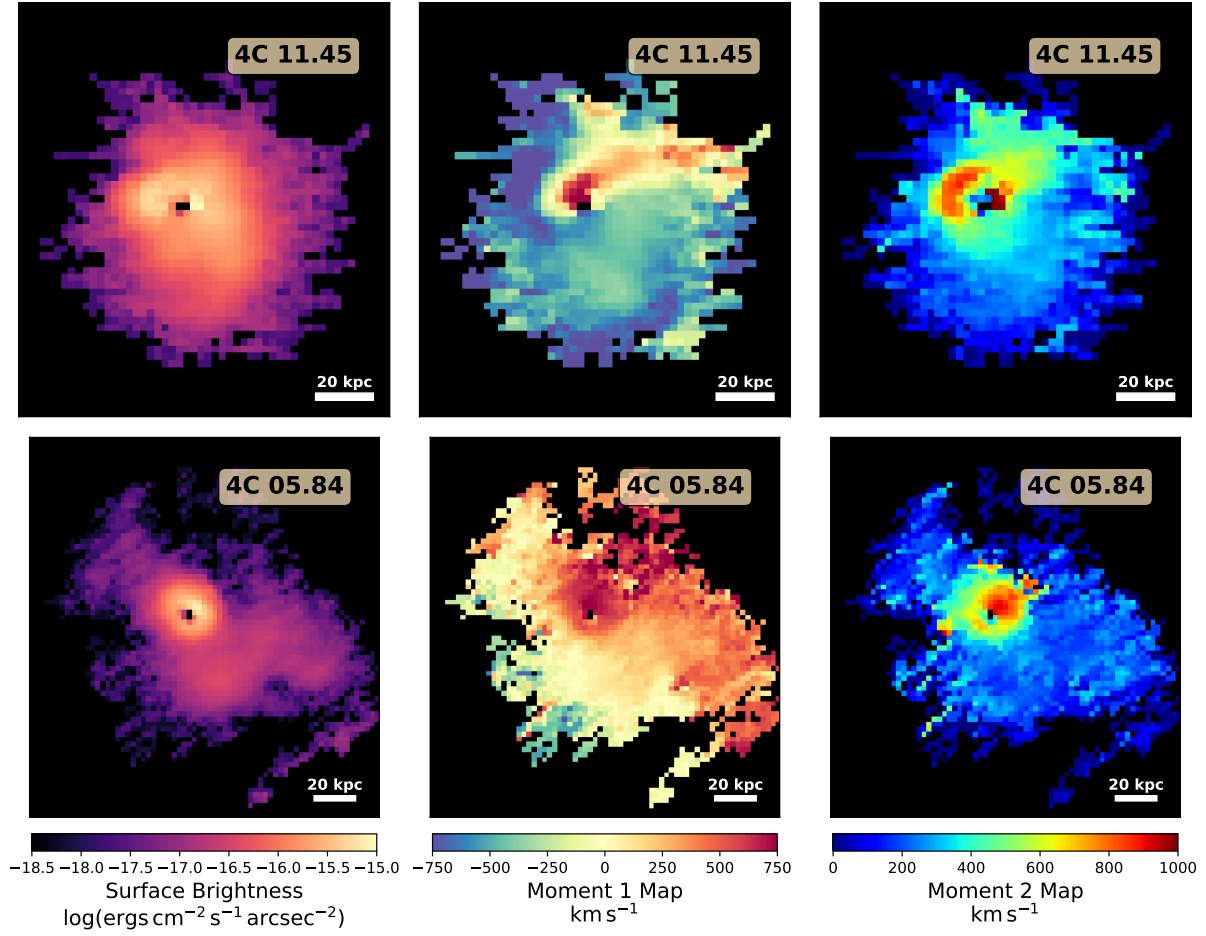


Figure 3.1. PSF-subtracted images of the Ly α surface brightness, Moment 1 and Moment 2 maps for the two sources with the lowest (4C 11.45) and highest (4C 05.84) exposure times on source from the QUART sample. All figures have an on-sky position angle of 0. The systemic redshift used to calculate the moment maps is used from OSIRIS measurements in Vayner et al. (2016) and as shown in Table 3.1. The complete figure set (7 images) is available in the online journal.

of detected emission is spatially resolved and free of any PSF subtraction residuals. The He II velocity suggests a small blueshift with respect to the quasar, corresponding to a velocity of -200 km s^{-1} .

4C 04.81

4C 04.81 displays a Ly α nebula $\sim 80 \text{ kpc}$ in diameter, with the majority of emission originating close to the quasar host galaxy. The emission close to the quasar host galaxy is

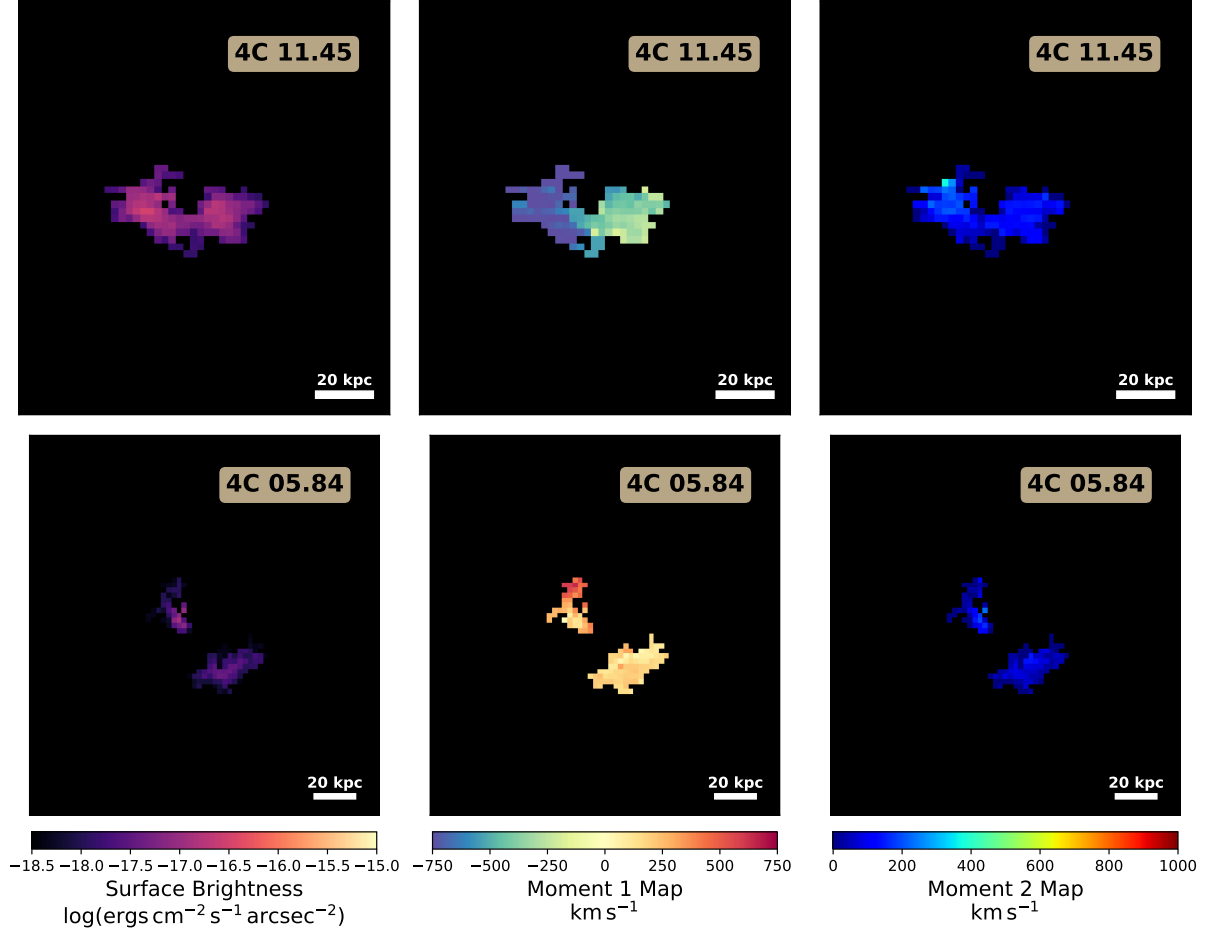


Figure 3.2. PSF-subtracted images of the He II surface brightness, Moment 1 and Moment 2 maps for the two sources with the lowest (4C 11.45) and highest (4C 05.84) exposure times on source from the QUART sample. All figures have an on-sky position angle of 0. The systemic redshift used to calculate the moment maps is used from OSIRIS measurements in Vayner et al. (2016) and as shown in Table ?? . The complete figure set (6 images) is available in the online journal.

redshifted, with velocities $< 500 \text{ km s}^{-1}$. The nebula shows kinematic components with velocity -300 km s^{-1} SE and North of the quasar, but these are low surface brightness features, so it is hard to state whether this is a distinct kinematic component or tracing the multiphase turbulent structure in the CGM. We do not detect any He II or C IV for this source around the quasar host galaxy.

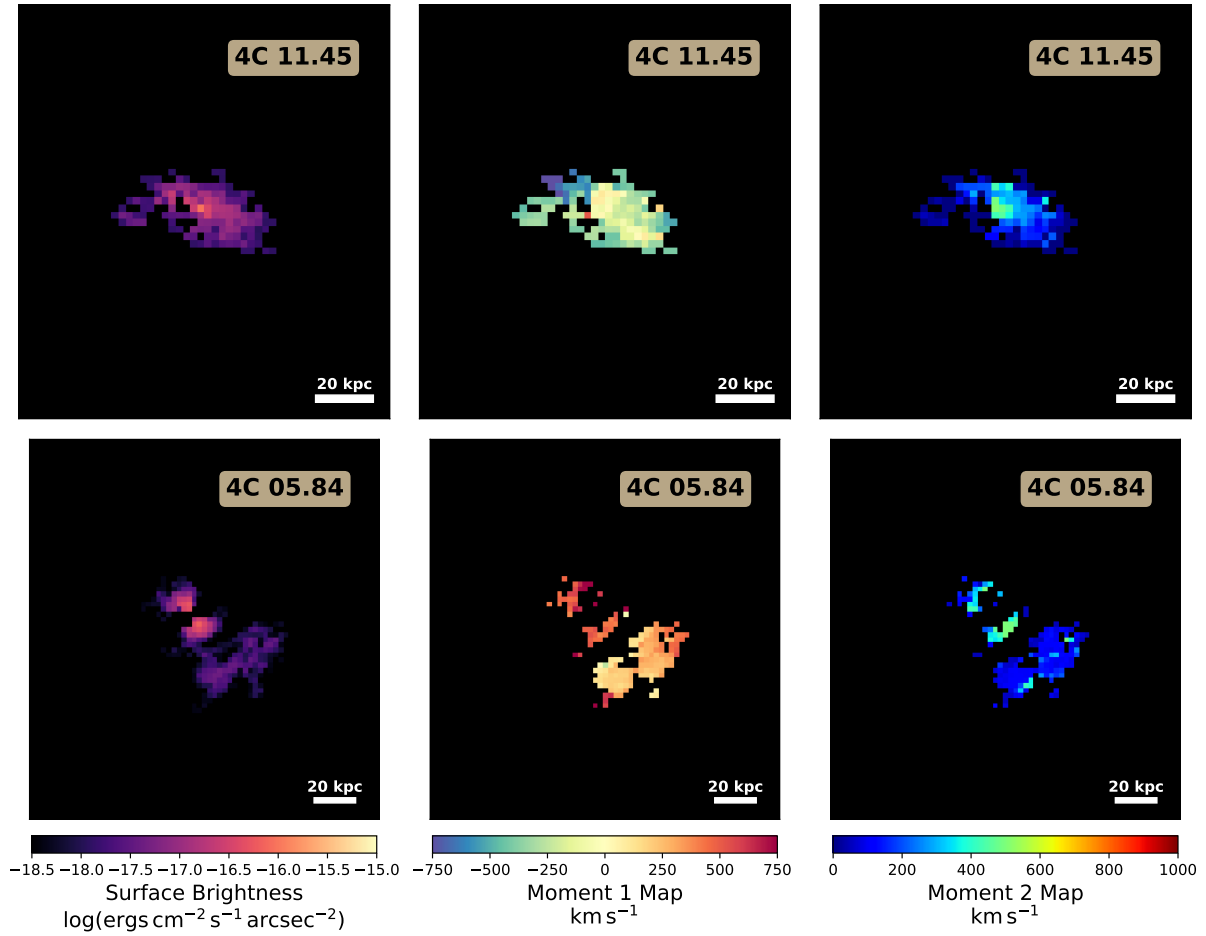


Figure 3.3. PSF-subtracted images of the C IV surface brightness, Moment 1 and Moment 2 maps for the two sources with the lowest (4C 11.45) and highest (4C 05.84) exposure times on source from the QUART sample. All figures have an on-sky position angle of 0. The systemic redshift used to calculate the moment maps is used from OSIRIS measurements in Vayner et al. (2016) and as shown in Table ?? . The complete figure set (7 images) is available in the online journal.

4C 11.45

4C 11.45 displays a Ly α nebula ~ 100 kpc in diameter. The nebula displays strong velocity gradients from -900 km s^{-1} to $\sim 500 \text{ km s}^{-1}$. 4C 11.45 also displays a distinct filament shaped kinematic component in Ly α , extending NW from the quasar ~ 40 kpc away, with a velocity that decreases from 400 km s^{-1} as the on sky separation from the quasar increases. This is also visible in the Moment 2 map, where the structure appears to create a high velocity dispersion,

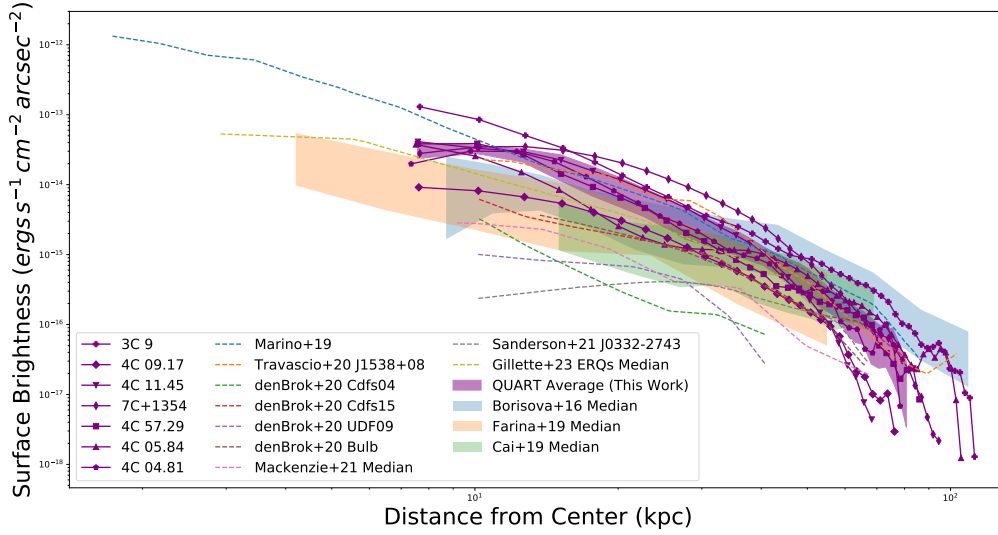


Figure 3.4. $\text{Ly}\alpha$ surface brightness radial profiles extracted from Moment 0 maps for the QUART sample shown for individual sources (purple). The 25th and 75th percentile centered on the median are indicated with the purple fill. Radial profiles start at 8 kpc from the quasar, to remove any contamination due to PSF subtraction residuals. We find the QUART sample profiles to be brighter than other samples shown here from the literature for the inner 30 kpc.

which is in fact two $\text{Ly}\alpha$ kinematic components superimposed on each other, artificially boosting the dispersion values. 4C 11.45 also displays an extended He II nebula about 40 kpc in diameter, showing a smooth velocity gradient from -700 km s^{-1} on the West to -300 km s^{-1} on the East of the quasar. We note that the filament visible in $\text{Ly}\alpha$ is at a perpendicular angle to the orientation of the radio jet. If we are looking at an accreting filament and the radio jet represents the direction perpendicular to the galactic plane, then this would suggest an accreting filament inflowing towards the disk from the equatorial direction with respect to the galaxy.

3.2.2 Radial profiles

Figure 3.4 shows the radial profiles around the QUART sample in comparison to other $\text{Ly}\alpha$ nebulae from literature. Emission from the inner 8 kpc is not considered for the entire sample to avoid any issues due to residuals from PSF subtraction.

The QUART sample has exquisite sensitivity due to deep observations and dedicated sky

subtraction, as indicated by the detected $\text{Ly}\alpha$ emission ~ 100 kpc from the quasars. However, we only indicate the percentile values indicating 25th and 75th percentile of the sample radial profiles out to ~ 80 kpc, since half our sample have maximum extent up to this distance.

The maximum variation in the observed radial profiles is within a factor of 10. This is interesting since the environments around these quasars exhibit a range of substructures. The quasars 3C 9 and 4C 05.84 display evidence of companion galaxies in the CGM, confirmed with follow up spectroscopy (Sabhlok et al., 2024) whereas 7C +1354 and 4C 09.17 show $\text{Ly}\alpha$ substructure in absorption (Vayner et al., 2023). The quasar 4C 11.45 displays a kinematic component suggestive of a cosmic filament in $\text{Ly}\alpha$. He II mapping around the quasars, likely a tracer of strongly ionized gas, suggests ionization states ranging from extended nebulae around quasar host galaxies and companion galaxies to no detection around the quasar host. Thus, for radial profiles of $\text{Ly}\alpha$ to follow a relatively small scatter indicates that a wide variety of CGM substructure can exhibit similar $\text{Ly}\alpha$ emission.

The $\text{Ly}\alpha$ emission in the inner 10 – 30 kpc is found to be brighter than other samples in literature. While this could be due to a selection bias, it can also originate due to enhanced emission in the inner CGM due to an increased contribution from scattering of $\text{Ly}\alpha$ photons from the quasar. Due to the KCWI field of view, the observations are limited to within 8–10'' of the quasar, which translates to ~ 64 –80 kpc from the quasar at this redshift. As literature observations from MUSE have a wider field of view, the higher brightness of $z \sim 3$ quasars beyond the inner 60 kpc can be due to the wider field of view and may not be representative of the QUART sample's intrinsic brightness.

3.2.3 Redshift evolution

Figure 3.5 shows the total $\text{Ly}\alpha$ luminosity as a function of redshift for the QUART sample and other $\text{Ly}\alpha$ nebulae in literature. While we observe an increase in luminosity from $z = 2.5$ to $z = 2$, this is statistically not a large enough sample to robustly identify an evolution

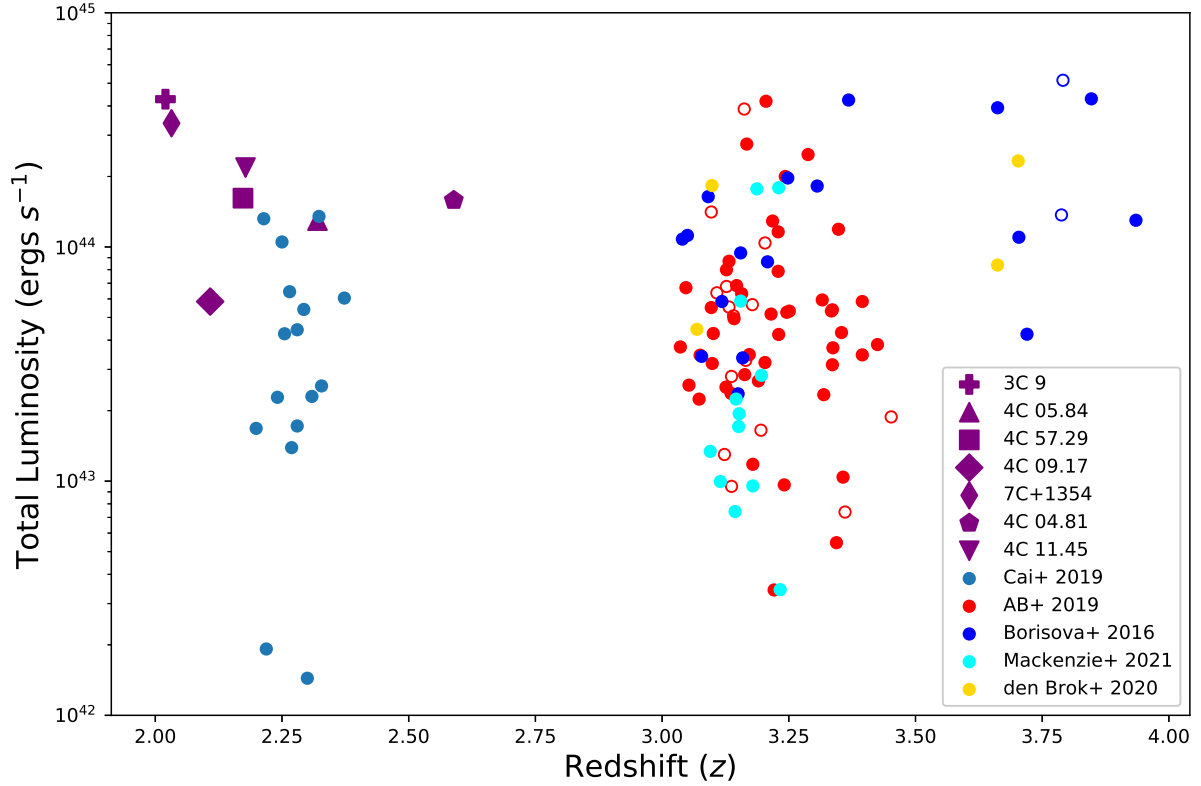


Figure 3.5. Redshift evolution of total Ly α luminosity from the CGM. The luminosity is calculated from PSF subtracted surface brightness map so contributions from the quasar have been subtracted. For papers in the literature, the radio-loud sources are shown with open circles, whereas radio-quiet and sources whose radio-loudness cannot be confirmed are shown as filled circles.

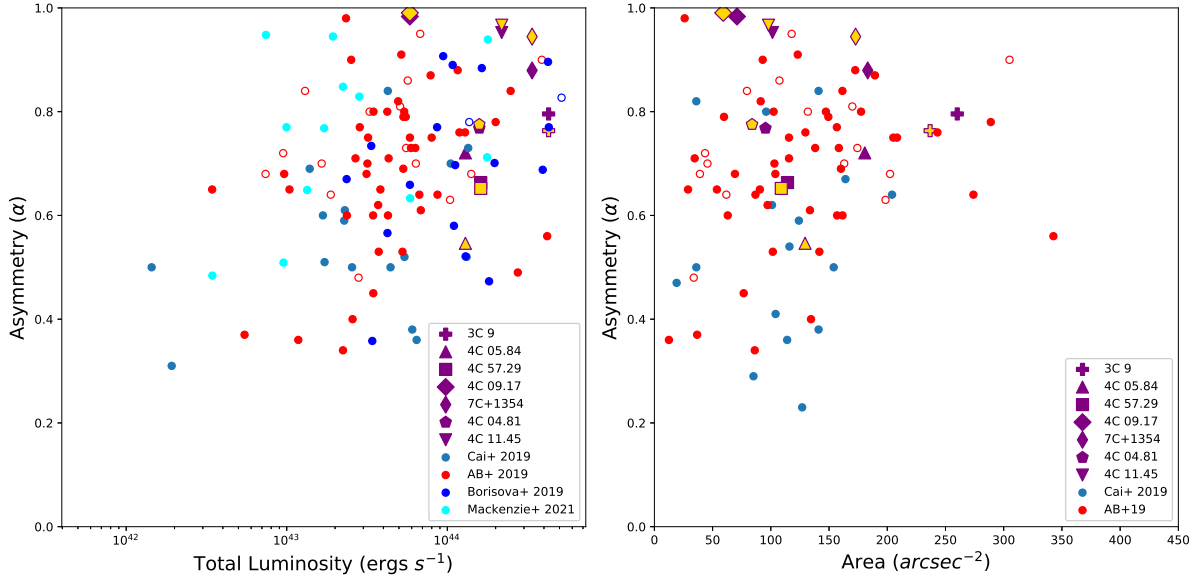


Figure 3.6. Asymmetry of $\text{Ly}\alpha$ nebulae as a function of total luminosity and area on sky. Radio loud sources from Arrigoni Battaia et al. (2019) and Borisova et al. (2016) are indicated with open circles. While the purple filled points denote the QUART observations, we have recalculated these values to match the sensitivities of other studies to show how the values change depending on the sensitivity.

with redshift. However, we note that the QUART sample displays higher total luminosity compared to other quasars at this redshift from (Cai et al., 2019) and the median luminosity is comparable to the upper end of the range seen in $z > 3$ $\text{Ly}\alpha$ nebulae bluequantify medians for all samples. Particularly, we indicate the radio loud sources in (Arrigoni Battaia et al., 2019) with open circles and they indicate a larger scatter in luminosity than the QUART sample. This indicates that radio-loudness may not be the only contributing factor in the enhanced luminosity of the QUART sample.

3.2.4 Asymmetry

We calculate the asymmetry factor α for all QUART sources similar to the procedure followed in (Sabhlok et al., 2024). This asymmetry is compared to the total $\text{Ly}\alpha$ luminosity and the on-sky projected area of the quasars in Figure 3.6. Due to the exquisite sensitivity of the QUART sample, we need to compare the asymmetry in other literature sources at a lower

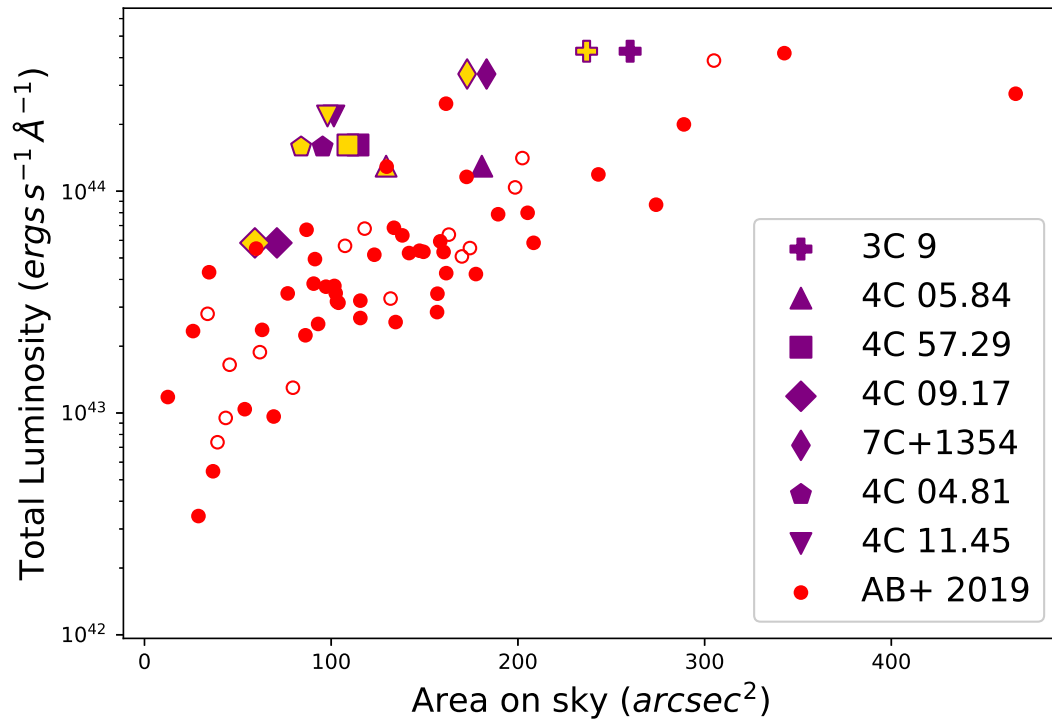


Figure 3.7. Total Luminosity as a function of area on sky. Radio loud sources from Arrighi Battaia et al. (2019) are indicated with open circles.

sensitivity of $2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$. These datapoints are indicated for the QUART sample with a gold fill, showcasing the change in asymmetry and on-sky projected area as a result of higher sensitivity. We find that the asymmetry and on-sky area do not change significantly due to improved sensitivity except for two sources, 3C 9 and 4C 05.84. These sources have the highest on-sky exposure times in the QUART sample, but also display signatures of companion galaxies in the CGM. A priori we would expect the presence of companion galaxies to make the Ly α emission more *asymmetric*, as they enhance emission in a small area at a fixed distance from the quasar. Thus, the observed *increase* in asymmetry is actually due to detection of low SNR features in the extended Ly α emission all around the quasar, making the nebulae more symmetric due to higher sensitivity. We also note that the observed asymmetry does not systematically increase or decrease with improvement in sensitivity, as both are observed in our sample.

3.2.5 Luminosity

Figure 3.7 shows the dependence of total Ly α luminosity on the observed on-sky area in square arcsec. We reproduce the observed increase in total luminosity as a function of area as seen in literature, showing the sources from (Arrigoni Battaia et al., 2019), where the radio-loud sources are indicated with open circles. The QUART sources do indicate a higher luminosity compared to the Arrigoni Battaia et al. (2019) sample for the same area. This comparison gets stronger when we compare for reduced sensitivity of $2 \times 10^{-18} \text{ erg s}^{-1}$, as shown with gold filled symbols for the QUART sample. This trend holds even when comparing only to the radio-loud quasars in the Arrigoni Battaia et al. (2019) sample, where several nebulae with comparable area on sky but lower luminosity are detected, even after accounting for the difference in the sensitivities of the two samples.

3.2.6 He II and C IV emission around the QUART sample

Extended He II emission is detected around 6 out of 7 QUART sources whereas C IV emission is detected around all 7 sources. The He II and C IV nebulae extend from $\sim 20 \text{ kpc}$

(4C 57.29) to ~ 80 kpc (7C+1354). The nebulae range in velocity from -800 to $+800$ km s^{-1} as indicated by the moment maps.

Comparing the nebulae to the location of the radio jets in each quasar offers an avenue to explore the role of geometry and photoionization in powering these nebulae. Since all radio jets in the QUART sample are FR-II one sided jets, the direction of the jet with respect to the quasar indicates the near side beaming towards the observer. If the observed He II and C IV emission is due to quasar photoionization, the emission should be coincident with the direction of the jet, since the photoionization cone of the quasar should be aligned with the radio jet. This photoionization cone can be clearly seen in He II and C IV emission in 3C 9, and in C IV emission in 4C 05.84. These photoionization cones are consistent with the direction of the radio jets, notwithstanding projection effects along the line of sight. While the majority of He II and C IV emission is in the same direction as the radio jet, there are a few exceptions -

1. 3C 9 shows a large 15–30 kpc He II nebula south of the quasar offset from the radio jet emission. The nebula shows no spatially resolved C IV emission. Moreover, while the jet in 3C 9 is brighter SE of the quasar, the biconical structure seen in C IV and He II is in fact more extended north of the quasar.
2. While the radio jet in 4C 09.17 points SW of the quasar, the He II and C IV emission is located to the North of the quasar.
3. 7C+1354 shows the most extended He II nebula in our sample. However, the radio jet points West of the nebula, with no eastern lobe is detected. Additionally, two radio jet relics can be seen North and South of the quasar, ~ 40 kpc away from the quasar. If these are radio relics of past quasar activity, they indicate a significant change in the direction of the radio jet. If the AGN ionization cone is also presumed to have changed direction in the same time, that could explain the significantly larger He II and C IV emission around the quasar and relatively symmetric nature of this emission compared to the other sources in the sample.

3.3 CGM and Radio Jet comparisons

The radio jets around the QUART sample are shown in Figure 3.8 and described in Table 3.1. Originally presented in the 3C (Smith et al., 1976), 4C (Pilkington & Scott, 1996) and 7C (McGilchrist et al., 1990) radio catalogs, these sources all consist of a compact FRII radio jet. The jets are fully contained within the KCWI field of view, making it possible to correlate the jet emission with observed nebular emission in the CGM. All jets show hotspots brighter than the emission at the core far away from the quasar at on-sky projected distances of 8 – 30 kpc away. Due to Doppler boosting, the brighter hotspot can be identified in all the sources, which informs us that the jet is travelling towards the observer along the line of sight, in the foreground of the host galaxy. This allows us to identify the morphology and geometry of radio jet emission with respect to the quasar host galaxy and will be useful when comparing with nebular emissions.

A comparison between the astrometry of radio jet emission with the nebular emission observed using KCWI is used to investigate if the two are related or not, or if there is insufficient data to make a determination. The underlying theoretical rationale for this exercise is as follows. In (Sabhlok et al., 2024) we discussed how the observed nebular emissions for 3C 9 and 4C 05.84 can be described by using a two component model, where the Inner CGM (with on-sky projection < 30 kpc) is ionized directly by the quasar, whereas the outer CGM is only visible in $\text{Ly}\alpha$, and is likely emitting due to scattered ionizing and recombination radiation. If the radio jets are indeed aligned with the ionization cone of the quasar, then we would expect to see the nebular emission aligned with the radio jet major axis. Since the opening angle of a quasar’s ionizing cone is a difficult quantity to constrain, we consider a typical opening angle of 45° to compare if the major axes of nebular emission is aligned with the radio jet or not in the following section.

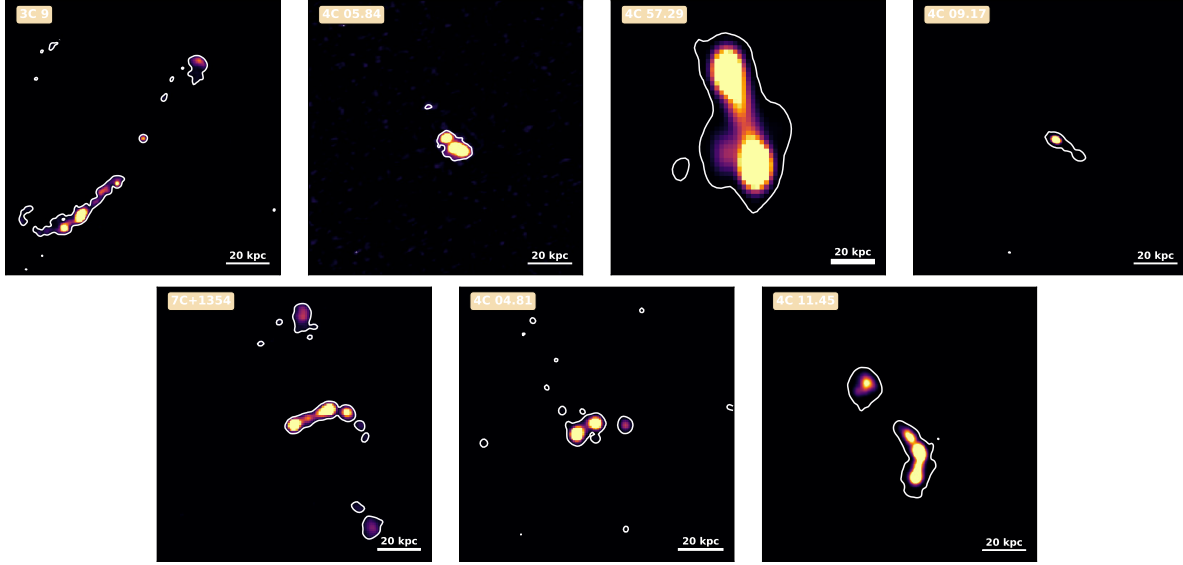


Figure 3.8. Radio jets around the QUART sample. The outermost contours represent a 5σ SNR extraction limit.

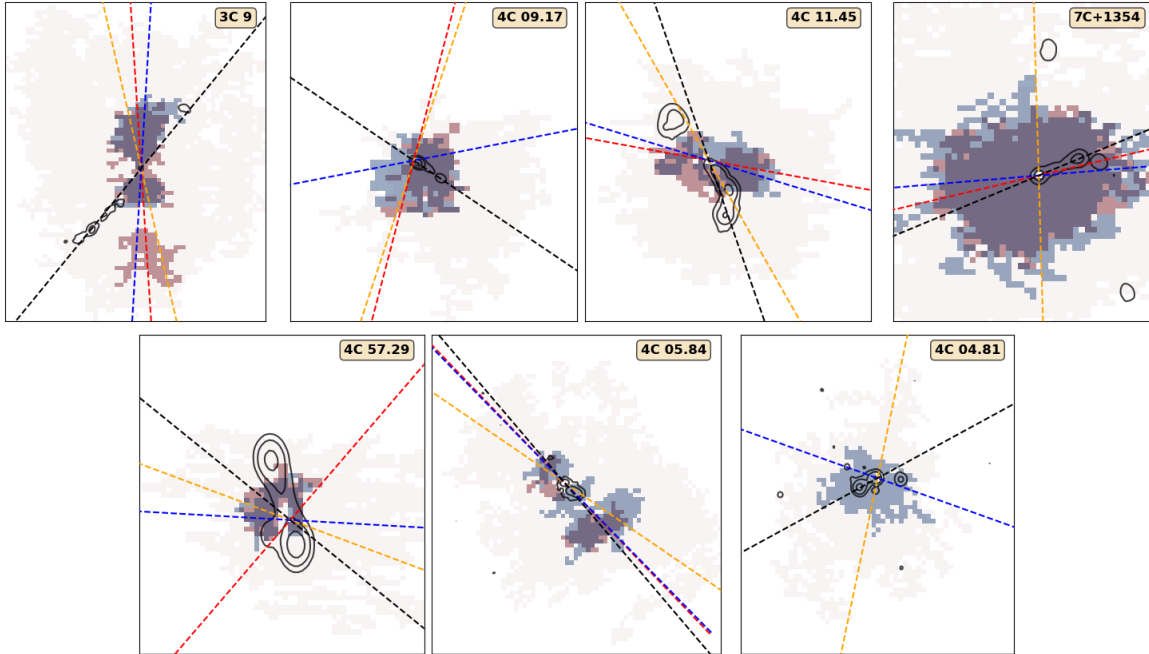


Figure 3.9. The major axes for the radio and nebular emission around all QUART sources. The radio contours are shown in black, with the flux weighted major axis shown in black dashed lines. Similarly, $\text{Ly}\alpha$, He II, and C IV are shown in orange, red and blue shades, with the major axes plotted as dashed lines with the same colors respectively.

3.3.1 Major axes of emission

The calculation of the major axes orientation for nebular emission results from the asymmetry estimation as described in Section 3.2.4 following the procedure described in Sabhlok et al. (2024). Figure 3.9 shows the major axes derived for Ly α (orange), He II (red) and C IV (blue) emission, in addition to the major axis of the radio jet emission (black). Considering a typical ionization cone opening angle of $\sim 45^\circ$, the He II and C IV emission is aligned with the radio jet emission in 4 out of 6 and 7 out of 7 sources respectively. The He II, and C IV nebulae are spatially resolved in all of these sources, so the agreement or lack thereof cannot be attributed to unresolved emission. However, the Ly α emission definitively aligns with the radio jet in 4 out of 7 sources, with 4C 04.81 being slightly misaligned whereas 4C 09.17 and 7C +1354 are misaligned by larger angles. This is discussed further in Section 3.3.2. Unlike Ly α , He II and C IV emission must be powered largely by ionizing radiation from the host galaxy AGN. The detection of extended He II and C IV emission around most of our sample and the alignment of major axes of emission with the radio jet emission indicates the emission is powered by quasar photoionization.

3.3.2 Ly α emission at the location of radio jets

We extract Ly α and He II spectra at the location of the radio jets by taking the 5σ contours from radio maps and extracting nebular emission from the KCWI data from those regions. Data from spaxels that are less than 3 pixels away from the quasar are excluded to remove any residual emission from the AGN. The spectra thus represent the integrated emission from the CGM at the location of the radio jets. Figure 3.10 shows these spectra.

Before we discuss individual sources, it is useful to consider what is expected from the nebular emission, based on radio jet models. All the jets considered in this sample are FR-II jets, which implies their emission from the hotspots far away from the AGN dominates the emission from the core (Bridle & Perley, 1984; Lonsdale et al., 1993). As FR-II jets typically have one

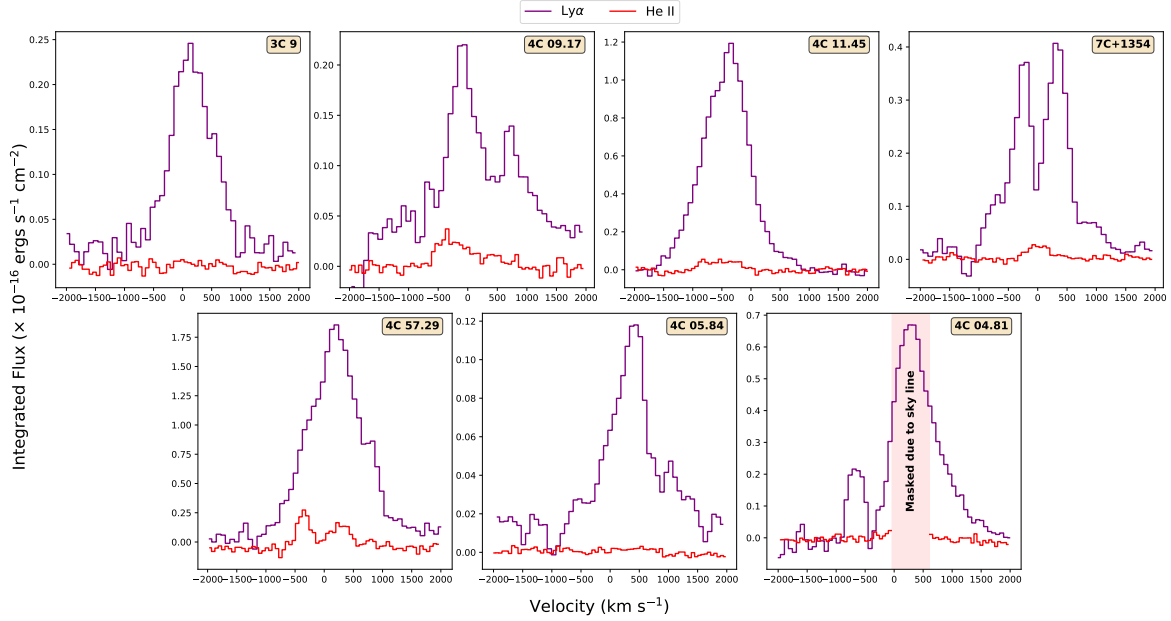


Figure 3.10. Ly α and He II emission at the location of the radio jets. The velocity is calculated with respect to the systemic redshift of the quasar.

lobe appear brighter than the other due to Doppler boosting of the synchrotron radiation, it establishes whether that side of the jet is in front (if brighter) or behind (if fainter) the quasar. Thus, if these jets are driving outflows, the emissions from outflows in front of the galaxy should appear to be blueshifted, whereas outflows behind the galaxy should be redshifted. This is particularly helpful since many of the jets in this sample are largely one sided, and thus the expectation is for the blueshifted component of nebular emission to dominate. However, as Ly α is the primary emission line being observed, it is difficult to directly ascribe gas motions to observed components due to the resonant nature of the line that can lead to scattering. Or to rephrase, the broadening of Ly α due to the presence of an outflow is degenerate with the broadening due to the random walk in frequency/wavelength space experienced by the photons as a result of repeated scattering throughout the medium. The presence of He II emission from the same region helps resolve this degeneracy to some extent, as the presence of He II likely indicates the true gas velocities in the CGM. The absence of He II in these spectra is thus indicative of either lower density gas being primarily responsible for the Ly α emission or larger

contributions due to scattering of $\text{Ly}\alpha$. An additional problem in identifying components occurs due to the degeneracy in distinguishing two separate kinematic components or one component with a foreground absorber. Vayner et al. (2023) and Wang et al. (2023) have shown these foreground absorbers cover a large fraction of the $\text{Ly}\alpha$ nebula and can be spatially resolved by mapping the absorption depth and width across the nebula. The presence of He II emission can help distinguish between these degeneracies as well, as multiple $\text{Ly}\alpha$ peaks with corresponding He II peaks are likely to be two independent components, whereas the presence of a single He II component in between two $\text{Ly}\alpha$ components likely indicates the absorption scenario.

We now consider individual sources and comment on the nebular emission, given the observed radio jet emission.

3C 9: 3C 9 shows $\text{Ly}\alpha$ emission centered at the quasar redshift. Potential absorption is seen at $\sim 400 \text{ km s}^{-1}$. If true, this is likely due to foreground absorbers sitting in front of the redshifted component, which is being emitted by the gas behind the quasar. There is no evidence of significant He II emission corresponding to the $\text{Ly}\alpha$ emission, indicating that the emission largely originates from recombination radiation and scattering from low density ionized gas in the CGM.

4C 09.17: 4C 09.17 shows distinct red and blueshifted components with a potential redshifted broad component in the spectrum. Since the on-sky projection of the radio jet is small and relatively close to the quasar, the nebular emission originates in the CGM close to the quasar host galaxy. It is interesting to note that the presence of a red and blueshifted He II component corresponding to the $\text{Ly}\alpha$ emission, indicating these are two independent components and not a single component with foreground absorption. The $\text{Ly}\alpha$ nebula around 4C 09.17 and the radio jet are both largely on the same side of the quasar, and thus the expectation is for $\text{Ly}\alpha$ to be originating in at or in front of the quasar along the line of sight. This suggests the redshifted component corresponds to foreground gas moving towards to quasar.

4C 11.45: 4C 11.45 is a really interesting source due to the presence of a bent radio jet. Radio jets typically bend in the presence when encountering hot gas from the intergalactic

medium. The fact that the bend here is seen at the boundary of both the He II and C IV emission detection indicates that the He II and C IV emission is tracing the cold components of the inner CGM. The Ly α emission here shows only a blueshifted component with a small contribution from He II. This agrees with the expectation that the He II only represents a fraction of the gas giving rise to the Ly α emission, namely the cold inner CGM component.

7C 1354: The He II emission around this source is by far the largest individual He II nebula around any of the QUART sources. The Ly α emission from the radio jet regions shows a bimodal distribution centered at the systemic velocity of the quasar. The He II emission is centered at the quasar redshift. These results are in agreement with the picture presented in Vayner et al. (2023) that the quasar sits behind a system of foreground absorbers.

4C 57.29: 4C 57.29 shows the smallest He II and C IV nebulae in the QUART sample with the projected on-sky radio jet emission extending beyond the nebulae. Nevertheless, the Ly α and He II emission spectra at the location of the jet indicate the presence of two distinct blue and redshifted kinematic components.

4C 05.84: 4C 05.84 is an interesting source that shows only a redshifted component, with no contribution from He II at the location of the jet. The quasar system is home to companion galaxies SW of the quasar (Sabhlok et al., 2024) and this is the direction the radio jet also points in. The largely redshifted component indicates the gas at the location of the jet is likely moving towards the quasar, potentially due to tidal interactions with the CGM subhalo of the companion galaxy.

4C 04.81: 4C 04.81 shows a distinct asymmetric profile at the location of the radio jet. The jet itself is interesting since the on-sky projection remains close to the quasar host galaxy, and yet both hotspots have comparable peak intensities. We note that this is exactly the kind of spectrum we would expect to see if Ly α were to exactly trace the gas motion, and if the extraction was from a brighter foreground (blueshifted) component and a fainter background (redshifted) component. However, due to the lack of He II detection around the source, the determination cannot be made definitively.

To summarize, we use the assumption that the nebular emission from the locations of the radio jets originates from the foreground or the background of the galaxy, and use the He II emission to confirm whether the Ly α emission is originating from multiple kinematic components or a single component with foreground absorbers. Under these assumptions, we detect evidence for cases with multiple kinematic components in the quasars 4C 09.17 and 4C 57.29, whereas the emission in 4C 11.45 is due to a single component. The quasars 3C 9 and 4C 05.84 show no He II emission at the location of the radio jets, indicating the origin of the Ly α radiation to be from lower density cold CGM with significant contributions from scattering. We also see in the case of the quasar 7C 1354+2552 that the Ly α emission is likely due to a single component at the redshift of the quasar and is absorbed by foreground absorbers. For 4C 04.81, we detect two components but are unable to comment on their origins due to inability to extract He II emission from the regions. We also see the potential impact of a bent jet on the CGM in the case of 4C 11.45, where the bend occurs precisely at the boundary of He II and C IV emission. Thus, 3 quasars show evidence of multiple kinematic components whereas 2 show evidence of a single component, whereas for 2 sources the origin cannot be determined based on the available data.

3.4 Discussion

3.4.1 Comparison with OSIRIS observations of quasar host galaxies

We compare the integrated luminosities of nebular emissions in the CGM with measurements of the quasars bolometric luminosity Q_{bol} , and the total host galaxy H α and [O III] emissions (after subtracting emissions from the PSF) in Figure 3.11 as calculated in Vayner et al. (2021b) and Vayner et al. (2021c). We find that for our sample, the Ly α luminosity shows no trends with the quasar bolometric luminosity or the host galaxy's H α and [O III] emissions. As the quasar bolometric luminosity is representative of the ionizing radiation due to the AGN and the H α and [O III] emission from the host galaxy represent ionizing radiation

from potential star formation in the host galaxies, the independence of the total $\text{Ly}\alpha$ emission from the CGM indicates that scattering likely plays an important role in the total luminosity, as discussed previously in Sabhlok et al. (2024).

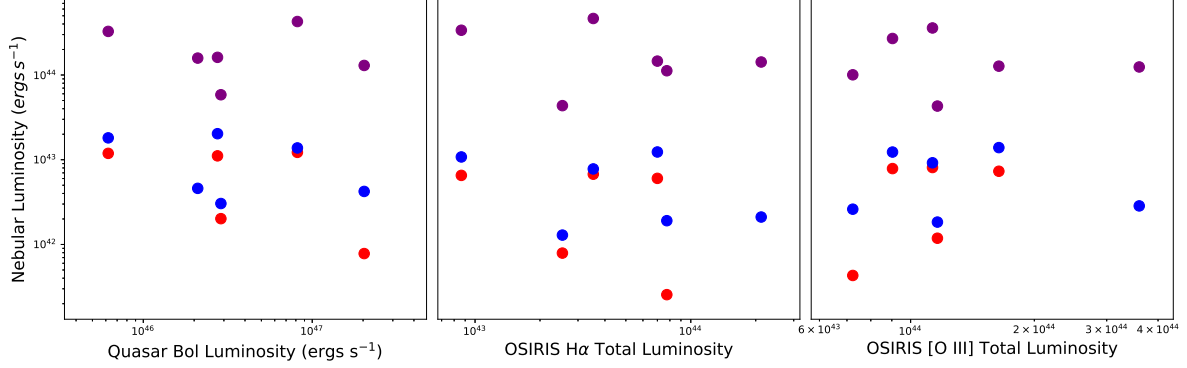


Figure 3.11. KCWI Nebular luminosities with $\text{Ly}\alpha$ (purple), He II (red) and C IV (blue) plotted against the quasar bolometric luminosity (Left), the total $\text{H}\alpha$ luminosity (Middle) and the total [O III] luminosity (Right). No significant correlation is observed based on these observations although a weak trend can be seen in all cases, most prominently when looking at the bolometric luminosity.

When comparing the total He II and C IV luminosities, we do not find a significant correlation with the [O III] emission, however, there seems to be a weak correlation with the total $\text{H}\alpha$ luminosity and a slightly stronger correlation for the quasar’s bolometric luminosity. Given the morphologies of C IV and He II emission around the quasars, we expect these to be powered by quasar photoionization, so the decreasing luminosities with increased Q_{bol} are puzzling. One possible explanation for this can be due to the finite duty cycle of AGN. AGN episodes have typical lifetimes of $\text{O}(10^5)$ years, and the distance covered by the light in this time period is comparable to the sizes of the detected nebulae ($\text{O}(10 \text{ kpc})$). We assume the total He II and C IV luminosity is proportional to the total amount of ionizing radiation received at the time of observation. Thus, the largest He II and C IV luminosities represent a larger cumulative ionizing radiation. Thus the quasars with the lowest Q_{bol} have already emitted a larger amount of ionizing radiation and thus it is plausible that they are closer to the end of the AGN episode. The opposite is also true, as a quasar that is closer to the beginning of an AGN episode has not

had enough time for the ionizing radiation to propagate outward and ionize the He II and C IV nebulae. Thus, this negative correlation is potentially tracing the AGN episode lifetime. While we caution that this is only a tentative correlation and is susceptible to sample bias due to a small sample, the fact that we see this for both He II and C IV is an encouraging sign.

3.4.2 Comparison with other Ly α samples

In section 3.2, we compare our results with other studies of Ly α emission in the CGM in the literature, namely Cai et al. (2019) at $z=2$, Borisova et al. (2016) and Arrigoni Battaia et al. (2019) at $z=3$, which have established the ubiquity of large Ly α nebulae around high z quasars. We find a 100% detection rate for Ly α , and C IV, emission and detect He II for 6 out of 7 sources in our sample. The detected Ly α nebulae range in radius from 70 to 110 kpc, whereas the He II and C IV nebulae range from 10 to 40 kpc.

The QUART sample differs from these studies due to deeper observations, probing lower 2σ sky residual noise ($2 - 10^{-20}$ erg s $^{-1}$ cm $^{-2}$), dedicated targeting of radio-loud sources with compact jets and the presence of extensive multi-wavelength data including spatially resolved observations of the quasar host galaxies. We detect He II and C IV emission around all of our sources, although He II detection around 4C 04.81 could not be extracted effectively due to proximity with a sky line. The brightness of the nebulae indicates the detections are not solely due to longer exposure times and improved sensitivity. Lastly, since the gas motions associated with Ly α are difficult to constrain from Moment 1 maps alone, we associate the radio jet orientation with Ly α emission to constrain the geometry of the Ly α emission.

We suggest that the visibility of radio jets on sky implies that all these sources are being viewed at an angle that allows the ionization cone to be projected on sky, which allows us to view the He II and C IV nebulae being ionized around the quasars. Confirming this will require comparing to a larger sample of sources where the radio emission can be categorised as either extended or compact. It is possible that the low rate of He II and C IV detection in the other sources is due to the radio source being confined to the seeing disk around the quasar and thus not

distinguishable from the quasar PSF. Some Extremely Red Quasars (ERQs) and a few radio-quiet type-1 quasars show He II and C IV emission (Cantalupo et al., 2014; Lau et al., 2022). If the visibility of He II and C IV was solely due to the viewing angle, then we might expect to detect nebulae around radio-quiet sources and ERQs. This suggests that He II and C IV ionization is linked to the duty cycle of quasars and are only visible when the ionization is high enough to create a jet.

We compare our results with the recent observations of ERQs (Lau et al., 2022; Gillette et al., 2023). This is particularly useful since ERQs are AGN viewed through the dusty torus. We note that the W3 magnitudes for our sources are comparable to those for ERQs in these samples and the differences between the samples are due to the color selection for ERQs. If these quasars are viewed through the dusty torus, then the ionization cones must be projected on the sky and He II and C IV emissions must be visible in the inner CGM. While Lau et al. (2022) do find He II and C IV emission, across a broader sample, He II and C IV is not detected by (Gillette et al., 2023). Gillette et al. (2023) argue based on the observed He II/Ly α ratios that the ERQ sample is dissimilar from the larger Type-II quasar samples based on more than differences due to viewing angles. This is in agreement with our hypothesis that the He II and C IV nebulae are linked to the duty cycle of the AGN and show variability over similar timescales, thus not always being visible. Gillette et al. (2023) make a similar argument, attributing the lack of any observed quasar feedback in the CGM nebular emission, with temporal variability and delays in quasar feedback affecting the CGM.

Lastly, we compare our results with recent observations of $2.9 < z < 4.5$ radio galaxies in Wang et al. (2023) (W23), to compare the Ly α emission around quasars with radio jets at higher redshifts. They find a higher asymmetry in comparison to other samples, which is also true for comparison with the QUART sample, we have shown that deeper observations can change the asymmetry of the observed nebula. However there is a caveat when comparing the QUART sample with the results in W23. The maps used for asymmetry and radio jet axis comparison with nebular major axes are corrected for intrinsic absorption by foreground absorbers. We have

masked the PSF region to remove any issues due to PSF residuals, so the two samples are not strictly comparable. With that caveat in mind, it is reasonable that while W23 find all radio jets are aligned with the $\text{Ly}\alpha$ emission, we only find alignment for 4 out of 7 sources. Moreover, W23 propose a model for $\text{Ly}\alpha$ emission in the CGM being elongated along the ionization cone axis, arguing that the asymmetry for $\text{Ly}\alpha$ nebulae for cases where the jets are pointed towards the observer should be lower (more symmetric nebulae, centered on the jet) or projected on-sky for cases where the jets are visible (less symmetric due to a rugby ball like ionization along the jet axis). The problem here is that $\text{Ly}\alpha$ scatters resonantly and thus the observed $\text{Ly}\alpha$ surface brightness does not necessarily describe gas motion. We have made a similar argument, but for He II emission due to the non resonant nature of the line. We have also shown that indeed, He II and C IV are better aligned with the radio jet axes in our sample compared to the $\text{Ly}\alpha$ emission. This is supported by the two component CGM model. If we assume that the inner CGM is largely influenced by galactic dynamics and the outer CGM is influenced by the larger environment, then it stands to reason that *only the inner CGM asymmetry and orientation should be aligned with the radio jet.*

3.5 Summary

We have carried out an observational IFU survey of 7 radio-loud quasars with radio jet emissions at $z=2$ using Keck KCWI and present our conclusions here -

1. We detect spatially extended $\text{Ly}\alpha$ and C IV nebulae around 100% of our sources. We detect He II around all of our sources but the extraction of moment maps is only possible around 6 out of the 7 sources due to the presence of the sky line.
2. The $\text{Ly}\alpha$ nebulae have diameters from 80 – 120 kpc, whereas the He II and C IV nebulae are smaller, with diameters ranging from 10 – 40 kpc.
3. We find radial profiles for $\text{Ly}\alpha$ have higher surface brightness than previous studies in the

inner 30 kpc. We also find the median of the integrated total Ly α luminosities is brighter than other sample medians including those at higher redshifts.

4. We compute the asymmetry for the Ly α nebulae and compare them to previous works, finding our sample to be more symmetric than previous studies. We also find that improved sensitivity can increase or decrease the observed asymmetry of the nebulae.
5. We reproduce the trend of increased total luminosity for a given on-sky projected area. We do find our sources to be brighter than other nebulae in Arrighi Battaia et al. (2019), even when adjusting for the different sensitivities of the two studies.
6. We suggest that the He II and C IV emission is likely caused due to photoionization by the quasar and represents the extent of the inner CGM around the quasar host galaxies, where gas dynamics are influenced by host galaxy processes, as compared to the outer CGM where gas dynamics are likely more affected by the larger environment and gas turbulence.
7. We compare the major axes of CGM nebular emission with the axes of the radio jets and find that the He II and C IV emission is aligned within the ionization cone of the quasar for 4 out of 6 (He II) and 7 out of 7 (C IV) sources. The Ly α emission is found to be aligned only for 4 out of 7 sources and the lack of alignment can be attributed to either the Ly α nebula filling the KCWI field of view or due to the scattering of radiation in the outer CGM decoupling the Ly α radiation emission from the quasar photoionization cone.
8. In the context of a two component CGM model with an inner and outer component, the alignment of the nebular emission in the CGM with the radio jets indicates that *only the inner CGM is aligned with the radio jets*.
9. We compare the quasar bolometric luminosity, total H α and [O III] luminosities of the quasar host galaxy as seen with OSIRIS with the integrated Ly α , He II, and C IV

luminosities. We find no correlation with $\text{Ly}\alpha$ emission in the CGM with either quantity but the integrated He II and C IV luminosities show a weakly declining trend when compared to the bolometric luminosity and a weaker trend when compared to total $\text{H}\alpha$ luminosity. We speculate this trend is related to the AGN duty cycle, but caution that we only have a small sample and a larger sample is required to confirm this.

10. We extract $\text{Ly}\alpha$ spectra at the locations of the radio jets and detect evidence for multiple kinematic components, as seen with He II, as well as a single component with foreground absorbers. We find blue and redshifted components and do not find a systematic trend in the extracted spectra for either $\text{Ly}\alpha$ or He II emission.
11. For 4C 11.45, we detect two special characteristics in the nebular emission. We detect a filament like structure as traced out in the Moment 1 and Moment 2 maps, perpendicular on-sky to the radio jet emission. We also find that the bent radio jet location coincides with the edge of He II and C IV nebulae, indicating a transition from the inner CGM influenced by galactic processes to an outer CGM influenced by the larger environment.

Appendix

3.5.1 Ly α maps

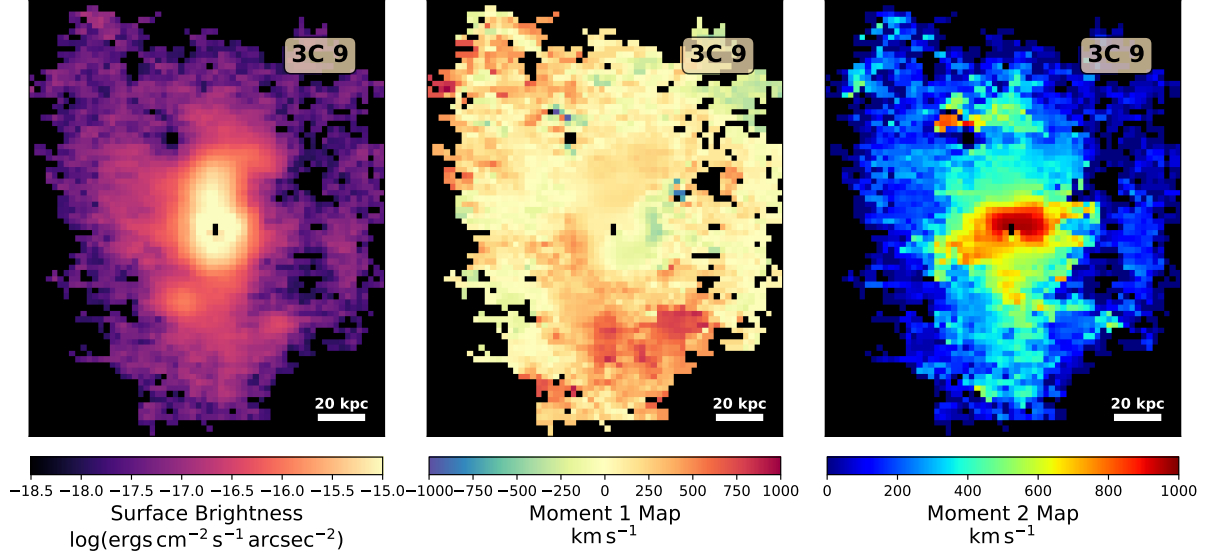


Figure 3.12. KCWI Ly α Moment maps for 3C 9.

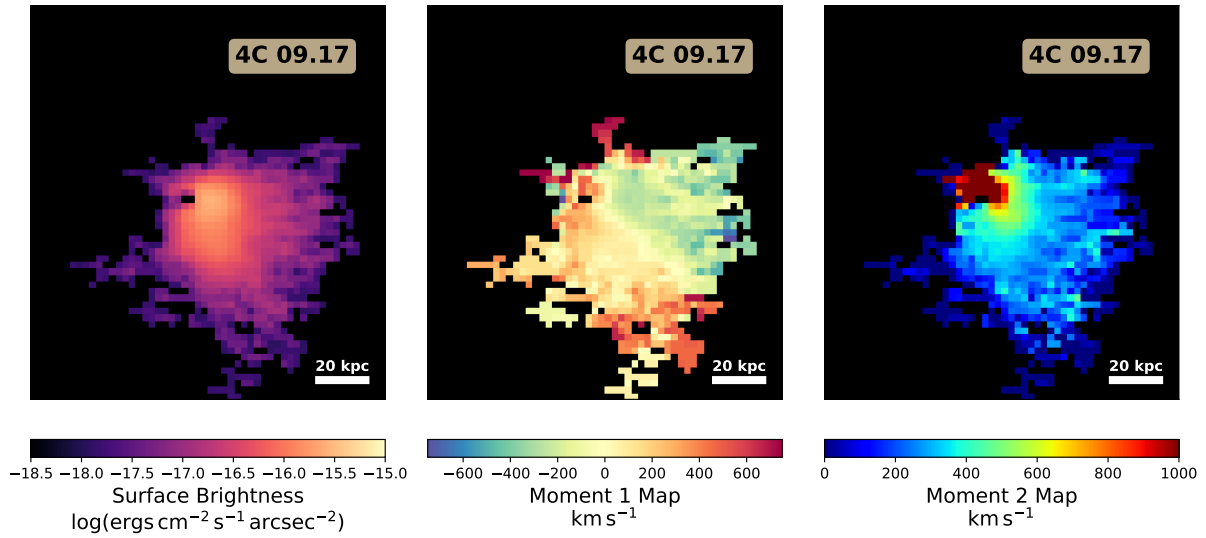


Figure 3.13. KCWI Ly α Moment maps for 4C 09.17.

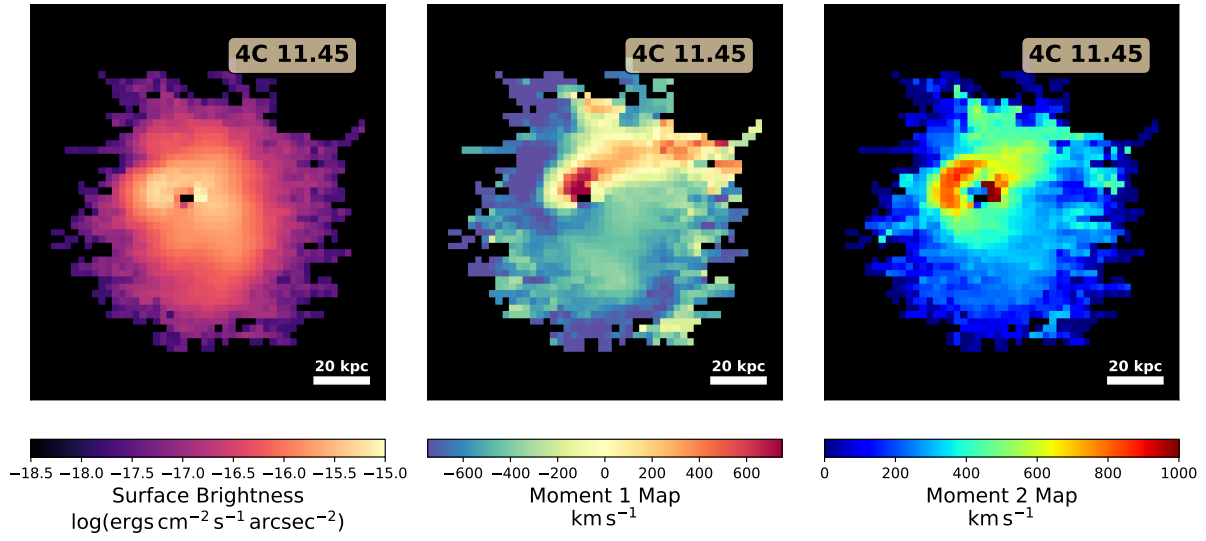


Figure 3.14. KCWI Ly α Moment maps for 4C 11.45.

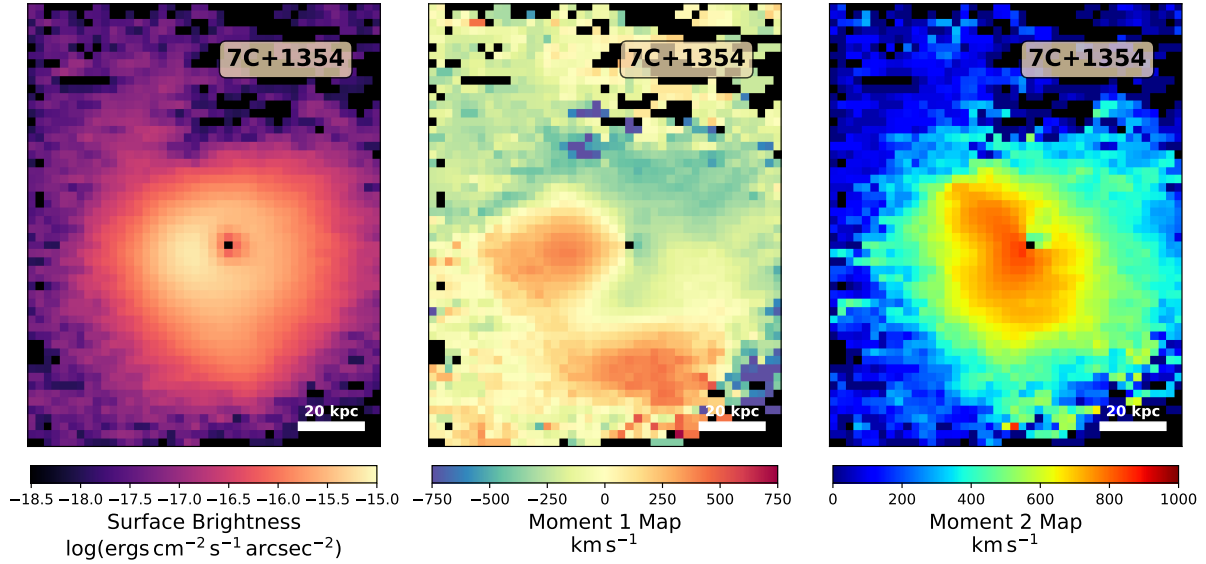


Figure 3.15. KCWI Ly α Moment maps for 7C 1354+2552.

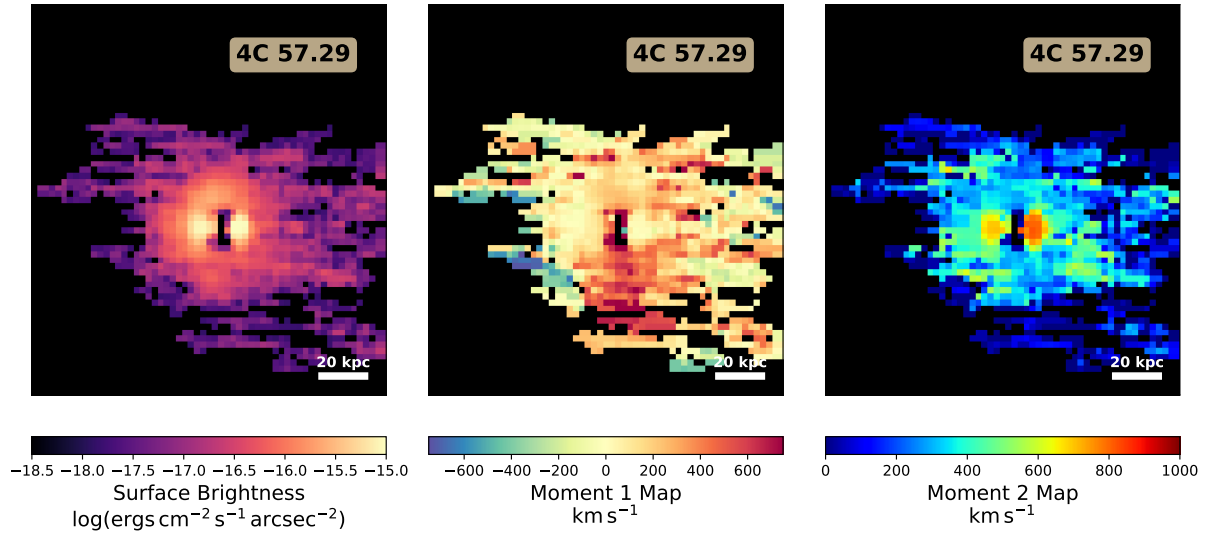


Figure 3.16. KCWI Ly α Moment maps for 4C 57.29.

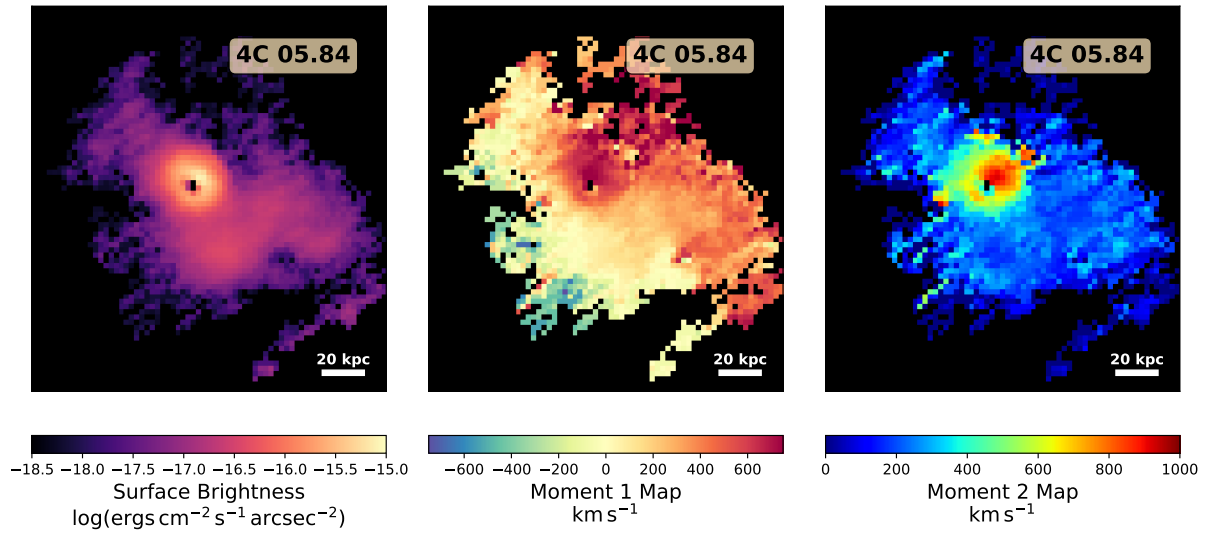


Figure 3.17. KCWI Ly α Moment maps for 4C 05.84.

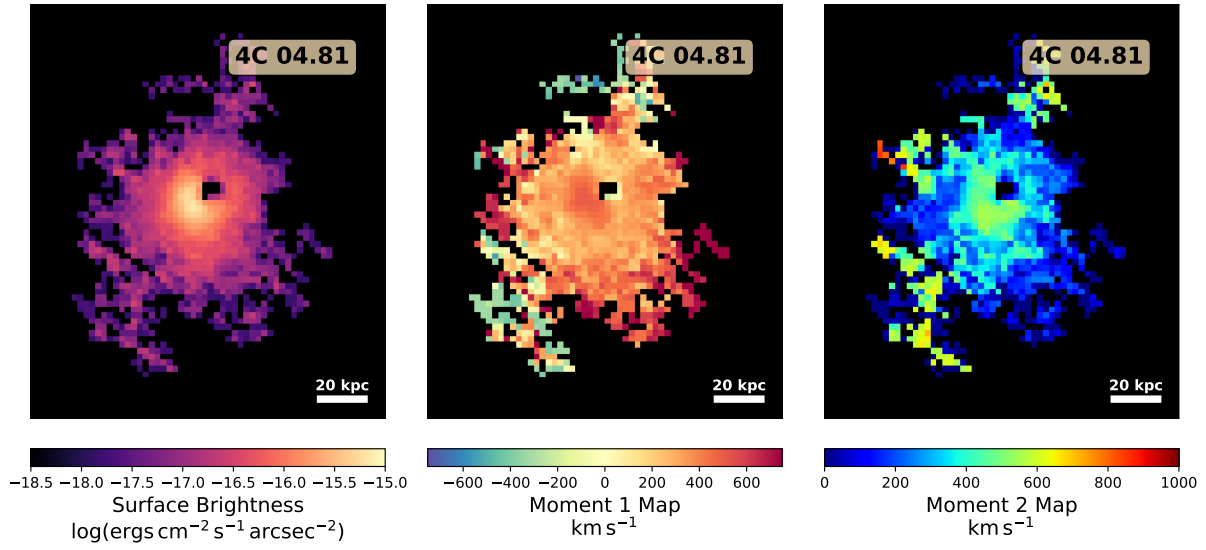


Figure 3.18. KCWI Ly α Moment maps for 4C 04.81.

3.5.2 He II Maps

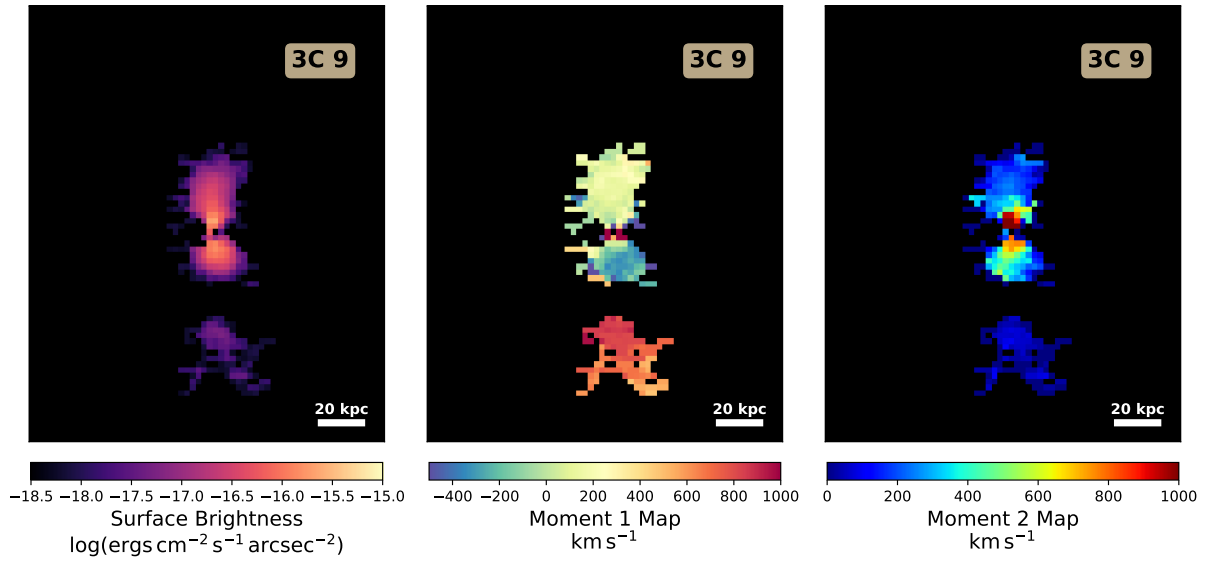


Figure 3.19. KCWI He II Moment maps for 3C 9.

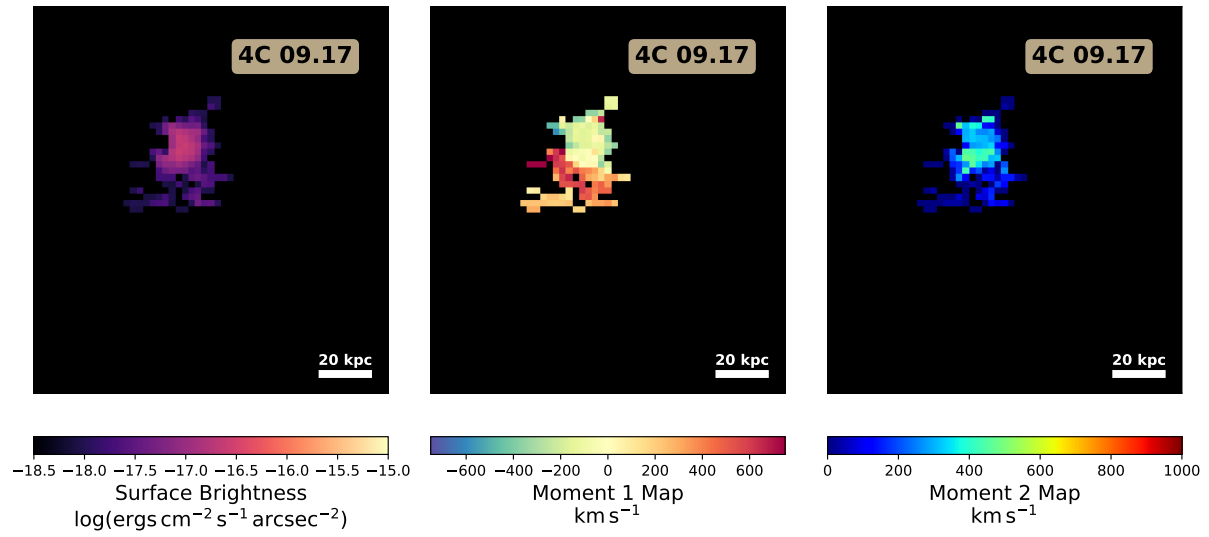


Figure 3.20. KCWI He II Moment maps for 4C 09.17.

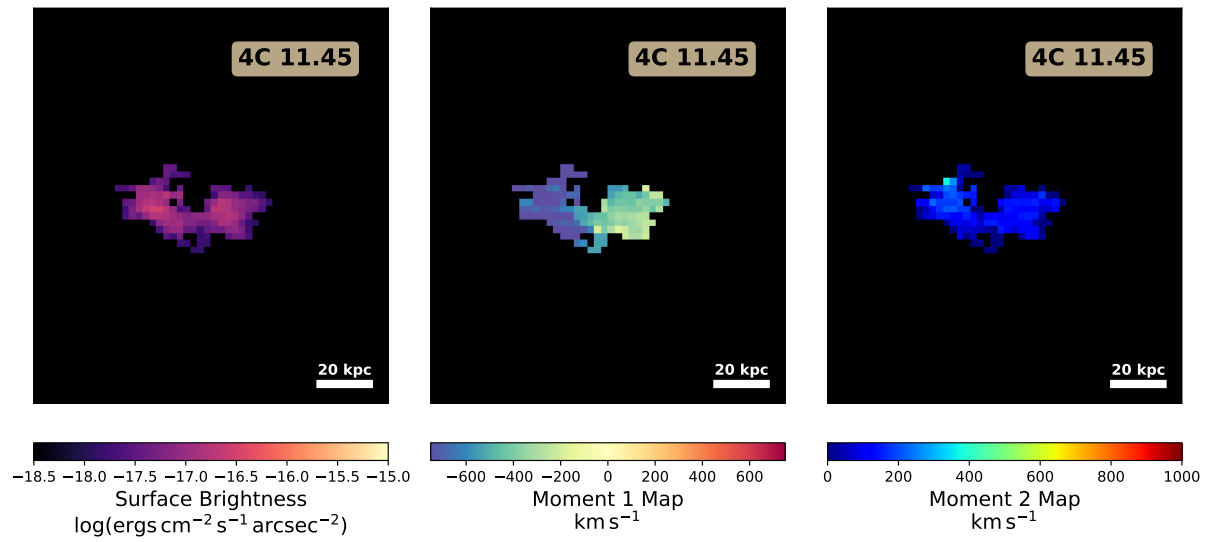


Figure 3.21. KCWI He II Moment maps for 4C 11.45.

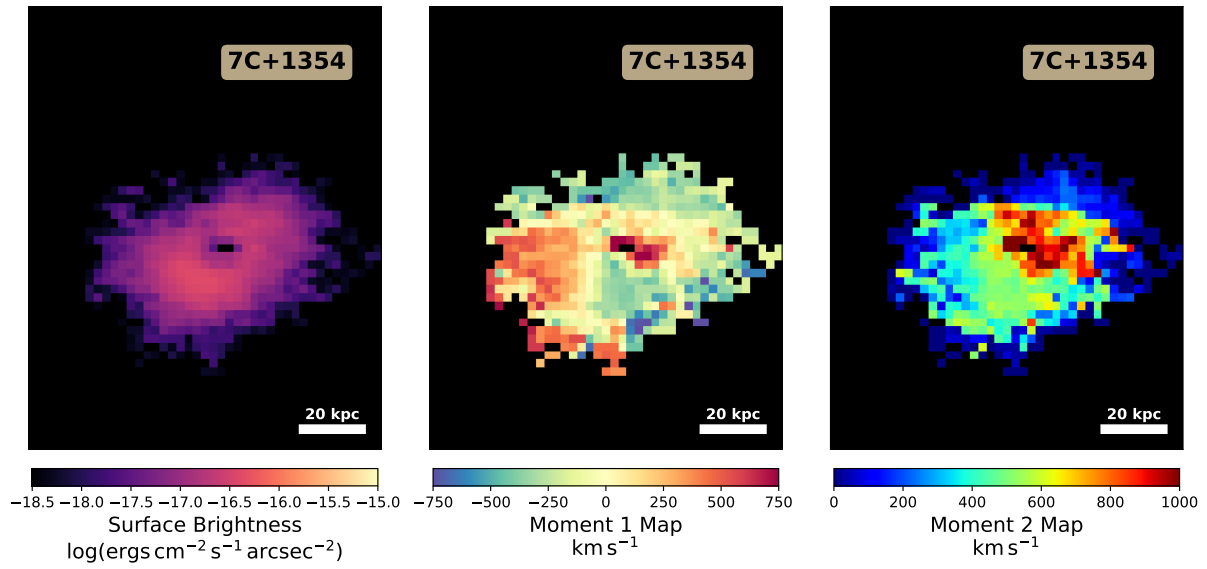


Figure 3.22. KCWI He II Moment maps for 7C 1354+2552.

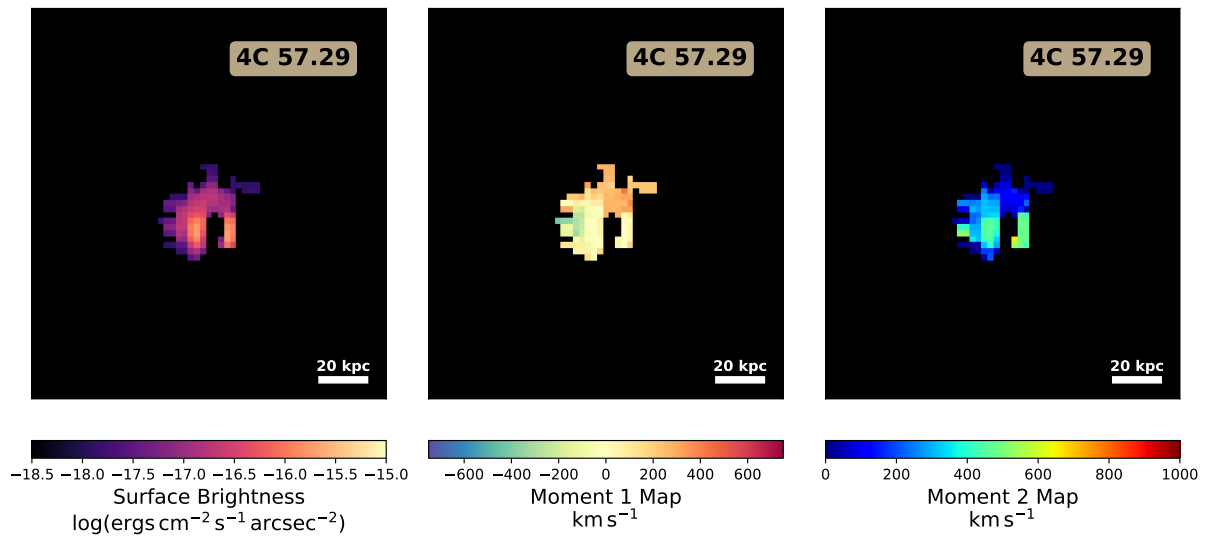


Figure 3.23. KCWI He II Moment maps for 4C 57.29.

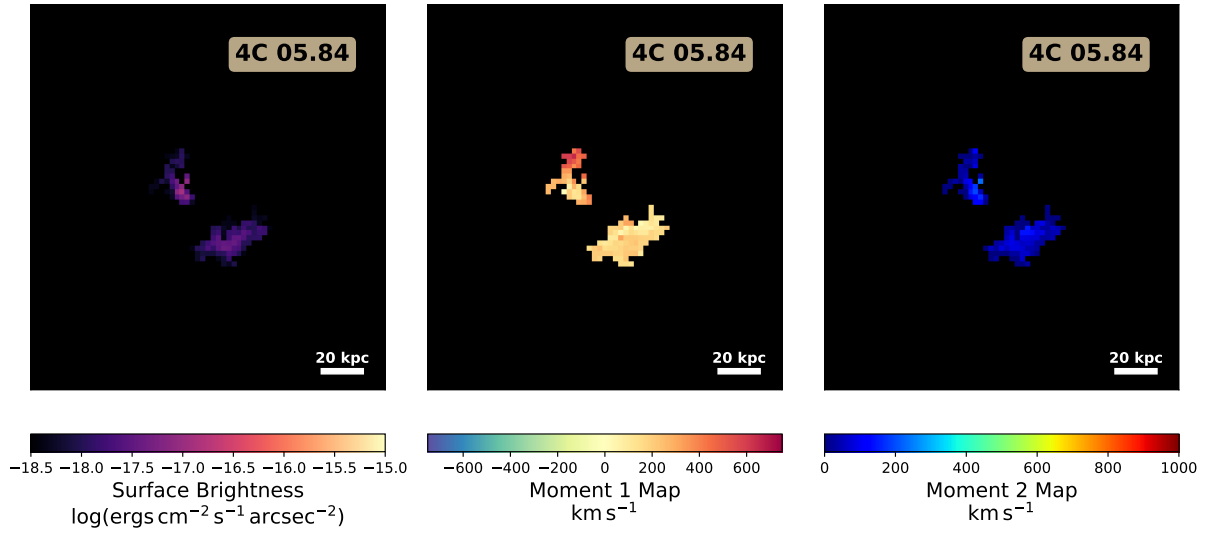


Figure 3.24. KCWI He II Moment maps for 4C 05.84.

3.5.3 C IV Maps

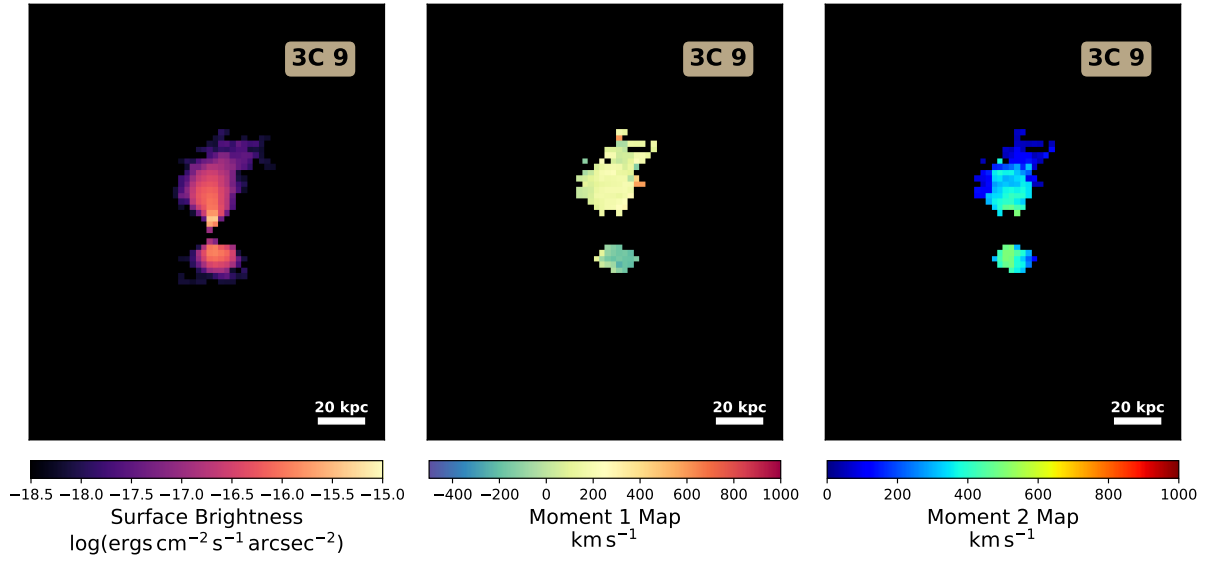


Figure 3.25. KCWI C IV Moment maps for 3C 9.

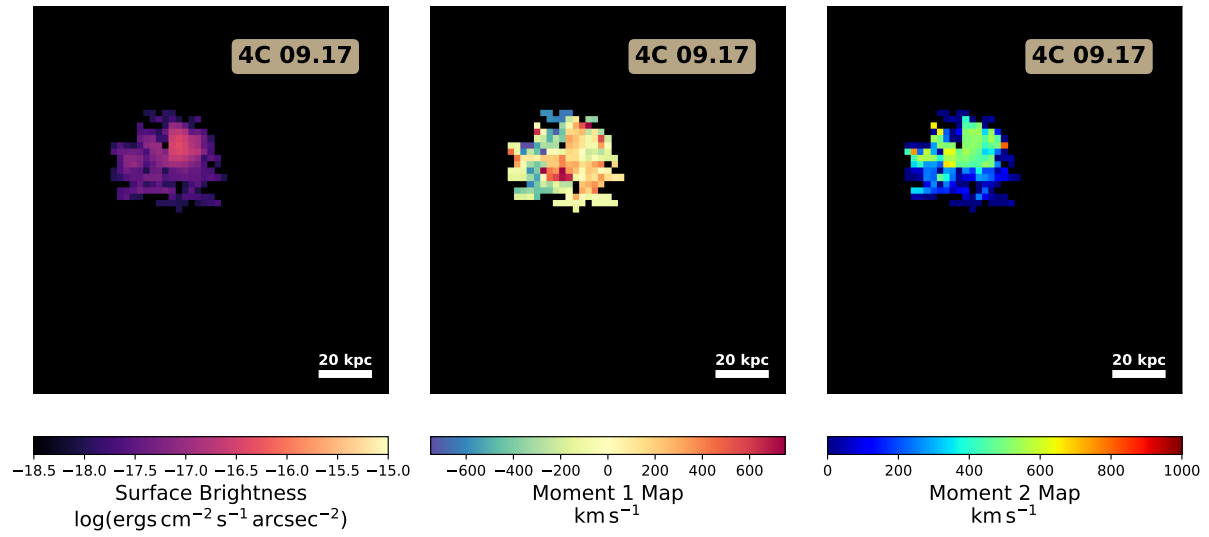


Figure 3.26. KCWI C IV Moment maps for 4C 09.17.

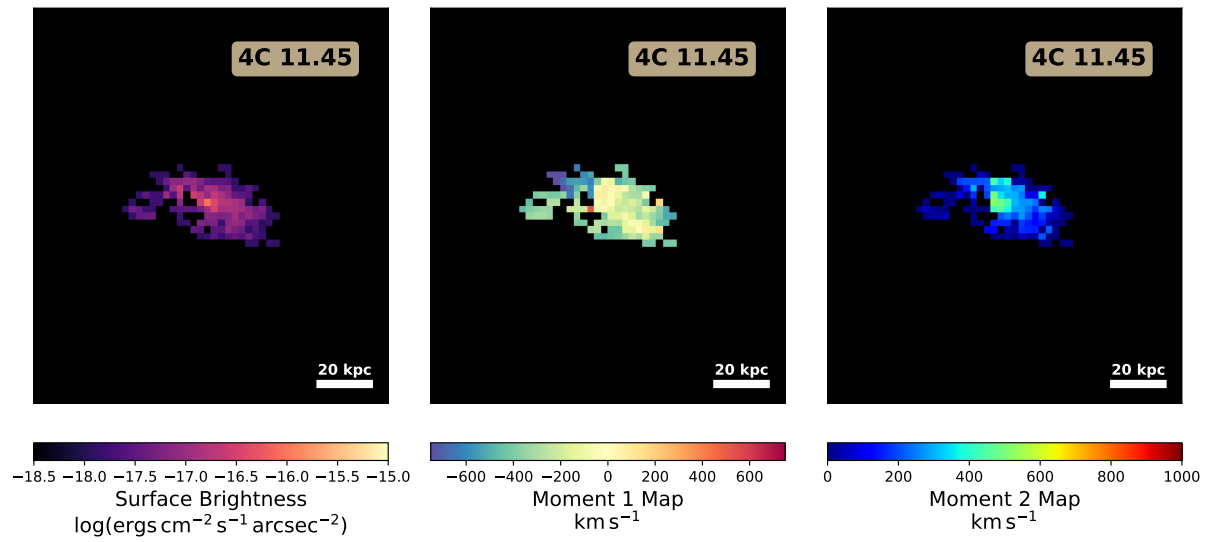


Figure 3.27. KCWI C IV Moment maps for 4C 11.45.

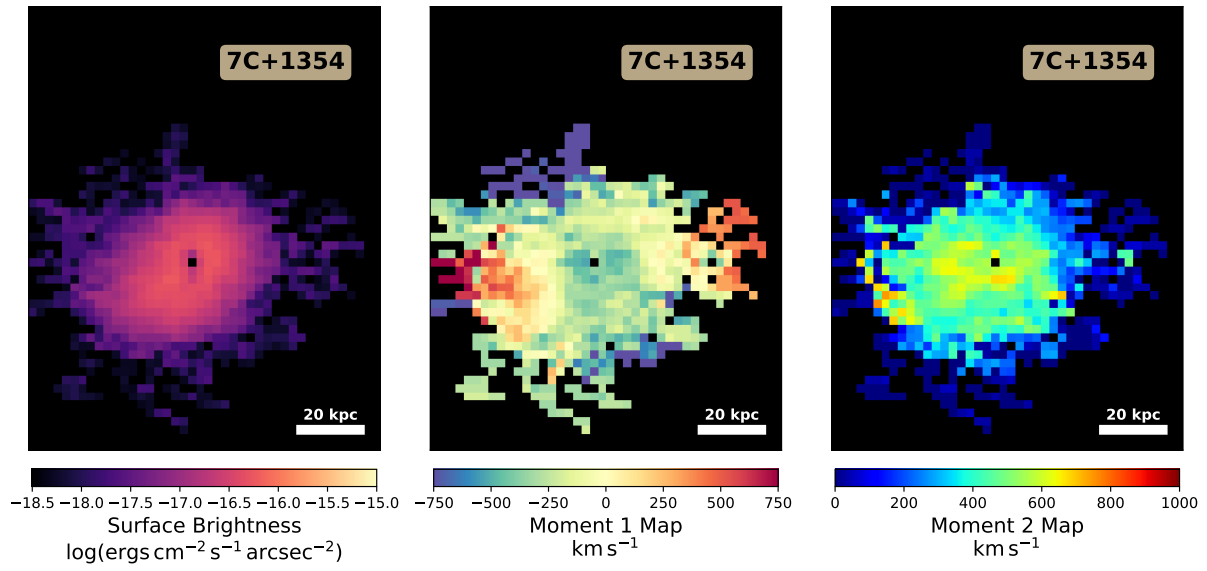


Figure 3.28. KCWI C IV Moment maps for 7C 1354+2552.

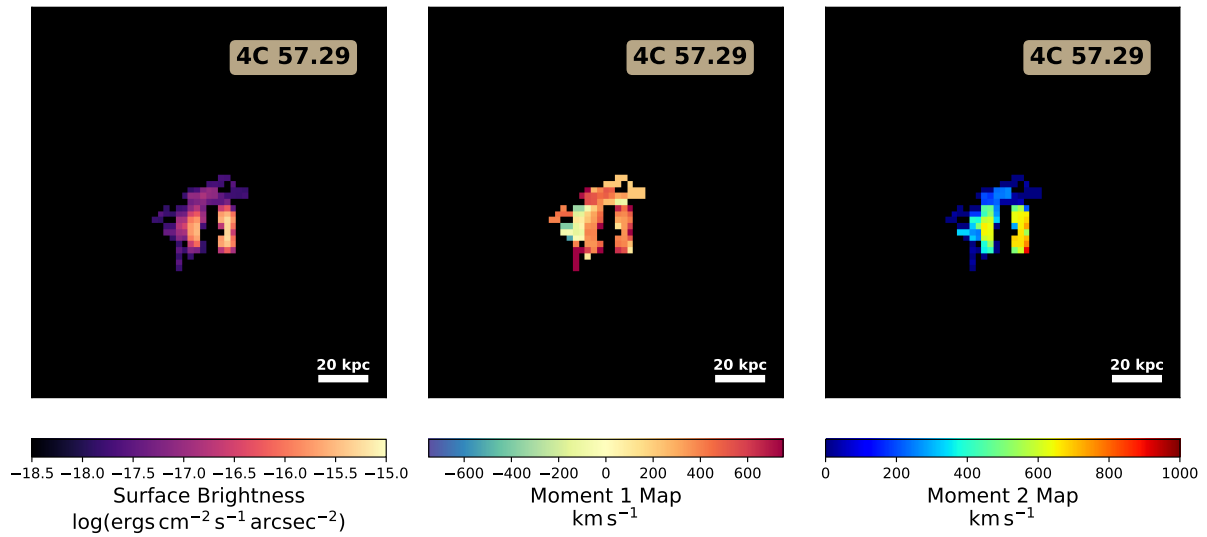


Figure 3.29. KCWI C IV Moment maps for 4C 57.29.

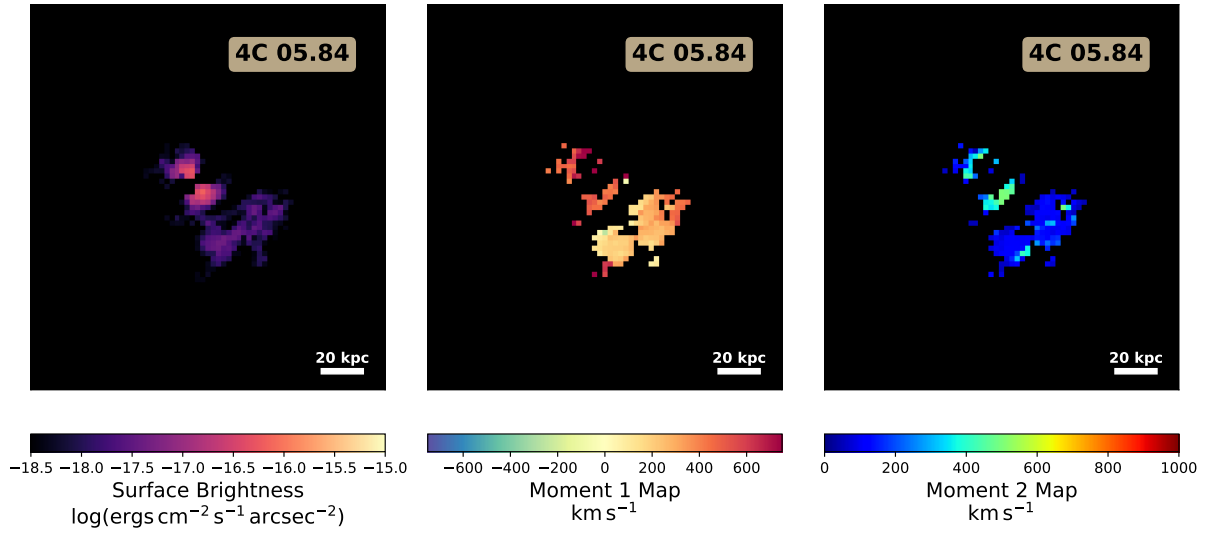


Figure 3.30. KCWI C IV Moment maps for 4C 05.84.

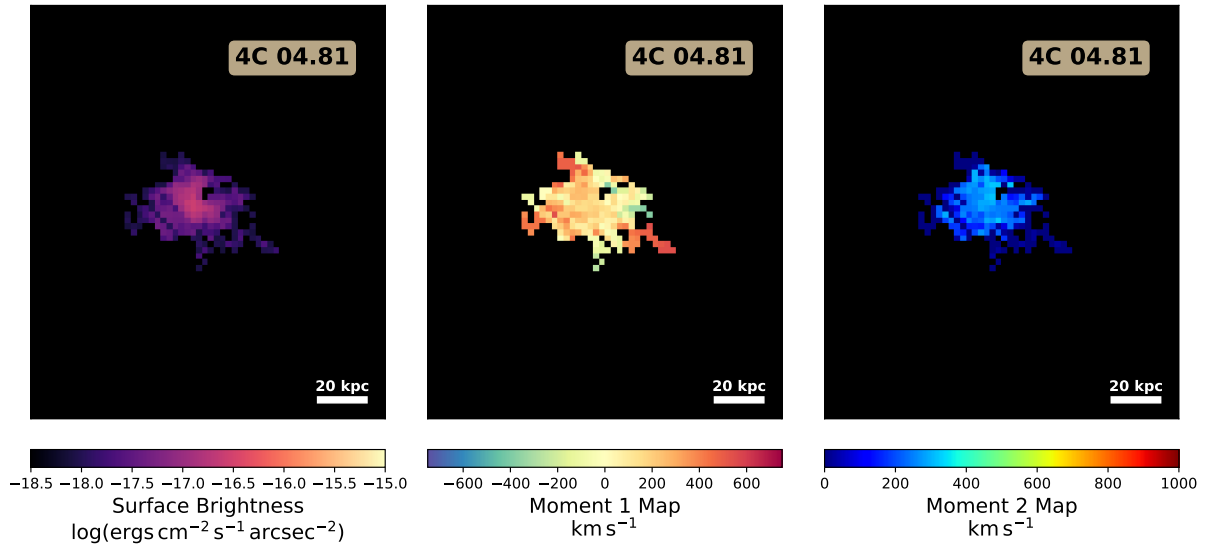


Figure 3.31. KCWI C IV Moment maps for 4C 04.81.

Chapter 3, in full, is currently being prepared for submission for publication of the material. Sabhlok, Sanchit; Wright, Shelley A.; Vayner, Andrey; Cosens, Maren; Wiley, James; Simonaitis-Boyd, Sonata; Murray, Norman; Armus, Lee. The dissertation author was the primary investigator and author of this paper.

Chapter 4

Advanced Techniques in Point Spread Function Reconstruction

4.1 Introduction

A Point Spread Function (PSF) is the term used to describe the image of a point source formed by a telescope, detector or more generally, an imaging system. A point source by definition has no spatial extent, however, in the astronomical context, a point source can be described as any source whose spatial extent cannot be sampled by the optical detector, or the optical system as a whole. Modern digital detectors have finite sized pixels collecting photons, and each pixel corresponds to a finite area on sky that can be imaged. The pixel scale depends on many factors, but even in systems assisted by Adaptive Optics (AO), the pixel scale is typically of the order of 10s of milli arcseconds (mas), assuming the diffraction limit of the diameter of the telescope, in this case 8-10m class telescopes. Thus, if a source on sky is significantly smaller than 10 mas, it will necessarily appear as a point source on the detector.

The natural question to ask here is: Why is the PSF not a *Point*? The answer is that when an imaging system tries to focus the light from a point source onto one point in the image plane, since light is a wave, it will undergo diffraction and create an extended pattern on the image plane, i.e. the *Point Spread* Function. The relationship between a PSF and the imaging system is described in Section 4.2. All stars are point sources, as are quasars (light from accretion disks of

accreting SMBHs) as they are at infinity for all practical purposes.¹ Thus the extent of the PSF determines how accurately we can perform **astrometry**, i.e. the positions of the point sources in question, or **photometry**, i.e. the total light emitted by the point sources. In the optical or infrared, the atmosphere blurs the starlight passing through it and as a result, any telescope larger than 8 inches will always form an image dependent on how good the astronomical conditions are on a given night, quantified by the **Seeing**. The seeing is the Full Width at Half Maximum (FWHM) of a point source image. Typical values for seeing at good astronomical sites in the optical and infrared are of the order of FWHM 0.5-0.7 ''.

The PSF is important to observers across the electromagnetic spectrum. Radio telescopes typically measure the *beam size* for a given observation to quantify the angular resolution of the image. For any space-based telescopes, the atmosphere is no longer the limiting part of the imaging system, so PSFs can be simple or extremely complex, depending on the optical system throughput and the number of optical components before the detector. Due to its limited moving parts, the Hubble Space Telescope (HST) had a complicated but stable PSF for most of its life, as was the case for Spitzer. However, due to the independent degrees of freedom of the individual segments in the James Webb Space Telescope (JWST), the PSF is complicated and varies temporally, although within the design tolerances so as to not affect science results.

Adaptive Optics allows a ground-based telescope to correct for the atmospheric blurring and recovering the original signal by rapidly correcting for atmospheric distortions of the incident light. At its simplest, a typical adaptive optics setup involves a **deformable mirror (DM)**, a **real time controller (RTC)** and a **wavefront sensor (WFS)**. The wavefront sensor detects the atmospheric distortions in the incident wavefront, the real time controller calculates the required reconstruction matrices to correct the atmospheric blurring and sends the commands to the deformable mirror, which deforms to counteract the impact of blurring on the incident wavefront.

As we know the optical system that the incident light needs to travel through well (by

¹This is not true strictly speaking as Betelgeuse is resolvable by some telescopes with a size of 50 mas and of course the Sun is a well resolved star. Thank you to Karin Sandstrom for pointing this out!

design), if we can save all the commands sent to the DM to correct for the atmosphere, we essentially have a series of snapshots, of atmospheric corrections applied for any long exposure. If we can determine the PSF of the system for each of these individual snapshots, we should in principle be able to reconstruct the PSF for the long exposure. *This is the primary objective of forward modelled PSF Reconstruction.*

This chapter serves as an introductory basis for the remainder of this thesis. Section 4.2 describes the mathematics used to derive the Point Spread Function given an optical system. Sections 5.2 and 4.4 introduce the motivation for the individual projects described in Chapters 5 and 6.

4.2 Fourier Optics

Fourier optics offers a particularly elegant way of describing the relationship between incident wavefront, the pupil and the resulting PSF (Hardy, 1998). While a full treatment of the topic is beyond the scope of this thesis, relevant terms and concepts are introduced here.

An **Aperture Function** is a binary mask that defines the aperture through which light is collected. This can be a simple analytic function such as a circular aperture or a realistic complicated aperture such as the primary mirror of the Keck Telescope, both shown in Figure 4.1. The **Incident wavefront** is the wavefront of the incoming light in the plane of the aperture function, and can be treated as a complex quantity with both an amplitude and a phase term. If this wavefront propagates in the z direction, and the plane of the aperture is denoted as the (x,y) plane, we can denote the incident wavefront as -

$$A(x,y) = A_0(x,y)e^{i\phi(x,y)} \quad (4.1)$$

Where $A_0(x,y)$ is the amplitude variation across the aperture and $e^{i\phi(x,y)}$ is the phase variation. Now, if the image plane is represented by the coordinates (X,Y) , then the electric field in the

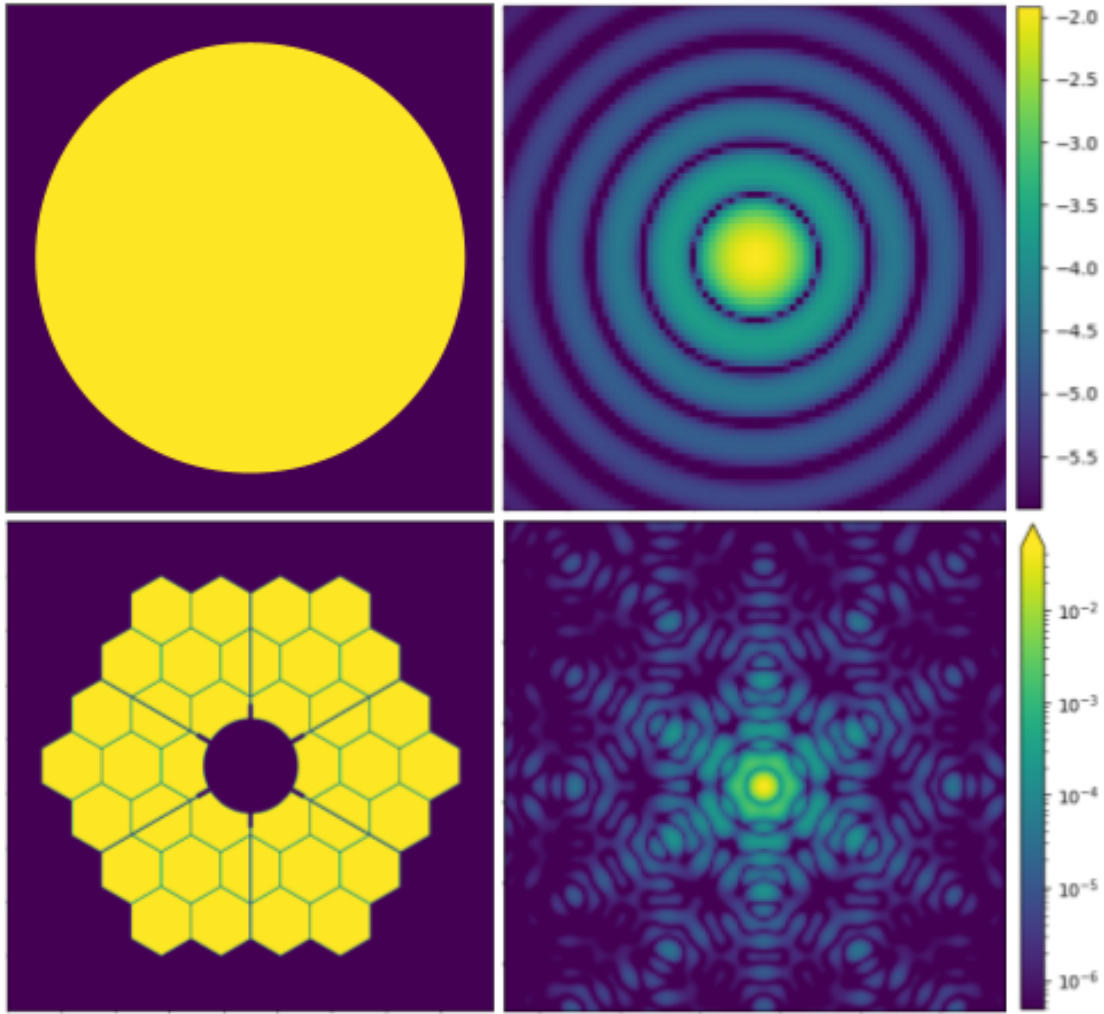


Figure 4.1. Figure demonstrating the expected PSFs for two different Pupil or Aperture functions assuming a plane incident wavefront. The PSF for a circular aperture (Top Left) function is an Airy Ring (Top Right), whereas for the aperture function defined by the Keck Telescope primary segments (Bottom Left), the PSF (Bottom Right) is more complicated and does not have an analytic form. Both PSFs are shown on the log scale.

image plane is related to the incident wavefront by -

$$E(X,Y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(x,y) e^{ik(Yy+Xx)/R} dy dx \quad (4.2)$$

If we denote the **Spatial Frequencies** f_x and f_y as -

$$f_x = k \frac{X}{R}; \quad f_y = k \frac{Y}{R} \quad (4.3)$$

Where R is the distance between the aperture and image planes along the Z axis. Additionally, instead of integrating over the entire plane, we only need to integrate over the region where the Aperture Function is non zero, thus the electric field is given by -

$$E(f_x, f_y) = \int \int_{Aperture} A(x, y) e^{i(f_y y + f_x x)} dy dx \quad (4.4)$$

This is the Fourier transform relationship. Thus the field distribution in the image plane is the Fourier transform of the incident wavefront in the aperture plane. The intensity distribution of this electric field given by $|E(f_y, f_x)|^2$ is the Point Spread Function. Thus, *the PSF is the modulus squared of the Fourier transform of the incident wavefront at the pupil plane.*

Thus, by quantifying and tracing the wavefront distortions on the incident wavefront, we can reconstruct the PSF. The distortions can be due to a variety of physical factors, such as atmospheric turbulence, corrections imposed by a deformable mirror, or due to physical distortion of the optic at the aperture.

The **resolving power** of an optical system is the ability to distinguish two closely spaced point sources. In the best case, when given two diffraction limited PSFs, the separation between the two sources needs to be at least the Full Width at Half Maximum (FWHM) of the PSF for the objects to be spatially resolved. However, from a Fourier optics point of view, we can see that this is a limited approach to quantifying the performance of an optical system. Since each point in the image plane corresponds to a spatial frequency, the resolving power corresponds to a higher cutoff frequency beyond which objects can no longer be resolved. However, the system can be subject to a frequency spectrum, and thus it is useful to quantify the response to the entire frequency range, instead of just the cutoff frequency. This is the idea behind an **Optical Transfer**

Function (OTF).

Given the irradiance of an image $I_i(X, Y)$, the object $I_o(x, y)$ and the PSF $PSF(x, y)$ -

$$I_i(X, Y) = I_o(x, y) \circledast PSF(x, y) \quad (4.5)$$

Where $\circledast$ represents the convolution operator. To consider the same statement in the spatial frequency domain, we can take the Fourier Transform of the equation -

$$\mathcal{F}(I_i(X, Y)) = \mathcal{F}(I_o(x, y)) \cdot \mathcal{F}(PSF(x, y)) \quad (4.6)$$

Now, the function $\mathcal{F}(PSF(x, y))$ multiplies the spatial frequencies for the object spectrum to give the spatial frequencies of the image. This is defined as the **Unnormalised Optical Transfer Function** -

$$OTF(k_x, k_y) = \mathcal{F}(PSF(x, y)) \quad (4.7)$$

As a PSF is typically normalized to the total flux in the image plane, and the OTF is the Fourier Transform of the PSF, the OTF can be normalized with the same constant, thus the normalized OTF is given by -

$$OTF(k_x, k_y) = \frac{\mathcal{F}(PSF(x, y))}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} PSF(x, y) dx dy} \quad (4.8)$$

The OTF is a complex valued function and can be written as -

$$OTF(k_x, k_y) = MTF(k_x, k_y) e^{i \Phi(k_x, k_y)} \quad (4.9)$$

Where $MTF(k_x, k_y)$ is the **Modulation Transfer Function (MTF)** and $\Phi(k_x, k_y)$ is the **Phase Transfer Function (PTF)**.

The formulation offers computational advantages, since the OTF is simply a Fourier transform of the PSF. Given the objective to use the AO telemetry information to derive a long exposure PSF, reformulating the PSF as an OTF can be used to multiply a series of Transfer

Functions instead of convolving the same number of PSFs. The question remains as to how to derive the transfer functions for typical processes associated with astronomical observing, such as the atmospheric fluctuations, errors associated with the guide stars used for AO, the limited spatial resolution of a deformable mirror and the inherent noise of the associated electronics. This is described in the next section.

4.3 Applications to Optical and Infrared Astronomy

Adaptive Optics allows us to observe at the diffraction limit of the telescope from ground-based Optical or Infrared observations. Even at good telescope sites, it is important to characterize the performance of a telescope system compared to a theoretically perfect benchmark. Typically, the **Strehl Ratio** is used to quantify the quality of a night with AO observations. The Strehl ratio is a simple measure which is a ratio of the peaks of the observed PSF as compared to the diffraction limited PSF -

$$S = \frac{Max(PSF_{obs})}{Max(PSF_{diff})} \quad (4.10)$$

For nights with good seeing, the Strehl ratio is related to the RMS wavefront error of the incident wavefront σ_P given by -

$$S = e^{-\sigma_P^2} \quad (4.11)$$

Thus, as a metric, the Strehl ratio is particularly useful for forward modelled PSF since it allows the observer to quantify the quality of AO performance but also relates the performance with the total RMS wavefront error. The RMS wavefront error at the pupil plane is an important quantity as it can be translated into the OTF and the PSF.

The atmosphere is a turbulent fast changing system. It can nominally be characterized by the Pressure P and the Temperature T . Solar flux can drive turbulent eddies in the atmosphere leading to mixing of gas at varying length scales. The Kolmogorov model of turbulence describes this model very well, based on the following principle. Energy is continuously transferred to

smaller and smaller length scales starting from the largest **Outer Scale** L_0 , driven by viscous dissipation of energy. For this to be a stable process, energy dissipated at any given length scale must equal the input energy driving the turbulence.² While the full treatment and derivation of the Kolmogorov is beyond the scope here, the key takeaway is that the one dimensional power spectrum density of the Temperature fluctuations $\Phi_{T,Kolmogorov}(\kappa) \propto \kappa^{-5/3}$, where κ represents the spatial frequency for temperature fluctuations.

For the purposes of reconstructing a forward modelled PSF from AO telemetry, the atmosphere need only be modelled for individual snapshots corresponding to each DM command. Since the DM commands have typical speeds of the O(KHz), this is the rate at which we need to describe the atmosphere. This is accomplished by assuming that the atmosphere is frozen for the small interval of time between each DM command and its changes from one time step to the next are random. The goal then is to model the refractive index variations in the atmosphere for this small interval of time. The problem with this approach is that while the atmosphere does vary randomly from one time interval to next, this includes slow longer term changes. This can be illustrated with an example. For any observing night, at the start of observing Seeing is typically variable and gradually settles as the sun sets and then stabilises (on a good night). If we model the seeing for this night, it will show random fluctuations with a decreasing trend over the period of hours. Thus, to appropriate model the atmosphere as random and non stationary, a **Structure Function** $D(\tau)$ is used, defined as -

$$D(\tau) = \langle [f(t + \tau) - f(t)]^2 \rangle \quad (4.12)$$

Here, $f(t)$ is any arbitrary function of time t here, but the concept can broadly be applied to any arbitrary variable. The advantage of using a structure function is that any slow changes

²This was described to me in my undergraduate fluid mechanics class by converting the popular (British) adage “Big fleas have little fleas on their back to bite ’em. Little fleas have lesser fleas and so on ad infinitum” into the more appropriate “Big whirls have little whirls that feed on their velocity. Little whirls have lesser whirls and so on to viscosity.”

occurring on timescales longer than τ are subtracted. Thus it is an effective way of measuring the fluctuations on timescales smaller than τ . When using this formulation to model refractive index variations in the atmosphere, the function will have a temporal and a spatial (angular on sky) component. Since the function inside the $\langle \rangle$ is a stationary function, the $\langle \rangle$ represents a spatial (angular) average. The goal now is to define the structure function for the refractive index variation in the atmosphere.

The refractive index for the atmosphere is given by -

$$N = (n - 1)10^6 = 77.6P/T \quad (4.13)$$

Where P is the pressure in millibars, T is the temperature in K and n is the refractive index of the medium. Since pressure fluctuations in the atmosphere are smoothed at the speed of sound -

$$\delta N = -77.6 \frac{P}{T} \delta T \quad (4.14)$$

$$C_N = \frac{\delta N}{\delta T} C_T \quad (4.15)$$

Where C_N is the structure parameter for refractive index variations in the atmosphere. The three dimensional power spectrum for Temperature fluctuations is given by (Tatarski et al., 1961) -

$$\Phi_T(\kappa) = \frac{\Gamma(\frac{8}{3}) \sin \frac{\pi}{3}}{4\pi^2} C_T^2 \kappa^{-11/3} = 0.033 C_T^2 \kappa^{-11/3} \quad (4.16)$$

Where C_T is the structure parameter for Temperature variations. Similarly, the fluctuations in refractive index can be characterized as -

$$\Phi_N(\kappa) = 0.033 C_N^2 \kappa^{-11/3} \quad (4.17)$$

The obtained structure functions can be converted into an Optical Transfer Function (OTF) which can then be used to model the PSF. The Kolmogorov model is only valid in the

inertial range, i.e. between the inner and outer scales of turbulence. For adaptive optics, the outer scale L_0 is assumed to be larger than the telescope diameter D . The relevant inner scale is not necessarily the inner scale of turbulence, but the Fried parameter r_0 which is the length scale over which the RMS wavefront phase error becomes 1 radian. Since the phase error is a wavelength dependent quantity, the Fried parameter scales with wavelength as $\lambda^{6/5}$, and is usually stated at a wavelength of 500 nm. For a good astronomical site on a night with good conditions, typical values of the Fried parameter are ~ 20 cm.

In addition to wavefront aberrations due to the time varying components, an optical system can also have static aberrations. The static error in the PSF can occur because the WFS - RTC - DM loop optical path is different from the optical path to the science detector. Thus, any static errors that exist due to this non common path cannot be corrected by AO and must be present in the final PSF. These are known as the **Non Common Path Aberrations** and can be characterized using a **Phase Diversity** technique (Mugnier et al., 2008; Jolissaint et al., 2012; Ragland et al., 2016a).

In Chapter 5, we investigate a forward modelled PSF for NIRC2 on the Keck Telescope and compare predicted PSFs to the observed PSFs using the Strehl ratio and the FWHM as the comparative metrics. The atmospheric C_N^2 profile for the Keck telescope is obtained from on-site data, combined with the AO telemetry and the NCPA maps obtained using phase diversity measurements to create the PSF model. The model is compared to on-sky data using the Strehl ratio and FWHM.

4.4 PSF Reconstruction for the lunar corner cube retroreflectors

We have considered an astronomical point source incident on the pupil plane, with wavefront distortions induced by the atmosphere and investigated the possibility of correcting the incident wavefront. We now consider a special application where the wavefront is not deformed

primarily by the atmosphere, but at the source. The Apollo 11, 14 and 15 (hereafter A11, A14 and A15) missions left Corner Cube Retroreflectors (CCRs) on the moon, which have since been used for Lunar Laser Ranging (LLR) to measure the Earth Moon distance. The measurement enables an experimental test of theories of gravity and is used to constrain the rate of change of the gravitational constant, whilst also providing information on the lunar interior (Murphy et al., 2012).

The CCRs are a special kind of optic, allowing light to return exactly back to where it came from, making them particularly useful for this experiment. The CCRs on the moon are not individual corner cubes but arrays, A11 and A14 contain 100 corner cubes whereas A15 contains 300. The Apache Point Observatory for Lunar Laser-ranging Operation (APOLLO) has carried out Earth Moon LLR measurements since first light in 2005. However, the performance of the CCRs has been declining for some time now (Murphy et al., 2010). The behavior is particularly pronounced at Full Moon, which indicates solar illumination is at least partially the cause of the effect. The assertion was strengthened when the performance improved immediately when APOLLO ranged during a lunar eclipse (Murphy et al., 2014). The behavior can be explained if the CCRs have radial and axial thermal gradients set up in the bulk of the reflector, but the question is what would cause these thermal gradients to set up (Murphy & Goodrow, 2013).

Figure 4.2 shows a corner cube and its corresponding Far Field Diffraction Pattern (FFDP), in the absence of any thermal gradients. Murphy & Goodrow (2013) show that in the presence of radial or axial thermal gradients, the central maximum in the FFDP is suppressed. Since the telescopes on earth undertaking LLR primarily observe this central maximum, a suppression will decrease the return rate. The hypothesis is lunar dust accumulates on the CCR surfaces, and absorbs incident solar flux which then sets up a thermal gradient inside the corner cube via conduction.

In Chapter 6, using a thermal model we investigate whether solar illumination can create the thermal gradients required to suppress the central maximum in the FFDP as seen in observations. The model investigates both steady state and eclipse conditions on the lunar surface

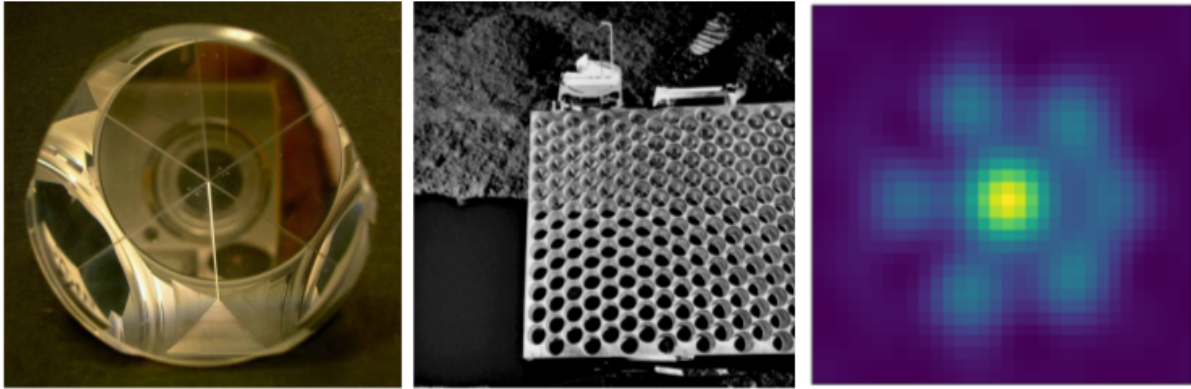


Figure 4.2. (Left) A corner cube retroreflector imaged from the front. Notice how the camera pupil is at the center of the cross hairs, illustrating the principle of how these devices work. (Middle) The Apollo 15 CCR array left on the moon. (Right) The far field diffraction pattern of an isothermal Corner Cube.

and generates a time series of corner cube temperatures. The corner cube temperatures can then be converted into a phase aberration map. This is the incident wavefront for the telescope used to generate the far field diffraction pattern. We then compare the results of this modelling with ranging measurements during the April 2014 lunar eclipse and find good agreement with the observed return rates. We find that a dust obscuration factor of 50 % best explains the observed deficit.

Chapter 5

Validating the on-axis Point Spread Function Reconstruction for NIRC2 imager

With Adaptive Optics (AO) now regularly deployed with natural or laser guide stars at 8-10 m class telescopes around the world, understanding of the Point Spread Function (PSF) of a telescope limits our ability to resolve phenomena at high angular resolution. While traditionally PSFs are extracted from a bright point source in a science image, ideally, one would like to reconstruct the PSF without using the science image by modelling the PSF based on knowledge of the telescope, atmosphere and the AO system. In this chapter, we investigate a PSF reconstruction model using the python based code PRIME using data from the NIRC2 instrument on the Keck Telescope Beltramo-Martin et al. (2018, 2020). We use PRIME to calculate the Strehl, Full Width at Half Maximum (FWHM) and Fraction of Variance Unexplained (FVU) for NIRC2 imaging data and compare the model calculations to independent estimates of the Strehl and FWHM. We investigate the stability of the derived PSFs by systematically varying input parameters in the model. We discuss the application of our results for the upcoming Keck All-sky Precision Adaptive Optics (KAPA) system.

5.1 NIRC2 Data

Our observations consist of AO Laser Guide Star (LGS) assisted imaging of the target in the Kp bands on NIRC2, using the narrow camera at a plate scale of $0.01''/\text{pixel}$. The dataset

comprises of 6 exposures, with each individual exposure observed the source for 30 seconds. The data considered for fitting the PRIME model in Section 5.2 was observed on 2nd May 2016, whereas the single exposure considered for forward modelled PSF reconstruction was observed on 17th April, 2019. Our data reduction follows the procedure outlined in Melbourne et al. (2005). The field of view is centered $\sim 0.3''$ from the tip tilt star with $m_K = 14.2$ and the laser is positioned in the center of the field. This ensures that the PSF reconstruction is for an on-axis target and any effects due to the cone effect of an LGS can be ignored.

5.2 Describe PRIME PSF Reconstruction

We use the PRIME model described in Beltramo-Martin et al. (2019) to fit a Fourier model to our data. PRIME fits a small number of parameters μ , including $C_n^2(z)$ (as defined for refractive index variations in Section), g_{TT} (Tip-Tilt loop gain), g_{DM} (WFS deformable mirror gain) and static terms expressed in zernike coefficients. In the absence of a full $C_n^2(z)$ profile, PRIME accepts and fits the Fried parameter r_0 instead. PRIME models the implementation of the AO WFS reconstructor (Correia & Teixeira, 2014; Correia et al., 2017a) and the AO loop controller (Correia et al., 2017b; Correia, 2018; Conan & Correia, 2014). PRIME models the power spectrum densities (PSD) to account for aliasing, WFS fitting error and noise due to the spatial reconstructor and AO loop controller. The PSDs are converted to a Phase Structure Function, which are then transformed into Optical Transfer Functions (OTF) for individual components. This is then converted into a PSF. The model can then be used to generate a PSF given the input parameters μ . The PSF is generated by fitting this model PSF to the image data and the input parameters are optimized to give the best fit results. Thus, for a best fit PSF, we can obtain the $C_n^2(z)$ profile, g_{TT} and g_{DM} parameters in addition to the Zernike coefficients for static variations.

We use the PRIME model to obtain the best fit PSF for the reduced NIRC2 dataset obtained on May 2nd, 2016. The images, model PSFs and residuals after PSF subtraction are

shown in Figure 5.1. The model Strehl and FWHM are compared to the image in Figures 5.2 and 5.3 respectively.

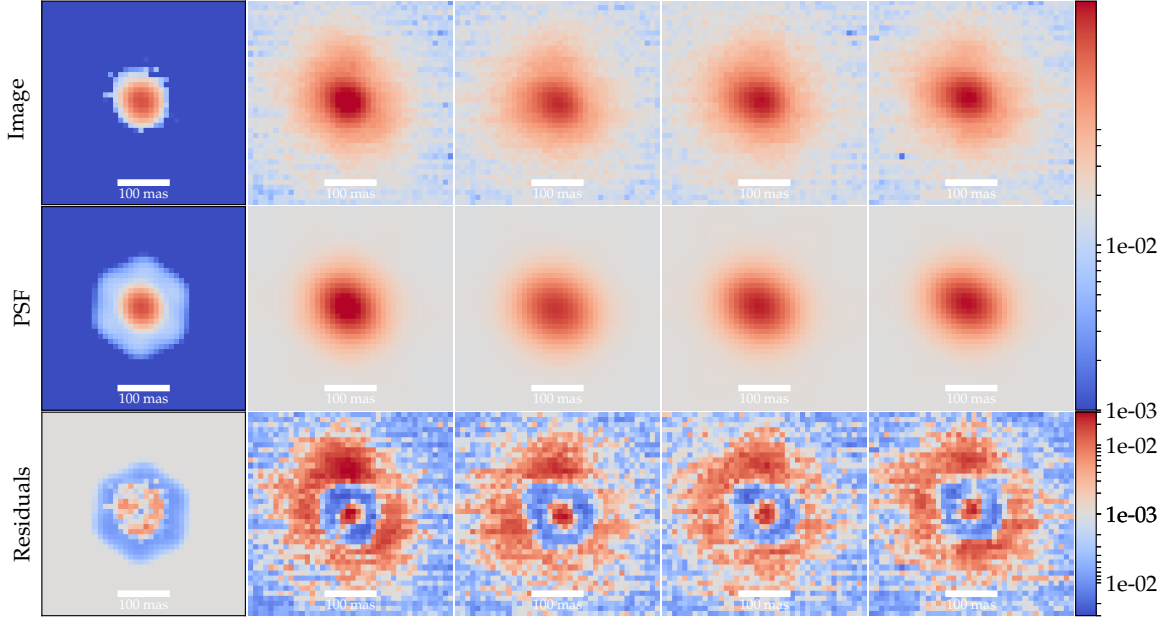


Figure 5.1. NIRC2 images (Top row), best fit PRIME PSFs (middle row) and resultant residuals (bottom row). The residuals are calculated as Image - PSF. No scaling is done for the PSF or image when subtracting to obtain the residuals. Note that the colorbar for the images and PSFs goes up to 0.3 whereas the one for residuals is an order of magnitude smaller.

There are a number of things to note about the dataset and the input parameters provided to the model for the fit. The first image in the series was taken with particularly bright skies which resulted in poor sky subtraction. While PRIME fits a small number of parameters, generating the PSF Fourier model requires a large number of inputs regarding the atmosphere, the sources being observed in the field, WFS and science cameras and the RTC. The atmospheric parameters in question include the wind velocities at the time of observation and the $C_n^2(z)$ profile. The wind velocity data can be taken from the Maunakea weather center, but the data is only available for a single layer and the cadence of data is not fast enough to accurately compare with the observations. Nevertheless, we have considered wind velocity obtained from the Maunakea weather center and provided an estimate for the Fourier model. Since we are unable to provide a full $C_n^2(z)$ profile

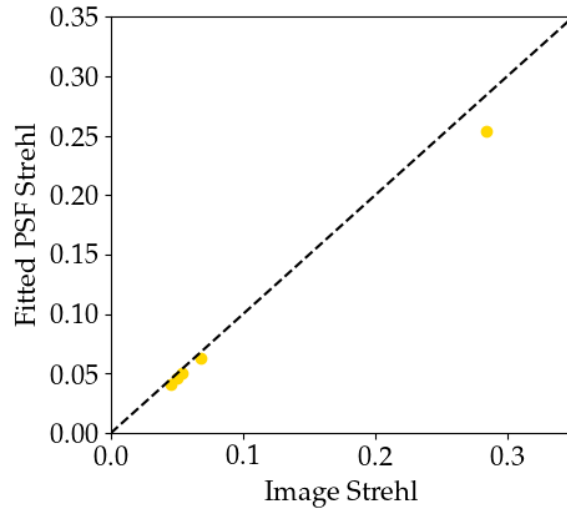


Figure 5.2. The Strehl ratio for the fitted model compared to the calculated Strehl for the image. While the Strehl values are low, fitted values from PRIME still show reasonable agreement with the image Strehl estimates.

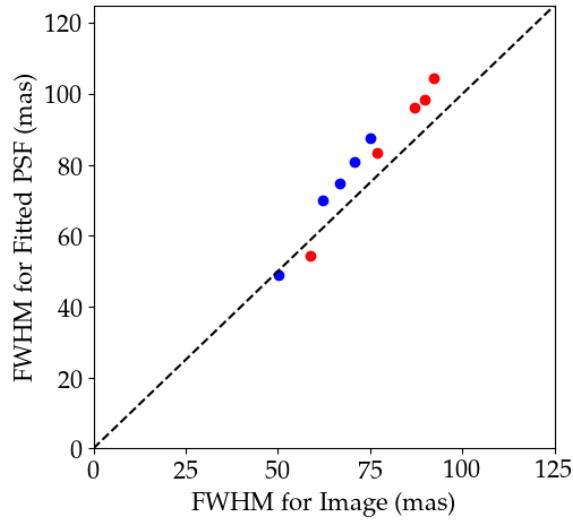


Figure 5.3. The FWHM for the modelled PSF plotted against the measured FWHM for the image. The red and blue points correspond to X and Y FWHM measurements for the dataset. We find the model does reasonably well at replicating image FWHM.

for the observations in question, we instead provide the model with only the Fried parameter r_0 and the seeing during the time of observation. The latter can be established by measuring the FWHM of the image, but also corroborated by the DIMM and MASS estimates of the seeing on site. On the other hand, the Fried parameter is poorly constrained, and particularly for nights with

poor seeing, is hard to estimate even from the seeing. The estimation of Fried parameter from Strehl ratio of an image relies on assuming a turbulence model for the atmosphere, typically taken to be the Kolmogorov model of turbulence. The Fried parameter can then subsequently be related to the Strehl via the Phase Structure Function of the atmospheric turbulence model. Thus, for low values of Strehl, the Fried parameter is difficult to determine due to the Marechal approximation breaking down. Thus, we have to rely on empirical estimates of the Fried parameter. This is also true for the outer length scale L_0 for the turbulence model, which is taken to be 25 meters, although this can also vary and is hard to estimate for individual observations with the data available.

The fitted PSFs agree with the image Strehl and FWHM reasonably well. However, there are a number of important disagreements to be highlighted here. Observing the residuals after PSF subtraction, it is clear that while PRIME achieves a least squares fitted PSF, it is systematically underestimating the core and the outer part of the PSF while overestimating the area around the core, i.e. the first diffraction minima. Moreover, when extracting the fitted parameters μ for the PSF, the model provides unphysical values for the fried parameter, often in excess of 1 meter, which are not possible for the low values of Strehl seen here. The implications are discussed in Section 6.5.

5.3 Forward modelled PSF reconstruction

We now discuss the results from a forward modelled PSF reconstruction, using the implementation in PRIME. The forward modelled PSF-R relies on constructing four phase structure functions, and adding any static Non Common Path Aberrations (NCPA) maps to the resulting Optical Transfer Function and obtaining the resulting PSF. In addition to the inputs provided for the PRIME Fourier model fitting, PSF-R requires the user to provide the NCPA maps for the telescope and the corresponding .trs file for each observation, which contains the AO telemetry and control loop data for NGS and LGS observations. These telemetry .trs files are

fairly large, with a file corresponding to a 30 second exposure on sky typically 300-400 MB in size. Thus implementation of this process for a large number of files would require substantial data management by the observatory.¹

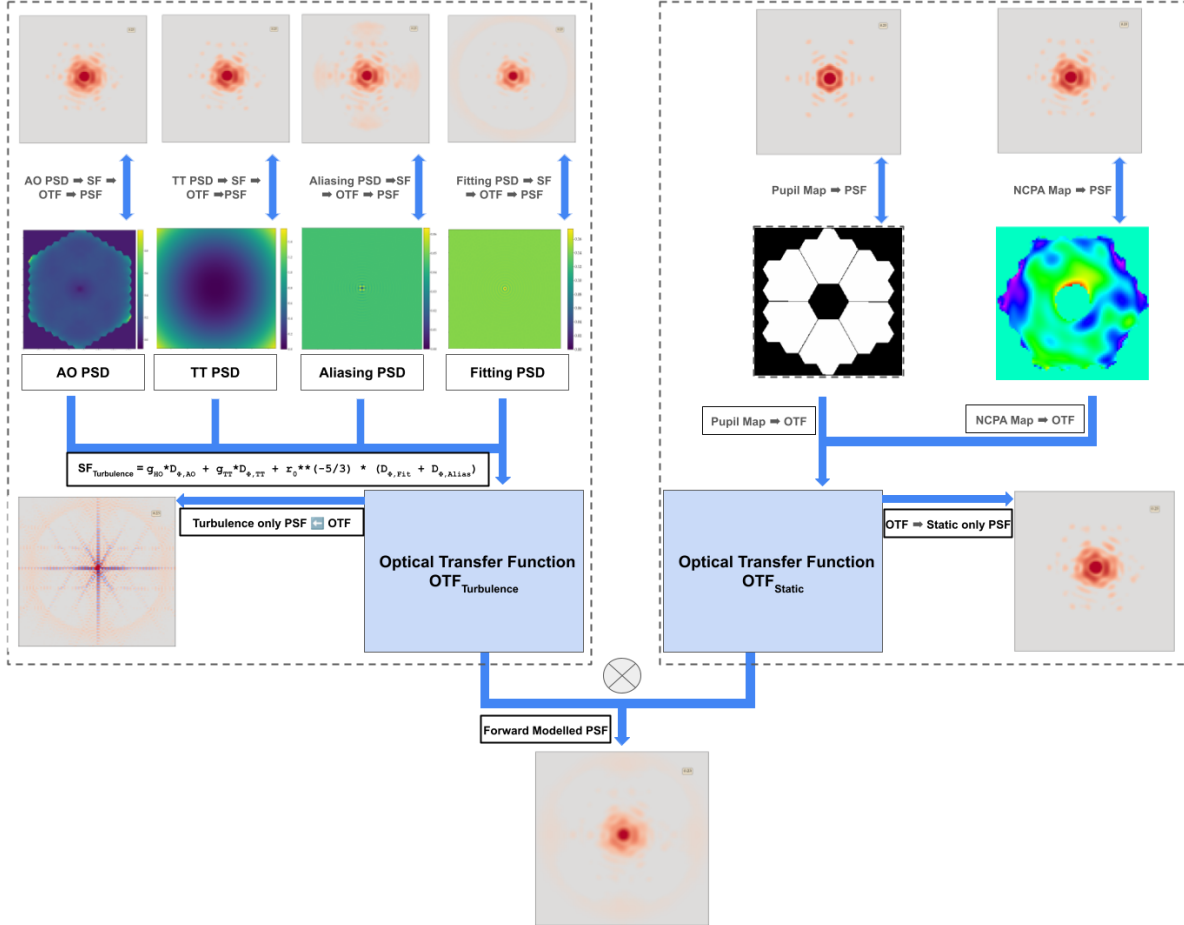


Figure 5.4. The schematic showing various stages of forward modelled PSF reconstruction, and a number of intermediate dataproducts that go into producing a PSF. The model consists of a static and turbulent component to construct the corresponding Optical Transfer Functions (OTFs). The static component consists of the pupil model and the Non Common Path Aberration (NCPA) map derived from phase diversity measurements in Ragland et al. (2016a). The turbulent component considers the AO telemetry and atmospheric information to construct power spectrum densities for the Aliasing, Fitting, AO and Tip-Tilt components, which when combined with a static component can generate a PSF by themselves as shown in the figure. Combining these PSDs gives the turbulent OTF which when combined with the static OTF gives the final PSF.

¹The Keck Observatory Archive now hosts all TRS files for NIRC2 science observations starting August 18th 2019. TRS files are described at https://vmkoaweb.ipac.caltech.edu/UserGuide/trs_data.html

PSF-R is carried out for a single exposure observed on 17th April 2019. The general schematic for the forward modelled PSF-R are shown in Figure 5.4. The model generates two Optical Transfer Functions (OTF), one each for the Static and Turbulent parts of the model. While the Static OTF relies on the pupil map and the Non Common Path Aberrations (NCPA) map as inputs, the Turbulent OTF is generated by first generating a Power Spectrum Density (PSD) for four components. The four phase structure functions computed in computing the PSF are due to Residual Tip Tilt, AO residuals, Aliasing and Fitting errors. The NCPA maps available currently are derived from Ragland et al. (2016b).

The model generates a turbulent structure function $D_{Turbulence}$ given by

$$D_{Turbulence} = g_{HO}D_{\phi,AO} + g_{TT}D_{\phi,TT} + r_0^{-\frac{5}{3}}(D_{\phi,Fitting} + D_{\phi,Alias}) \quad (5.1)$$

Where $D_{\phi,AO}$, $D_{\phi,TT}$, $D_{\phi,Fitting}$ and $D_{\phi,Alias}$ correspond to the structure functions for AO jitter, Tip Tilt residuals, Fitting and Aliasing respectively, r_0 is the Fried parameter, g_{HO} and g_{TT} are higher order and tip tilt gains respectively. The turbulent structure function is used to compute the Turbulent OTF, which is multiplied by the Static OTF, computed from the input Pupil and NCPA maps, which then gives the final PSF. However, due to the way the structure function is calculated, we still require the input parameters μ to compute a PSF.

To obtain the best forward modelled PSF for the data file in question, we need to determine a strategy to compute the input parameters μ . Ideally, the Fried parameter should be determined from an independent measurement and the TT and Higher Order gains would be tied to the gain values used in the AO controller loop hardware and stored in the header of the fits file for which the PSF is being determined. Since we do not currently have a robust independent calculation of these quantities, we have chosen an alternate approach to determine the best parameters. We first compute the Fraction of Variance Unexplained (FVU) (Ciurlo et al.,

2022; Terry et al., 2023) within a 80 pixel box around the PSF. This is calculated as follows -

$$FVU = \frac{\sum_x \sum_y [PSF_{obs}(x,y) - PSF_{mod}(x,y)]^2}{\sum_x \sum_y [PSF_{obs} - \overline{PSF_{obs}}]^2} \quad (5.2)$$

We then systematically scan each parameter to determine the lowest FVU value for the residual image after subtracting the forward modelled PSF. The PSF residuals with the lowest global FVU value is determined to be the best PSF. The residuals are shown in Figure 5.5.

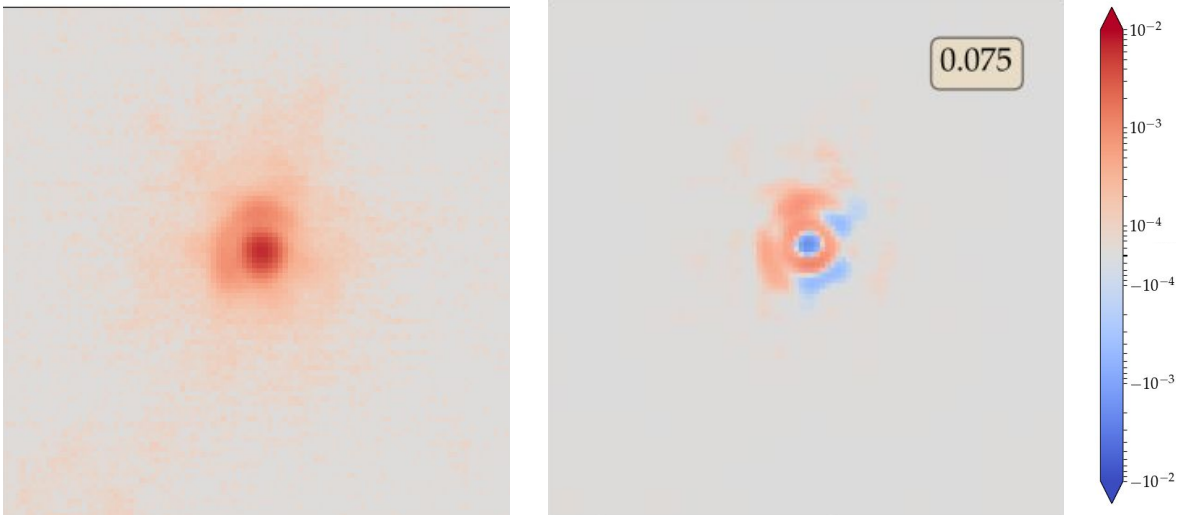


Figure 5.5. (Left) 80 pixel ($0.8''$) box centered on the K mag 14.2 star. (Right) Residuals after forward modelled PSF subtraction. The FVU for the best PSF was found to be 7.5 %.

While the forward modelled PSF produced in this manner gives reasonable values of FVU, and spans a reasonable range of values for the input parameters, there are a number of quality concerns. Firstly, the FVU minimization process results in a PSF that oversubtracts the core and undersubtracts the wings of the PSF. We investigated PSFs where the PSF peak was exactly matched to the image peak and when subtracting these PSFs, the calculated FVU was higher and the wings of the PSF were poorly determined. Secondly, the NCPA map used for this observation was determined for observations taken on March 15th, 2017, which was the closest NCPA map available. NCPA rms errors can change much faster than this so this map is likely incorrect. Lastly, the forward modelled PSF process currently fails to accurately reproduce the

asymmetry secondary maxima in the PSF surrounding the core. These asymmetries can arise due to a number of reasons, including but not limited to, phasing errors between primary segments, an incorrect NCPA map and potential high velocity winds at the time of observation. While the NCPA maps can be obtained using dedicated phase diversity techniques (Ragland et al., 2016b), the wind velocity data and $C_n^2(z)$ profile data is simply not available at the cadence and quality required by the model for an accurate assesment of the algorithm’s performance. The model does not currently include any primary segment phasing errors, although this can be incorporated in future, subject to availability of data.

5.4 Discussion and Future Work

5.4.1 On the merit of using various PSF metrics for forward modelled PSF reconstruction

We consider the use of prominent metrics used to determine the quality of PSF reconstruction and discuss how useful it is to consider these when discussing a forward modelled PSF. These metrics are Strehl, FWHM, radial profiles and FVU. Strehl and FWHM determination are the most widely used metrics to compare a fitted or modelled PSF with the image PSF since these quantities can readily be determined for any given image. The problem with using Strehl or FWHM for a forward modelled PSF however is that these metrics can match the image and yet not be a good indicator of the quality of PSF reconstruction. Since Strehl and FWHM are largely concerned with the core of the PSF, they offer no information regarding the secondary maxima, or the asymmetries of the PSF. Thus, figures indicating an agreement between reconstructed PSF and image Strehls and FWHM do not imply a good PSF reconstruction when the objective is to reconstruct the PSF wings and speckle pattern beyond the core. This can be illustrated with a trivial example. A good Strehl can be obtained simply by considering the Fourier transform of the telescope pupil to obtain the diffraction limited PSF and scaling the obtained PSF to match the image PSF. This method yields a PSF that agrees with the image Strehl by construction, but

will never successfully reproduce the wings and speckle patterns of a realistic PSF. A similar argument can be made for FWHM by simply convolving such a diffraction limited PSF with an appropriate Gaussian.

Radial profiles for the reconstructed PSF are significantly better, since these also show the wings of reconstructed PSFs, but are hard to collate for a large number of PSFs and thus are often shown for a few best cases. This was our chief motivation for using the FVU to determine the quality of PSF reconstruction. However, an FVU determination has its own issues. Primarily, an FVU is dependent on the size of the box used to calculate the residuals. It is not possible to standardize this to a given angular area, since some on axis targets can be isolated while others are in crowded fields, necessitating larger and smaller bounding boxes for FVU calculations respectively. It is however a better metric than Strehl for a forward modelled PSF since it does not rely on the PSF core. Thus future efforts in forward modelled PSF reconstruction must investigate metrics that do not rely on the PSF core, adequately describe the PSF-R quality beyond the core and are standardized so comparison across a large range of models and algorithms can be performed.

5.4.2 Applicability to the Keck All-sky Precision Adaptive Optics

The Keck All-sky Precision Adaptive Optics (KAPA) project will upgrade the Keck AO system with 4 laser guide stars, an improved RTC and the ability to use infrared Tip-tilt stars thus improving sky coverage. The PSF reconstruction method considered here will require a number of modifications to account for the upgraded AO system, namely the reconstructor matrix and controller loop to account for atmospheric tomography possible with four Laser Guide Stars instead of one and change in wavelength of the tip tilt star. The calculation of the residual Tip-tilt and AO jitter PSDs will have to be investigated on the new system alongside investigations of the quality of the WFS fitting errors. While the package we have used is equipped to tackle these new challenges, the upgrade represents a change in a large number of input parameters.

In addition to the changed hardware on Keck, unlocking the true potential of forward

modelled PSF reconstruction requires systematically obtaining atmospheric turbulence data, wind velocity data, alongside determination of NCPA errors in the optical path. Primary segment phasing errors need to be incorporated into current models of PSF reconstruction. These need to be coupled with on axis observations of stars with a range of magnitudes. This will require a concerted long term effort from Keck observatory, since obtaining NCPA maps, primary phasing errors and adding the capability to monitor atmospheric $C_n^2(z)$ profile and wind velocity data at the telescope site can only be pushed forward by on site staff. Theoretically, it should be possible to forward model the PSF based on the inputs described above.

5.4.3 Future Work and Machine Learning in PSF-R

The current version of the reconstructed model, while reproducing the broad features of the PSF, still needs refinement and verification. There are three components to the model, the theoretical model, the implementation of the theory in code and the large number of inputs required to run the model. We have largely validated the underlying theory, implementation and inputs required for the case where the LGS, NGS and the science source are all on-axis. This is not the case for most real observations. Additionally, the model currently requires the Fried parameter as an input, instead of automatically computing it from the input DIMM/MASS profiles. This is currently being implemented in the model so that $C_n^2(z)$ profiles can be directly used to compute the atmospheric layers and their impact on the resulting turbulent OTF. Due to the large number of inputs required, several of which require closely working with the personnel at the telescope due to the requirement for daytime calibrations on the AO bench and corresponding observations the same night, the input dataset is currently small. Moreover, we currently do not have a robust understanding of how the NCPA calibrations change over the course of a night and over longer timescales. Additionally, the wind velocity data is sparse and not measured at the cadence of individual observations, so we need to analyse the sensitivity of the model to perturbations in wind speeds and directions.

The nature of the problem combined with recent advances in Machine Learning represent

an exciting prospect for the future. Machine learning works really well when there are a large number of input parameters and the corresponding outputs to use as the “truth” values. Moreover, machine learning can skirt around the problem of having *all* input parameters being available for *all* observations. This is also an excellent chance to utilize the Keck Observatory Archive and use the engineering stars used for AO checkout on a nightly basis as the truth data for a machine learning model, since this is a large dataset. Thus, machine learning may be a complementary approach to predict PSFs and to compare the validation of a forward modelled PSF in the future.

5.5 Conclusions

We have determined the PSF for two datasets of the same target using a Strehl model fitting and a forward modelled PSF reconstruction. We summarize our results as follows -

1. While the Fourier modelled PSFs result in reasonable residuals, and show good agreement with the image Strehls and FWHMs, the best fitted input parameters, such as the Fried parameter, are often unphysical.
2. Forward modelled PSFs are determined via a FVU minimizing procedure, but show a systematic over subtraction of the core and under subtraction of the wings of the PSF. These do not reproduce the asymmetry in the wings of the PSF, although this can potentially be remedied by improved implementation of the anisoplanatism term in the model, which determines errors in the wavefront due to a separation between the NGS, LGS and the science target. Obtaining NCPA maps taken close to the date of observation and incorporating primary segment phasing errors into the model should also help improve the quality of PSF reconstruction.
3. The models considered above can be adapted to work on the KAPA upgrade on the Keck telescope, but will require extensive data collection and testing of the new laser guide stars, real time controller (RTC), and tip tilt star capabilities. The model will also greatly benefit

from a better determination of the full $C_n^2(z)$ profile and wind velocity data at the Keck site on Maunakea.

Chapter 5, in full is currently being prepared for submission for publication of the material. Sabhlok, Sanchit; Wright, Shelley A.; Lu, Jessica R.; Terry, Sean; Wizinowich, Peter L.; Neichel, Benoit. The dissertation author was the primary investigator and author of this paper.

Chapter 6

A clear case for dust accumulation on the Apollo Lunar Retroreflectors

6.1 Introduction

The corner cube reflectors (CCRs) placed on the moon by Apollo 11, 14 and 15 astronauts continue to produce scientific output more than 50 years after their deployment. The reflectors were designed to sit passively in the periodic temperature swings of the lunar environment in order to facilitate Lunar Laser Ranging (LLR) measurements. It would be fair to say that these reflectors have greatly outperformed expectations, continuing to operate for more than 50 years after placement. Measurements of the Earth–Moon distance provide precision tests of fundamental physics (e.g. general relativity, Lorentz Invariance, time evolution of fundamental constants), as well as geophysical information and constraints on the composition and dynamics of the lunar interior (Murphy, 2013).

The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) began its science campaign in 2006 (Murphy et al., 2008) with the goal of providing millimeter-accuracy range data to improve constraints on gravitational physics.

When APOLLO started ranging, it became clear that the measured return signal was lower than expected by about a factor of 10 from careful link budget calculations (Murphy et al., 2007). Surprisingly, the signal fell by an additional order of magnitude when the lunar phase was within $\sim 20^\circ$ of full moon (Murphy et al., 2010). Murphy et al. (2010) discussed

various scenarios that could lead to the degradation of performance over four decades in the lunar environment, the favored scenario being deposition of dust on the retroreflector surfaces. In a subsequent work, Goodrow & Murphy showed that thermal gradients of a few degrees in a CCR would lead to dramatic suppression of the central intensity of the far-field diffraction pattern (FFDP) Goodrow & Murphy (2012). While this does imply that the return signal from the reflectors would be lowered as a result of a thermal gradient, the paper did not perform any thermal modelling of the CCR under solar illumination.

Lunar dust particles must rely on impacts and on electrostatic charges to levitate and transport across the lunar surface due to a lack of atmosphere (Colwell et al., 2007). Evidence for dust levitation was first seen in the western horizon pictures taken by the Surveyor 5, 6 and 7 spacecraft (Criswell, 1973; Rennilson & Criswell, 1974) shortly after sunset. These images show a distinct glow just above the horizon, indicating forward scattering of the incident solar flux off a levitating dust cloud $< 1\text{m}$ from the ground. These images compliment the reporting of streamers originating from the lunar horizon as seen by the Apollo 17 astronauts from the spacecraft, indicating the presence of levitating dust at scale heights of 5–20 km (McCoy & Criswell, 1974; Zook & McCoy, 1991). Results from the Lunar Ejecta and Meteorites Experiment (LEAM) placed on the moon by the Apollo 17 astronauts indicated the presence of slow moving dust particles. These particles were not detected uniformly over the course of a lunar day, but peaked strongly around lunar sunrise, with detection rates increasing around 60 hours before sunrise and persisting 30-60 hours after sunrise (Berg et al., 1976). The origin of charge on lunar dust grains can be due to friction between meteorically-agitated dust grains, photoelectric charging from incident solar radiation or charging by the incident solar wind. The impact of solar radiation and wind on the lunar surface creates a plasma sheath over the sunlit and shadowed regions on the surface (Halekas et al., 2011). Experiments have verified that charged dust grains can levitate in such a plasma sheath, allowing for their transport across lunar surfaces (Arnas et al., 2001; Sickafoose et al., 2002).

In this work, we present a three-pronged approach to identify the cause of reflector

underperformance and lowered signal during the full moon. Firstly, we perform a detailed link budget analysis in Section 6.2, supplemented by observations of stars of known magnitudes and by beam scans across the lunar reflectors to carefully analyze the profile of the transmitted laser beam. We then compare these calculations to observed return rates from the moon, and indeed find that the actual return rates are 15–20 times lower than expected. Secondly, in Section 6.3, we describe results of APOLLO observations during lunar eclipses—especially one in April 2014, under photometric conditions—showing that the return rate improves by more than an order of magnitude soon after a reflector enters the umbral shadow and cools. Section 6.4 presents results from our custom thermal simulation of a CCR in which we model the expected lunar ranging return rate as a function of solar illumination during a lunar eclipse. We discuss the implications of these results in Section 6.5, and summarize our results in Section 6.6.

6.2 Link Budget

The laser used for APOLLO generates upwards of 10^{17} photons per pulse. Under good conditions, only about one round-trip photon is detected per pulse. A multitude of factors—dominated by divergence—contribute to such a high attrition rate. This section evaluates the link budget, aiming to account for all signal losses along the beam’s round-trip journey from the laser to the detector by way of the moon. We will compare the results of the link equation, Eq. 6.1, to observations on two high-performance epochs, adjusting some of the parameters to suit changing conditions. The nominal link budget is:

$$N_{\text{detect}} = N_{\text{launch}} \eta_{\text{launch}} \eta_c^2 \eta_r \eta_{\text{NB}} Q \eta_{\text{FOV}} \eta_{\text{refl}} N_{\text{refl}} p_{\text{gauss}} \left(\frac{d}{r\phi} \right)^2 p_{\text{refl}} \left(\frac{D_{\text{eff}}}{r\Phi} \right)^2 \prod_i D_i. \quad (6.1)$$

Here, the number of photons we expect to detect is denoted as N_{detect} . Table 6.1 elucidates the meaning of the terms on the right, elaborated in the text.

APOLLO’s laser operates at a wavelength $\lambda = 532$ nm, and the energy per pulse of the

Table 6.1. Parameters used in link equation (Eqn. 6.1). Values for η_r and Q are not determined separately, using the measured amalgam $\eta_c\eta_r\eta_{NB}Q$ instead. Blank uncertainties are either meaningless or too small to matter. Some parameters are adjusted for specific observations.

Parameter	Description	Value	Uncertainty
N_{launch}	Laser photons per pulse	2.7×10^{17}	0.14×10^{17}
η_{launch}	Central obscuration in uplink	0.60	0.03
η_c	Common-path optical throughput	0.53	0.09
η_r	Receiver efficiency	—	—
η_{NB}	Narrow-band filter transmission	0.99	0.003
Q	Photon detection efficiency	—	—
$\eta_c\eta_r\eta_{NB}Q$	One-way throughput amalgam	0.053	0.007
η_{FOV}	Limited detector field of view	0.787	adjusted
η_{refl}	Corner cube optical transmission	0.93	0.005
N_{refl}	Number of reflectors in array	100 or 300	—
p_{gauss}	Gaussian profile vs. top-hat	0.693	—
d	Diameter of single corner cube	0.0381 m	—
r	Earth-Moon distance	3.85×10^8 m	adjusted
ϕ	Uplink beam divergence	1.0 ''	adjusted
p_{refl}	TIR CCR diffraction vs. top-hat	0.182	—
D_{eff}	Effective telescope aperture	3.26 m	—
Φ	Downlink beam divergence	2.89 ''	—
D_i	Adjustments for epoch particulars	Table 6.2	—

laser is ~ 0.1 J, resulting in $N_{\text{launch}} \approx 2.7 \times 10^{17}$ generated photons per pulse. Transmission losses are accounted later, but we separately address the geometrical loss of the outgoing Gaussian beam due to the secondary mirror obstruction via $\eta_{\text{launch}} = 0.60 \pm 0.03$.

Various transmission and reflective efficiencies associated with specific segments of the photons' overall path are captured by η factors in Eq. 6.1. The first efficiency, η_c , is the one-way optical efficiency that is common to both the transmit and receive paths of the APOLLO system—including atmospheric losses. For Apache Point, η_c evaluates to 0.53 ± 0.09 at 532 nm under clear skies and pointing at zenith (three reflections at 0.85 ± 0.05 and 0.87 atmospheric transmission). Because this path is traversed twice—once for the transmitted beam and once for the received signal— η_c appears squared in Eq. 6.1. The combined term $\eta_c\eta_r\eta_{NB}Q \approx 0.053$ relates to the total one-way throughput of the receiver/detector, which is

experimentally determined as a group in Section 6.2.2. The η_{FOV} term, nominally computed for a 1.0 arcsec seeing disk, represents the fraction of the point spread function (PSF) captured by the 1.4 arcsec square field of view of the APOLLO receiver, with one corner pixel in the 4×4 array detector unused.

The corner cube reflectors (CCRs) number N_{refl} in the reflector assembly (100 for Apollo 11 and 14; 300 for Apollo 15), have a front-surface reflection loss represented by η_{refl} , and diameter, d .

The first squared term in parentheses represents the fraction of the uplink beam reaching a single CCR, according to a top-hat profile having a nominal diameter of $\phi = 1.0$ arcsec (see Section 6.2.1). For the divergence geometry, the one-way telescope-reflector distance is set to the average Earth–Moon distance of $r = 3.85 \times 10^8$ m. We later correct for the geometry at the epoch of observation via derating terms, D_i . The erroneous top-hat model is then corrected to describe a Gaussian profile more characteristic of atmospheric seeing, whose full-width at half-maximum (FWHM) matches the diameter of the top-hat profile. The correction factor, $p_{\text{gauss}} = \ln 2$, accounts for the reduced central intensity of a Gaussian profile having the same total flux and FWHM as the top-hat (FWHM is $\sqrt{\ln 256}$ times the Gaussian sigma).

The second squared term in parentheses captures geometric loss in the returning beam, whose divergence is also initially treated as a top-hat illumination profile of angular diameter $\Phi = \lambda/d$. This is intercepted by a telescope whose effective diameter is such that the collecting area is $\pi D_{\text{eff}}^2/4$. The top-hat model is then corrected to represent the central intensity of a far-field diffraction pattern arising from total internal reflection (TIR) by the parameter p_{refl} Murphy & Goodrow (2013).

Note that while not appearing explicitly in Table 6.1, a characteristic uncertainty of 0.05 arcsec is applied for ϕ , which propagates into an uncertainty value for η_{FOV} of 0.03. These uncertainties are applied with the rest in Section 6.2.4.

6.2.1 Beam Scan Test: Lunar Beam Profile

In order to assess the uplink divergence, ϕ , we contrive to scan the telescope-fixed laser across the reflector while keeping the detector centered on the reflector. This requires a coordinated move of the receiver’s adjustable offset pointing angle to counter the motion of the telescope (and thus outgoing beam). We perform a scan in two dimensions, effectively in a plus-shaped pattern centered on the nominal pointing. As each pixel in the 4×4 detector only spans 0.35 arcsec, very small motions are noticeable.

As such, a scan of this sort is easily thwarted by pointing drift. Moreover, even when maintaining the pointing to the best of our ability, factor-of-two variations in signal on the timescale of tens of seconds are routine, largely due to seeing variations (APOLLO is highly sensitive to seeing, both due to target illumination and overfilling of the small detector). This makes interpreting a beam scan tricky: how much of the variation is due to the pointing offset, how much is variable seeing, and how much is due to variation in other terms in the link budget?

To mitigate this, we execute a pattern of moves that returns to the central position after every offset, thus interleaving central positions between each excursion. During the times pointing at the nominal (central) position, we sometimes adjust the pointing to re-center and maximize signal. Furthermore, we only consider the signal change in the several seconds surrounding the transition from one position to the next, rather than averaging the whole offset result. Each pointing therefore gives two signal ratios: at the beginning of the move, and again at the end.

Fig. 6.1 shows an example from one epoch, in orthogonal dimensions. Each data point averages the beginning and end ratios for the excursion. Since all measurements are in relation to the return rate at the central position, the result is normalized to the (changing) central value for each paired measurement.

We report here results from beam scans on two epochs. For 2018 February 25, we measure an uplink beam FWHM of 1.00 ± 0.05 arcsec, while on 2018 September 28 we get

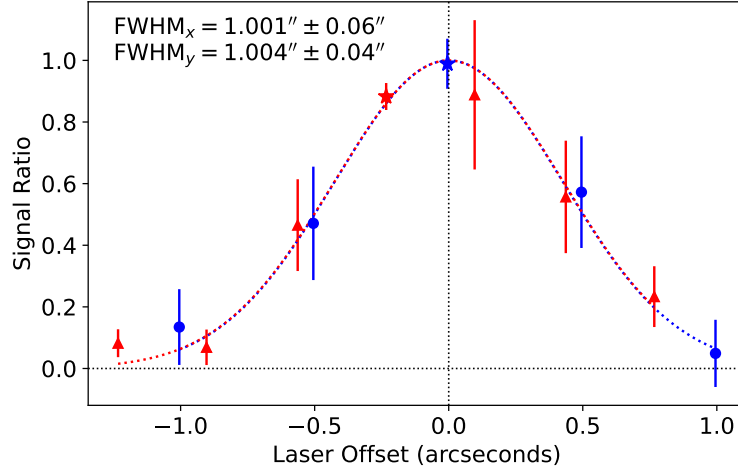


Figure 6.1. Beam scan results on 2018 February 25 for x (blue circles) and y (red triangles) directions, normalized to the peak. The nominal center positions are denoted by stars. In this case, the FWHM of the Gaussian fits are 1.001 ± 0.06 and 1.004 ± 0.04 arcseconds.

1.07 ± 0.19 arcsec. Because the ϕ parameter in Eq. 6.1 is set to 1.0 arcsec, and squared in the link equation, we apply a derating factor of 0.88 to the latter case (the former needing no correction), as will be summarized in Section 6.2.3. The distribution of lunar return photons on the receiver array further corroborates—and closely matches—the beam scan results by providing an in-situ characterization of the seeing at the time of observation.

6.2.2 One-Way Throughput

A number of the terms in Eq. 6.1 can be simultaneously determined by pointing to a non-variable bright star of known magnitude and spectral type, measuring the photon counts, then comparing to theoretical expectations. We first assess the top-of-atmosphere flux density at 532 nm (in $\text{W m}^{-2} \text{nm}^{-1}$, e.g.) for the spectral type and magnitude, correct for the zenith angle, sum over the effective telescope aperture, multiply by the 2.1 nm bandwidth of the narrow-band filter, and by the effective integration time (typically 500 exposures at 100 ns each), and divide by photon energy to arrive at the number of photons we would detect in the case of no losses. By comparing actual counts, we effectively measure the product $\eta_c \eta_r \eta_{\text{NB}} Q \eta_{\text{FOV}}$.

In practice, we fit a two-dimensional symmetric Gaussian profile to each $50 \mu\text{s}$ ex-

Table 6.2. Link budget derating factors for the two beam profile experiments.

Cause	Epoch A Value 2018 Feb 25	Derating	Epoch B Value 2018 Sep 28	Derating
Range (r)	3.6008×10^8 m	1.31	3.7724×10^8 m	1.08
Zenith Angle	19.9°	0.98	47.8°	0.87
Angular Offset (libration)	5.7°	0.75	8.13°	0.66
Sun Angle (θ)	-67.3°	0.84	40.8°	0.74
Velocity Aberration	$0.946''$	0.762	$1.003''$	0.736
Uplink Beam (ϕ)	$1.00''$	1.0	$1.066''$	0.88
Detector Capture (η_{FOV})	$0.90''$	1.05	$0.91''$	0.950
Total Derating		0.648		0.282

posure (typically delivering about 1,000 counts across 15 active elements) to determine the theoretical total flux: $2\pi A\sigma^2$, where A is Gaussian amplitude and σ is the standard deviation width parameter—if unconstrained by η_{FOV} . This produces a more stable flux estimate than the variable, jumpy seeing produces in raw terms—since the fraction of light captured in the detector is sensitive to offset and width of the PSF in a way that the total flux is not.

Several such tests on 2019 July 20 under the same detector configuration as for the beam scan epochs resulted in a determination for $\eta_c\eta_r\eta_{\text{NB}}Q$ of 0.053 ± 0.007 . We need only multiply by another factor of η_c to represent a cluster of terms in Eq. 6.1. The term η_{FOV} can be computed exactly for a centered Gaussian in a 4×4 grid whose pixels are 0.35 arcsec and missing one corner. For example, a Gaussian whose FWHM is 1.0 arcsec delivers 78.7% of its flux to such an array, while 1.5 arcsec seeing would result in 50.6%. We use the 1.0 arcsec value in Eq. 6.1, then correct for conditions in Section 6.2.3.

6.2.3 Derating Factors

Some of the parameters in Eq. 6.1 are not constant, and require adjustment for the time of observation. Moreover, a few additional factors impact the link and need to be considered. These terms appear at the end of Eq. 6.1 as a product of derating factors. The various derating factors applied in this analysis appear in Table 6.2.

First, the Earth–Moon distance varies by as much as 13% (full range), and appears to the fourth power in Eq. 6.1. Based on the distance, r_{obs} , at the time of observation, we apply a “derating” factor (that indeed enhances the link result as often as not) of $(r/r_{\text{obs}})^4$.

The second factor accounts for the fact that we do not operate at zenith pointing, and is provided by the expression $0.87^{2(\sec z - 1)}$. Here, z is the zenith angle of the Moon. The base of 0.87 comes from the atmospheric loss by passing through one atmosphere at 532 nm. The factor of two in the exponent is to account for the beam passing through the atmosphere twice. Finally, we subtract one in the exponent because we already account for one atmosphere of thickness in η_c .

Three other derating factors come from the geometry of the Earth–Moon and Moon–Sun relationships. First, libration of the moon results in an angular offset of the CCR array relative to the Earth–Moon line, producing a reduction of the central irradiance of the far-field diffraction pattern via reduced area and increased diffractive spread. Next, thermal computations by the reflector manufacturer Faller et al. (1972) anticipated modest dependence of reflector behavior on sun angle (θ). Finally, velocity aberration shifts the return far-field diffraction pattern on the surface of the Earth by approximately one arcsecond, so that the telescope sits not at the peak of the pattern, but on the dimmer shoulder. The central lobe of the complex TIR diffraction pattern closely follows that of an Airy pattern from a circular aperture of the CCR’s diameter Murphy & Goodrow (2013). The derating amount is thereby computed using this profile based on the relative tangential velocity at the time of observation—dominated by Earth rotation.

Lastly, atmospheric seeing impacts both the outgoing beam divergence (ϕ), and the fraction of light captured by the detector, η_{FOV} . The latter is calculated according to a Gaussian fit to the lunar return distribution on the 4×4 detector, whose FWHM is given in Table 6.2, along with the corresponding adjustment relative to the nominal case presented in Table 6.1. It is reassuring that the FWHM values for the beam scans are not much larger than the FWHM values of the lunar signal on the detector—indicating good beam collimation so that the outgoing beam is essentially seeing-limited. Note that on 2018 September 28, an additional detector element

near the center was inoperative, which is why the derating factors are different, despite similar FWHM measures for the two cases.

6.2.4 Link Assessment and Implied Dust Fraction

The previous sections laid the groundwork for comparing observed lunar return rates to theoretical expectations. Application of Eq. 6.1 using values in Table 6.1 and Section 6.2.2 produces for Apollo 15 a nominal expectation of 19.1 ± 4.8 photons per shot, before derating factors are applied. For the two epochs considered, the derating factors yield approximately 12.4 and 5.4 photons per shot.

On these two nights—the ones for which beam scans were performed, thus obtaining confident optimization of the signal—we assess the photon return rate at the many visits to the central beam position. Because the LLR signal rate is extremely sensitive to telescope pointing and atmospheric seeing (via ϕ and η_{FOV} parameters), we see much variation in central-position rates throughout the roughly ten-minute scan procedure. We therefore take special care in assessing a “reasonable” return rate, looking to identify a consistent “best” central rate that recurs multiple times throughout the scan and that is therefore compatible with the beam divergence assessed over the entire scan period. We believe these “best” rates are more representative of the theoretical link performance of APOLLO, for more meaningful comparison to the link calculation.

The estimated return rates for the two epochs are assessed to be 0.66 and 0.35 photons per shot in February and September of 2018, respectively. The observed rates are therefore well below the theoretical expectations of roughly 12 and 5 photons per shot. The ratios are similar, at 5.2% and 6.7% for the respective epochs. It should be noted that the derating factors produce expectations roughly a factor-of-two different for the two epochs, and that the observed rates are likewise different by approximately the same factor—indicating consistent results.

We therefore conclude that observed return rates are at least an order-of-magnitude lower than expectations, and are unable to account for the difference by careful analysis and

experimental characterization. A proposed explanation that runs through this paper, and others before it Murphy et al. (2010, 2014), is that dust accumulation on the front surfaces of the CCRs simultaneously accounts for the link deficit, the additional full-moon deficit, and eclipse response.

Treating the dust as a set of geometrical obstructions, we recognize that the double-pass nature of the CCR makes each dust grain count *twice*, blocking both entering and exiting light paths. If the geometrical covering fraction is f , the probability of passage through the surface is $1 - f$. Independent probabilities for blockage in the two directions means that the probability of round-trip passage is $(1 - f)^2$. This amount of blockage will impact the central intensity of the far-field diffraction pattern (FFDP). Normally, the unobstructed CCR, with front surface area, A , will have a FFDP central intensity proportional to A^2 (effectively, a coherent sum of the electric field over the open aperture, squared for intensity). Since the obstructed CCR has an effective area of $(1 - f)^2 A$, the FFDP central intensity will be reduced by $(1 - f)^4$. This strong dependence on f means that, for instance, a 50% covering fraction results in a sixteen-fold reduction in the FFDP central intensity—which is indeed approximately the factor of signal deficit we deduce. Applied to the signal deficit ratios from the two epochs above, we compute dust fractions of 0.52 and 0.49 for February and September 2018, respectively. The two epochs are therefore telling a very similar story in the context of dust coverage.

We note that infrared observations may be less impacted by dust, as the particles may be less “geometrical” at longer wavelengths. This may be related to the success of recent infrared LLR operations, where reflector performance appears to be better (Courde et al., 2017). It is also the case the thermal lensing effect explored more below is less impactful at longer wavelengths.

6.3 Eclipse Observations

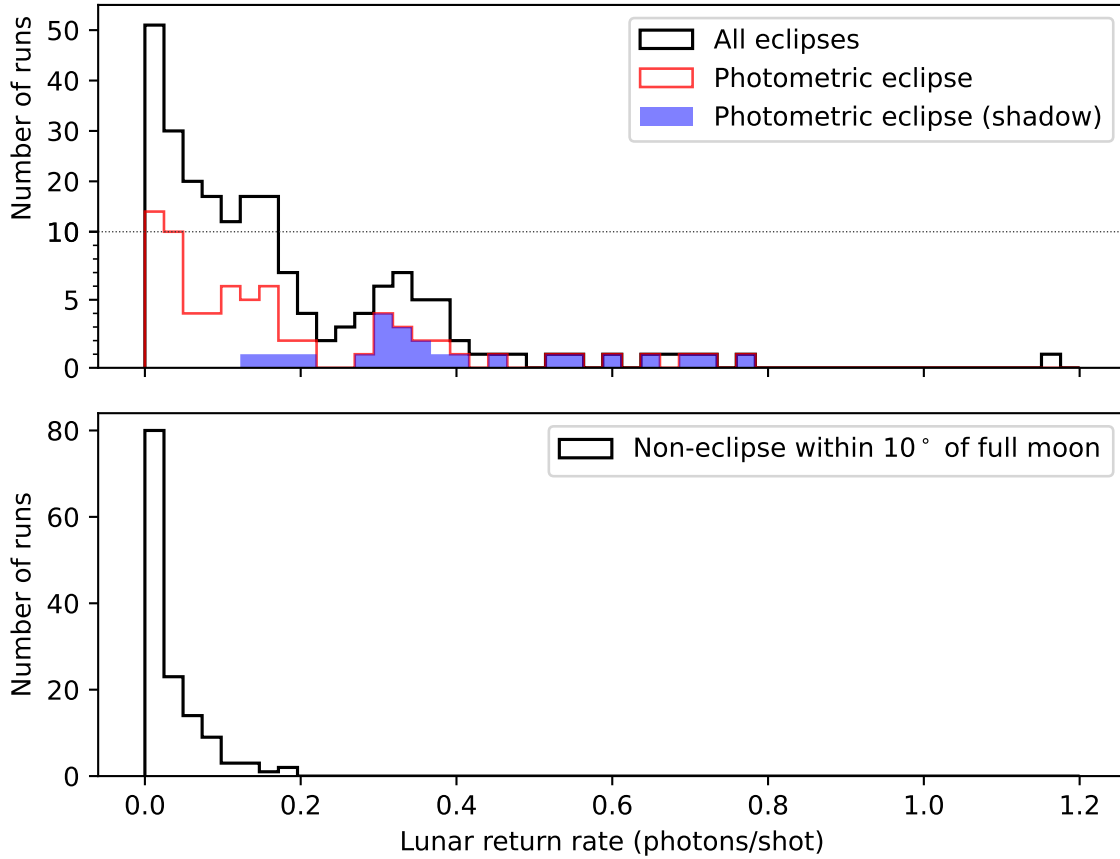


Figure 6.2. (Top) Histogram of the lunar return rate (photons per shot) during four eclipses (black line), as well as for the photometric eclipse on April 15, 2014 alone (red). Also shown (blue fill) is data from the photometric eclipse when the target reflectors are in full shadow. Note the change of scale on the ordinate indicated by the horizontal dotted line. (Bottom) Lunar return rate histogram when the moon is not in eclipse, but the lunar phase angle is close to full (within 10 degrees). All non-eclipse lunar return rates are less than 0.2 photons per shot. Both histograms aggregate data from all three Apollo reflector arrays (Apollo 11, 14 and 15). The Apollo 11 and 14 rates have been scaled up by a factor of three because those arrays contain three times fewer corner cube reflectors than the Apollo 15 array.

To study the effect of solar illumination on ranging throughput, we took advantage of the naturally occurring variation in the solar illumination incident on CCRs during lunar eclipses. During a lunar eclipse, the solar illumination changes from 100% to 0% (shadow) and back to 100% over the course of about five hours as the CCRs enter and then exit the Earth’s umbral

shadow. A measurement of the evolution of the lunar return rate during the eclipse provides an independent constraint on the CCR dust coverage fraction, which can be compared to the fractions derived using link budget calculations (Section 6.2.4) and thermal eclipse simulations (later in Section 6.4).

We undertook four lunar eclipse ranging campaigns (December 21, 2010; April 15, 2014; September 28, 2015; January 21, 2019). Here, we focus on the 2014 eclipse (MJD 56762 from 5:52 to 10:52 UTC) because photometric sky conditions that night enabled the most reliable study of the throughput of the APOLLO system and lunar retroreflectors. While data from other eclipses is not presented in this work due to cloud obscuration affecting the photometric conditions on those nights, the broad trends from the April 2014 eclipse hold for the other eclipses as well. We do observe an increase in observed return rate once the reflectors enter the shadow and the signal starts to deteriorate once the reflectors come out of the shadow. Range measurements were divided into short runs of ~ 150 second duration (3000 laser shots) in order to monitor the evolving lunar return rate as a function of solar illumination of the lunar retroreflectors.

We compare eclipse-night observations to lunar return rates measured during non-eclipse nights, but with the lunar phase within 10 degrees of full moon. In those cases, the median (mean) return rate is 0.02 (0.03) photons per shot, and the maximum is 0.2 photons per shot (see the bottom plot of Fig. 6.2). During the 2014 eclipse, before the Apollo 11 and 14 reflectors entered the earth's umbral shadow the median (mean) return rate was also low, at 0.06 (0.08) photons per shot (red histogram in the upper plot of Fig. 6.2). After the reflectors entered the umbral shadow and began to cool (blue shaded histogram in the upper plot of Fig. 6.2), the return rate rose as high as 0.77 photons per shot, with a median (mean) value of 0.35 (0.41) photons per shot, which is 17 times higher than the median rate during non-eclipse nights near full moon. The lunar return rate histogram for data from all four eclipses is shown in black in the top plot of Fig. 6.2, and it tells a consistent story: under overhead solar illumination, the optical throughput of the lunar reflectors degrades by at least an order of magnitude, but when the illumination is

suppressed (via a lunar eclipse) and the reflectors cool, the rate increases. As described more fully in Section 6.4.2, we attribute the rate increase to the cooling of the reflectors when they are in shadow, which in turn reduces the thermal gradients in the CCR and improves the FFDP (and therefore the optical throughput) of the corner cubes.

6.4 Thermal Modelling of the Corner Cube Retroreflectors

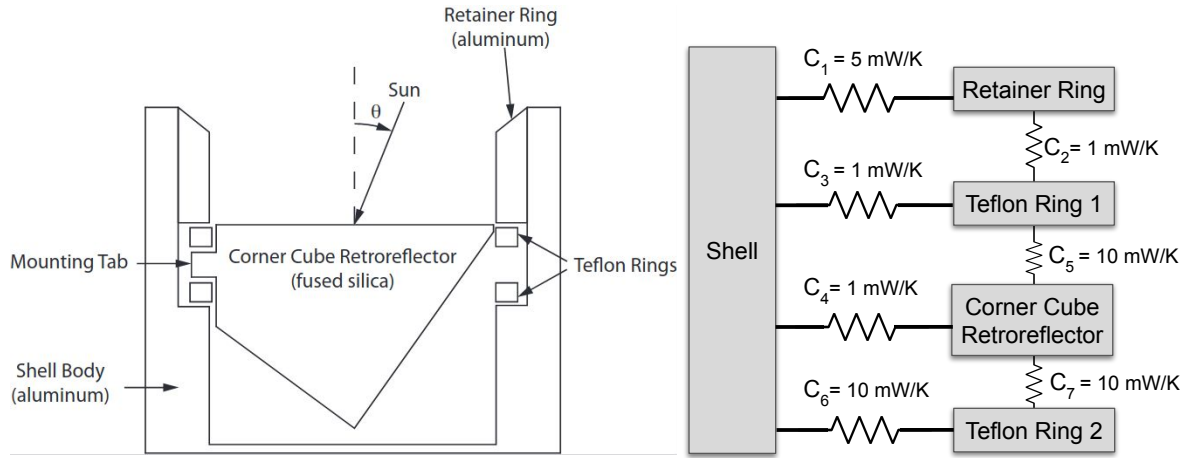


Figure 6.3. (Left) Schematic diagram defining the geometry of the CCR mounted in the aluminum casing ("shell") via Teflon mounting rings and the retainer ring. (Right) Elements and conductive paths used in our thermal simulation, with specified thermal conductances. The CCR, retainer ring, and the shell radiate heat to space. Solar energy is incident on the top surfaces of the CCR, retainer ring, and shell. The corner cube looks asymmetric from this angle because the tabs are placed at 120 degree intervals around its perimeter, so diametrically opposite sides do not both have tabs.

We model the optical response of a CCR under thermal load to estimate the dust coverage fraction for comparison with the degradation estimate from our link budget calculation in Section 6.2, the eclipse observations in Section 6.3, and the known degradation of performance during full moon (Murphy et al., 2010). Our simulations were done using a custom code in C developed by our group for this purpose. The simulation has three stages. First, we set up the geometry of the problem, defining the different surfaces, their thermal properties and initial conditions. In the second stage, the code calculates the analytic view factors from all boundary

point surface elements to all others and stores them into a view factor matrix to be referenced later for radiative heat transfer. Lastly, the code performs conductive and radiative heat transfer, based on the initial conditions for a specified amount of time. The details of the code implementation, including the geometry setup, view factor matrix construction and heat transfer, are described in Appendix 6.6.

A schematic diagram and corresponding thermal model of the mounted CCR is shown in Fig. 6.3. The fused silica CCR is mounted to an aluminum shell (aluminum 6061-T6), held in place by two teflon rings and an aluminum retainer ring (anodised aluminum 1100). For the CCR, retainer ring and the shell, we have to specify the net absorptivity and emissivity as a result of an impeding dust fraction sitting on the surfaces. To define the net emissivity and absorptivity, we consider a fraction f of the surface to be obscured by lunar dust, with an inherent emissivity ϵ_{dust} and absorptivity α_{dust} . For the shell and the retainer ring, the net emissivity is simply an area-weighted mean of the two emissivities. Effective emissivity and absorptivity for the top of the shell and retainer ring is given by

$$\epsilon_{eff} = (1 - f) \epsilon + f \epsilon_{dust} \quad (6.2)$$

$$\alpha_{eff} = (1 - f) \alpha + f \alpha_{dust}. \quad (6.3)$$

The case for the top of the CCR is slightly more complicated by the fact that light can be absorbed by the dust on the way back out of the CCR as well. So the effective absorptivity comes out to be

$$\alpha_{eff,CC} = [1 - (1 - f)^2] \alpha_{dust}. \quad (6.4)$$

Our simulation investigates both equilibrium and dynamic modes. First, a constant heat input, modelling the solar flux incident on the moon (1360 W m^{-2}), is used to simulate an equilibrated CCR temperature profile under full-moon illumination conditions. As our interest in this work primarily concerns observations near full moon, we do not consider the

Table 6.3. Properties of materials used in the thermal simulation.

Element	Material	Conductivity $\text{W m}^{-1} \text{K}^{-1}$	Density kg m^{-3}	Heat Capacity $\text{J kg}^{-1} \text{K}^{-1}$	Emissivity	Absorptivity
CCR	Fused Silica	1.38	2200	740	0.87	0.0
Rings 1 & 2	Teflon	0.25	2200	1500	0.8	0.8
Shell	Aluminum 6061-T6	167.0	2700	896	0.025	0.06
Retainer Ring	Anodized Aluminum 1100	222.0	2710	904	0.78	0.32
	Lunar Dust	—	—	—	0.9	0.9

possibility of sunlight illuminating the interior of the shell behind the CCR because all incident sunlight is rejected by total internal reflection when the solar illumination is within 17 degrees of normal incidence. The equilibrated temperature profile is then used as a starting point for an eclipse simulation, where the solar flux is varied according to an eclipse illumination profile. The simulation computes the temperature of all elements at each time step, from which the temperature profile of the CCR is extracted. Given the CCR temperature profile, the path length variations imposed by thermal modification of refractive index within the CCR are calculated, leading to a warped wavefront emerging from the CCR to produce a FFDP—the so-called thermal lensing effect Goodrow & Murphy (2012). The effect is largely driven by the temperature gradient from the surface to the corner of the CCR. The resultant FFDP can then be compared to the case of an isothermal CCR, to quantify the loss in return rate as a percentage. We calculate this loss for the full moon illumination, which can be compared to our measured return rate during full moon observations (Murphy et al., 2010). We also compare the modeled return rate improvement during the eclipse to that observed during the 2014 eclipse. The thermal properties for the different materials used in the simulation are outlined in Table 6.3.

6.4.1 Steady-state Simulation Results

To compute the steady-state thermal profile of the CCR in the presence of direct overhead solar illumination (as would be the case during a full moon), we begin the simulation with all elements set to a temperature of 300 K, and assume a solar constant value of 1360 W m^{-2} . We then run the simulation until the average temperature of all four simulated elements (CCR,

Teflon rings, retainer rings and shell) stabilize. The spatial temperature profile of the CCR is extracted and used to generate a FFDP for the CCR. Different values of f result in differing central maximum intensities compared to the isothermal CCR. We find that varying f from 0.5 to 0.65 changes the central maximum intensities of the CCR from $\sim 6\%$ to about $\sim 0.1\%$ of the isothermal case. The peak-to-peak phase difference in the wavefront at a dust fraction of 0.5 is ~ 4.9 radians due to thermal effects. This phase difference across the wavefront results in a diminished central lobe of the FFDP. The former result, at $f = 0.5$, matches the full-moon deficit factor of 10–15 reported in Murphy et al. (2010), and the results from Section 6.3 and Fig. 6.7 of this paper.

It is worth briefly discussing the qualitative thermal behavior of the CCR when we simulate equilibrating the geometry for a constant solar flux. As the run is started, a thermal gradient is set up quite rapidly within the CCR, within the first 100 seconds of temporal evolution. The surface of the CCR absorbs heat from incident solar radiation. This creates the thermal gradient in the CCR, with the front face being hotter than the vertex. This thermal gradient is responsible for the reduced intensity in the central maximum of the FFDP. It takes far longer, a few hours, for the system to reach a steady-state temperature. The main cooling channel for the system at this point is the radiative cooling from the CCR front surface, radiating heat to space. We confirmed that the final steady-state temperatures are independent of initial conditions. Since the thermal gradients within the CCR rapidly adjust to the incident solar flux, we expect that during the eclipse simulation, the return rate should quickly improve once the reflector enters the shadow, since the gradients, rather than the absolute temperature, affect the FFDP and therefore the return rate. This is indeed the case as shown in the next subsection.

6.4.2 Simulation Result Showing Eclipse Profile

We apply our simulation to the case of a lunar eclipse in which the solar illumination incident on the CCRs is modulated by the Earth’s shadow. The relative angular sizes of the Earth and Sun as seen from the moon are used to simulate an eclipse profile for different impact

parameters for the Earth's center passing in front of the Sun. This is compared to the illumination profile seen at the three different Apollo reflectors Chapront-Touzé & Chapront (1991). The computed illumination profile does not include limb darkening. The impact parameter that best describes the profile for all three reflectors is used as the incident solar flux profile, as shown in Fig. 6.4. While all reflectors remain under the shadow for different amounts of time, the total time difference between the shortest and longest eclipse times for different reflectors is approximately 6–7 minutes. When comparing to APOLLO observations, this is shorter than the circuit among reflectors, so the impact of different reflectors being under the shadow for different amount of times is minimized. The resultant temperatures for the CCR, teflon rings, the retainer ring and the shell are shown in Fig. 6.5. Since the FFDP evolution is largely driven by the corner cube gradients, we present the radial and vertical gradients within the CCR in Fig. 6.6. For the radial gradient, due to the trifold symmetry of the corner cube, we consider a radial gradient between the center and a point on the circumference which is a midpoint of one of the “tabs.” We also consider a point on the circumference equidistant from the two nearest tabs for a radial gradient.

The qualitative behavior of the system during the eclipse can be described as follows. Starting from an equilibrated geometry, as the incident solar flux gradually decreases, the amount of heat absorbed by the CCR decreases as well. According to Figure 6.6, very little radial gradient is initially present, and thus little conduction through the tabs (the shell and CCR being at a similar temperature). Consequently, the CCR loses thermal energy primarily through radiation from the front surface. Before long, the CCR becomes cooler than the shell, so heat conducts into the CCR through the mounting tabs, setting up radial gradients while maintaining a weak vertical gradient as shown in Figures 6.5 and 6.6. When the solar flux dwells at zero, the CCR continues to cool, but the gradient is relatively stable, thus resulting in the plateau region in the expected return rate shown in Figure 6.7. When the reflectors come out of the shadow, solar flux increases so that the CCR starts to absorb more heat and the strong vertical gradient develops again, depressing the expected return rate. Throughout this process, the CCR front

surface remains hotter than the vertex, i.e. the gradient maintains the same orientation.

The time dependence of the ratio between the intensity of the central maximum in the FFDP of the CCR during an eclipse with respect to an isothermal corner cube is plotted in Fig. 6.7, along with the measured return rates from individual Apollo reflectors during the 2014 eclipse. The simulated return rate increases rapidly after the CCR enters the Earth's shadow, and is correlated with a rapid reduction in the temperature gradient from the back to the front of the CCR as it cools as shown in Fig. 6.6. As the CCR stays in the shadow, it retains the low vertical gradient compared to steady state illumination during full moon. When the reflectors come out of the shadow, the gradient increases to pre-eclipse levels rapidly, destroying the central maximum in the FFDP resulting in low return rates from the CCR. The simulated ratio between the maximum intensity in the FFDP during the eclipse to the start of eclipse is ~ 7 , as the intensity goes from $\sim 6\%$ to $\sim 42\%$. This is comparable to the observed ratio of median return rate (0.35) during an eclipse with respect to the original rate (0.06), i.e. a factor of 6, as shown in Fig. 6.7 and reported in Section 6.4.2. Return rate observations in Fig. 6.7 show a low return rate prior to eclipse, followed by a rapid rise in the return rate (a factor of ~ 7 in 10000 seconds) after the CCRs enter the umbral shadow. Our simulation includes only one CCR, and therefore will not capture all elements present in the actual reflector array on the lunar surface. However, our objective is to show that (1) dust reduces the intensity of the central maximum in the FFDP of the CCR and (2) as the incident solar flux on the CCR decreases during the lunar eclipse, the temperature gradient between front face and the vertex rapidly decreases, improving the return rates. Discrepancies between our simulation and the eclipse-night observations are discussed in Section 6.5.

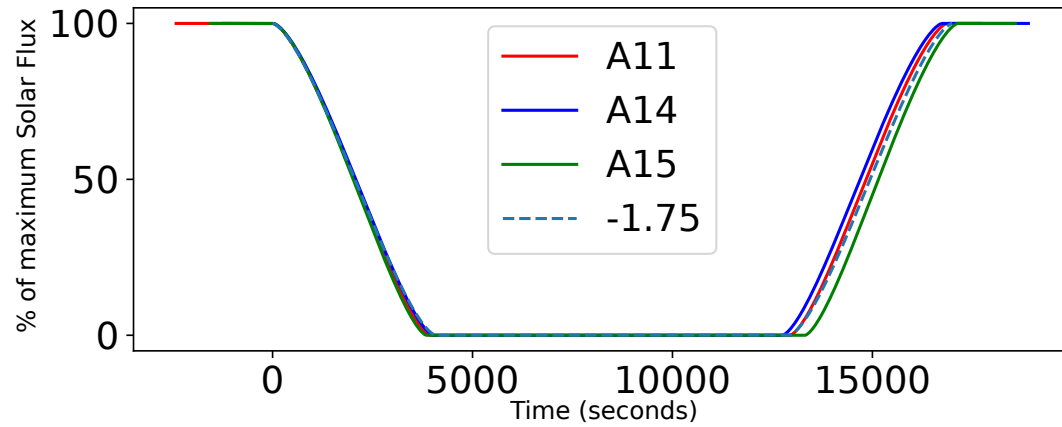


Figure 6.4. Percentage of maximum solar illumination as a function of time (in seconds) for the three Apollo reflectors Apollo 11 (red), 14 (blue) and 15 (green) for the eclipse on April 15th, 2014, shifted to have the same starting time. The blue dashed curve shows the eclipse profile corresponding to an impact parameter of 1.75 solar angular radii as seen from the moon, which we used in our thermal eclipse simulation since it best approximates the behavior of all three reflectors. Note that these models do not include limb darkening.

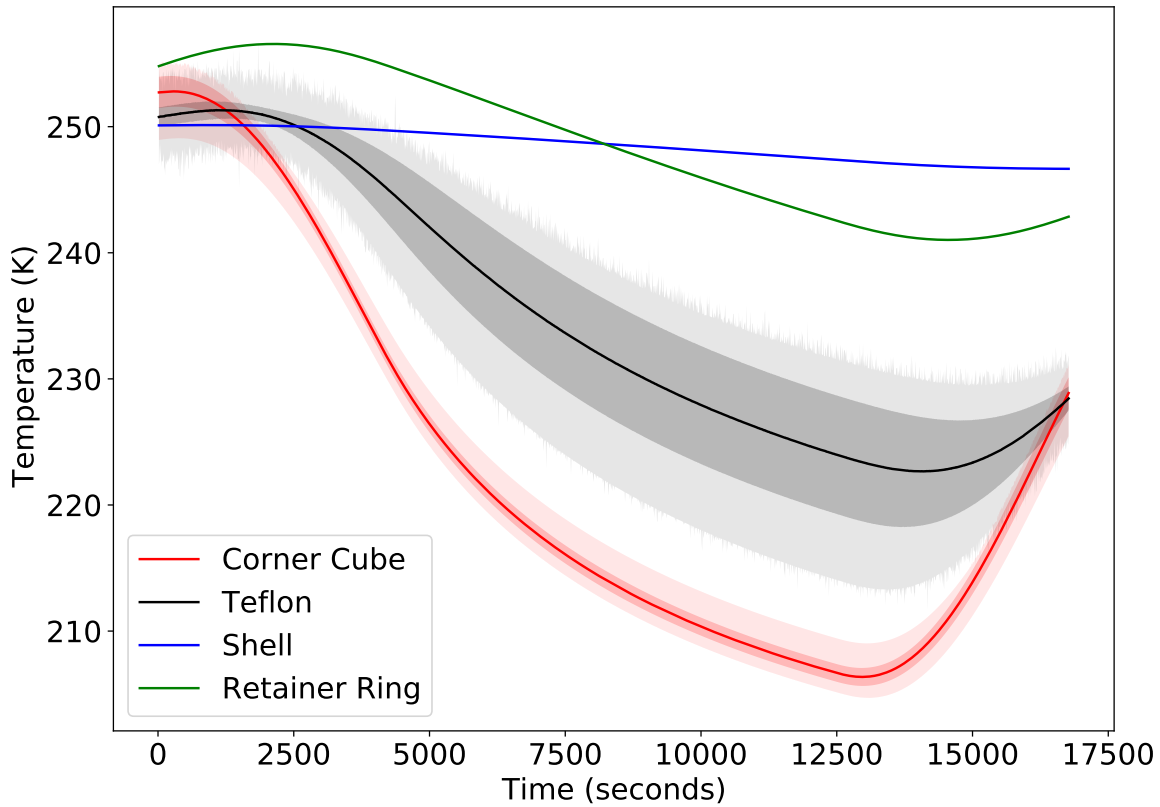


Figure 6.5. Average temperatures for the CCR, Teflon rings, retainer ring and shell over the course of the simulated eclipse. Dark shading indicates 1σ deviations from the mean, whereas the lighter shading indicates the min-max. The deviations for the shell and the retainer ring are too small to be seen here due to their high thermal conductivity. The range of computed temperatures for the Teflon rings during the simulated eclipse is larger than for the other three elements. This is due to the fact that the temperatures extracted from the simulation average the two Teflon rings that are above and below the CCR. The rings also have slightly different conduction pathways to carry heat from the CCR to the shell or the retainer rings. Some of these pathways have an additional temperature dependence due to the discontinuity in thermal conductance at the Teflon-Retainer Ring and Teflon-shell interface. All of these effects combine to result in a larger range of temperatures for the Teflon rings.

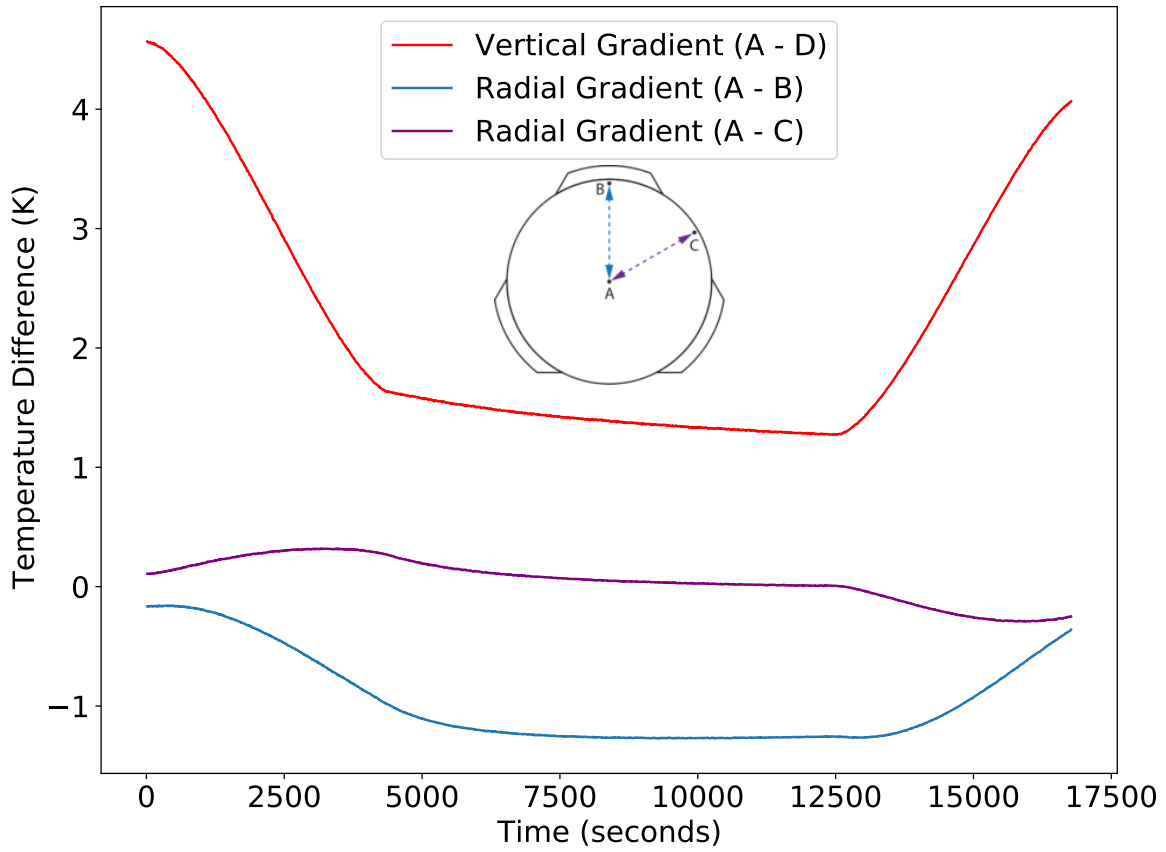


Figure 6.6. Temperature differences between three pairs of locations on the corner cube as a function of time during an eclipse. Corresponding solar illumination profile is provided in Fig. 6.4. As the CCR enters the umbral shadow it cools and the vertical temperature gradient drops from ~ 5 K to ~ 2 K, which reduces the thermal lensing and improves the optical throughput. The inset shows the front face of the CCR illustrating locations used for the temperature difference calculations, the center (A), tab midpoint (B) and a point between two tabs along the circumference (C). The dashed lines connecting the points correspond to the gradients shown on the plot. The vertical gradient is calculated by subtracting the temperature of the vertex (D, not shown in inset) from the center of the top surface (A - D). The radial gradient for the top surface is calculated for two points along the top surface circumference, the midpoint of the CCR tabs (A - B), and the midpoint between two tabs (A - C).

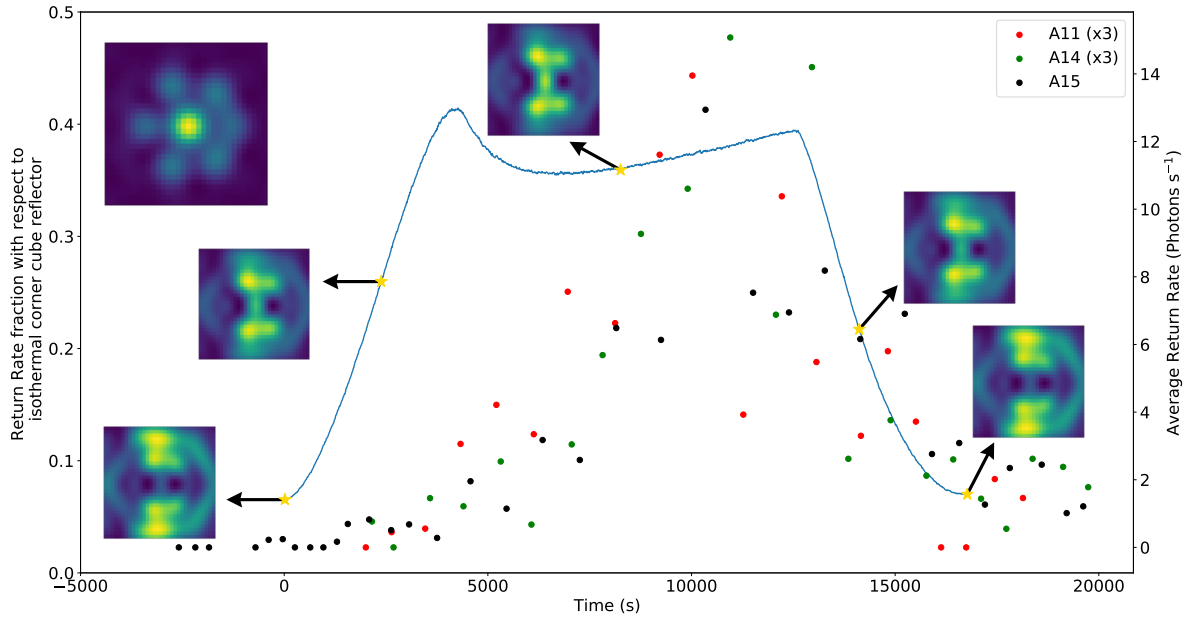


Figure 6.7. Fraction of light in the central diffraction maximum as compared to an isothermal CCR as a function of time during an eclipse. The measured return rates from the Apollo reflectors are also plotted (right-hand ordinate). Time is relative to when each reflector first enters the Earth shadow, which aligns all reflector time-series with the start of the eclipse simulation. Simulated CCR FFDs are shown at five representative times during the eclipse. Inset at top left shows the FFD for an isothermal CCR.

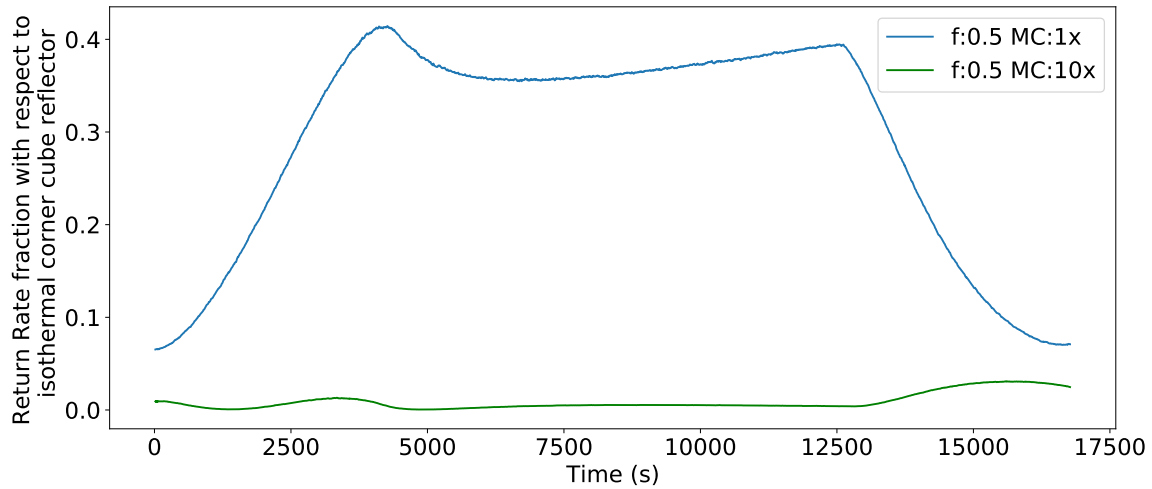


Figure 6.8. Simulated return rate fractions for the same dust fractions ($f=0.5$), but with the original and rescaled ($\times 10$) mount conductances (MC). The increased mount conductance almost completely depresses the intensity of the central maximum in the FFD throughout the eclipse, and is therefore disfavored as inconsistent with observations.

6.5 Discussion

While the qualitative results from our eclipse simulation are in agreement with the measured return rate during the photometric eclipse night, there are a few details worth expanding on.

6.5.1 Simulating a Single CCR

We consider the effect of using a single CCR versus an entire array set in a pallet. We model a single dust-obscured CCR to simulate its FFDP, and compare the intensity in the central diffraction maximum to that of an isothermal CCR as an estimate of the expected relative lunar return rate. The thermal and mechanical properties implemented in this simulation have been either taken directly or derived from the description in the original Arthur D. Little Report on the CCR design and performance Arthur D. Little, Inc. (1969). However, our single cylindrical shell and CCR is not likely to track the thermal mass and environmental couplings of the real array, which could result in incorrect temporal behavior. We did not model the changing radiative temperature of the lunar surface, the geometry of coupling, or the blankets in which the arrays are wrapped. We have attempted to approximate some of these factors, but surely these are not perfect.

6.5.2 The Effect of Mount Conductances

Our goal was to model the thermal properties of the CCR using the specifications indicated in the ADL design report Arthur D. Little, Inc. (1969). A complication, however, was that the report doesn't describe the individual contact conductances but rather the total conductances through various thermal pathways. The original report uses the term "Mount Conductance" to describe the total heat conductance from outside the shell into the surface and vertex of the corner cube. To convert mount conductance given in the ADL report into contact resistances used in the simulation, we use the fact that the conductance values in ADL report are

based on tests using steady state heat flux from the corner cube, through the teflon rings, through the retainer ring into the aluminum array which we have called the "shell" in our simulation. In the simulation, the conductance values for various interfaces between different materials can be tuned, however, the caveat is that the teflon-retainer ring interface is a special case. Since the retainer ring was tightened and then de-rotated by 36° at the time of assembly to prevent any thermal contact, it is likely to approximate a no-contact conductance. If this conductance value has changed since launch, it could only be due to physical contact between the two surfaces, which is likely to change conductance at this interface significantly. Thus, while our simulation can change conductance values smoothly, for the real retroreflectors, such a change will be discrete and significant. The computed conductance values for this interface were checked by calculating two extreme cases. First, we calculate the conductance for the case where there was perfect contact between teflon and the retainer ring and then we calculate the case where there is no contact between the retainer ring and the teflon ring and any thermal contact is purely radiative. Our computed conductance value lies between these two extremes, consistent with the value derived from steady state heat flux assumption based on the ADL report. We calculate that the conductance for perfect contact is approximately a factor of 10 larger than what we calculate for the APOLLO CCRs. Thus, we are satisfied that the conductance values used between the various interfaces are reasonable.

However, to study the possibility that the conductance between the teflon-retainer ring surface has increased drastically, we consider the special case of an eclipse where the mount conductance has increased by a factor of 10 as shown in Fig. 6.8. The mount conductance values only impact our simulation if they have increased since fabrication, since a decrease would result in smaller gradients in the CCR, in agreement with our simulation and the original predictions and measurements in the ADL report. In order to run a full eclipse simulation, the modified geometry with increased mount conductances is equilibrated. The initial temperature of the shell in this case was found to be higher than the eclipse run presented in Fig. 6.5, by ~ 20 K. The expected intensity inside the central diffraction maximum is decreased approximately by a factor

of 40 during the eclipse compared to the best match simulation with dust fraction of 0.5. Thus, adjusting the mount conductances completely destroys the FFDP.

Thus, given our link budget estimates and steady-state calculation of the dust coverage factor, we find that the mount conductance in our initial estimates based on the ADL report is consistent with the results from both the steady-state dust fraction calculation and the link budget analysis, and unlikely to have changed significantly from launch to present day.

6.5.3 Comparisons with Infrared LLR Observations

We can use the derived CCR temperatures for the steady state and eclipse simulations, and investigate what happens when an infrared wavelength is used ($\lambda = 1064$ nm). For this calculation, the thermal coefficient of refractive index for fused silica is adjusted for the wavelength 1064 nm (Toyoda & Yabe, 1983). In comparison to the steady state performance for the green laser, we find that at 1064 nm, the central intensity in the FFDP is $\sim 60\%$ compared to the case for an isothermal CCR, with a peak-to-peak phase variation of ~ 2.3 radians. This marks a factor of 10 improvement in FFDP in full-moon illumination conditions for an infrared laser compared to the green laser. This agrees with improved results seen by using the infrared laser for LLR at the Grasse laser station when ranging when the lunar phase is within $\pm 18^\circ$ of the full moon. (Courde et al., 2017). Note that this only includes the improved central intensity in the FFDP of the CCR, whereas observations will also depend on other factors such as detector quantum efficiency, atmospheric throughput and laser power, similar to the link budget calculation in Section 6.2.

6.5.4 The Effect of Changing Dust Fraction Coverage on the CCRs

Changing the dust fraction changes the equilibrium temperatures of the CCR, as well as the resulting gradients under solar illumination. The expected FFDP for the equilibrium temperature shows that the total intensity inside the central maximum increases as dust fraction is decreased. A smaller dust fraction creates a smaller vertical thermal gradient in the CCR,

which improves the return rate of the signal and vice versa. This return rate should become 100% as the total dust fraction goes to zero. Given a dust fraction, the qualitative behavior of the eclipse is very similar to the one presented in Figs. 6.5 and 6.8. We find that a dust fraction of 0.5 best matches the eclipse observations.

We also note that the three reflectors Apollo 11, 14 and 15 show remarkably similar improvements during the lunar eclipse. These reflectors are placed at significant distance from each other and were placed over the course of a few years. The similarity indicates that if the dust obscuration is taken as the reason for the degrading performance, then this dust deposition must be uniformly taking place across the surface of the moon. In this case, the dust transport results from the Apollo 17 LEAM experiment (Berg et al., 1976) combined with the experimental observations of dust levitation under a plasma sheath suggests a deposition mechanism (Arnas et al., 2001; Sickafoose et al., 2002; Halekas et al., 2011). The obscuration is likely caused by large particles, as indicated by the LEAM experiment, deposited due to solar wind and radiation during lunar sunrises and sunsets creating a plasma sheath, which transports these dust grains at low altitudes (< 2 m). Thus, our results are consistent with the lunar model of dust transport, where the transport is caused by electrostatic charges on dust particles enabling transport at low altitudes (< 1 m) due to the potential difference created at the time of sunrise.

6.6 Conclusions

Measurements with the APOLLO ranging system indicate a deficit in the return rate of Apollo lunar retroreflectors by a factor of 16 to 19, with an additional order-of-magnitude loss when the reflectors are under full moon illumination. We attribute the degraded reflector performance to the accumulation of lunar dust on the reflector surface, which partially blocks lunar ranging laser light and distorts the CCR FFDP by thermal lensing due to absorbed solar radiation near full moon. This conclusion is supported by three independent studies:

1. A detailed link analysis was undertaken, including a measurement of the APOLLO transmit

laser beam profile, and the one-way throughput of the telescope optics and the receiver. This study found that the measured lunar return rate was only 6% of the predicted value, corresponding to a dust fraction of $\sim 50\%$, which in turn results in thermal consequences under solar illumination.

2. Measurements during lunar eclipses reveal that the lunar return rate is highly dependent on solar illumination. For example, during one lunar eclipse on a photometric night, we found that the return rate improved rapidly once the reflectors entered the Earth's shadow, and subsequently degraded when the reflectors exit the shadow. When the reflectors are in shadow during a lunar eclipse, the median return rate is an order of magnitude higher than full-moon non-eclipse observations.
3. We developed a heat transfer model to include conductive and radiative effects and used the simulated temperature profile of the CCR to generate the associated FFDP. We explored two scenarios:
 - (a) Steady-state study: We ran our simulation until we achieved the equilibrium state of the CCRs during full moon solar illumination. In the equilibrium state, the thermal gradient across the CCR degraded the intensity of the FFDP's central lobe by a factor of ~ 16 compared to an isothermal CCR when a 50% dust fraction was used, in agreement with previous assessments of the full moon deficit Murphy et al. (2010).
 - (b) Time-dependent eclipse study: We then ran the equilibrated CCR setup through an eclipse simulation, roughly matching our observed eclipse conditions. Using the same dust coverage fraction of 50%, the eclipse response improves over the full-moon return rate by a factor of 7, which compares well to the temporal profile observed during the 2014 lunar eclipse.

Taken together, the studies above tell a consistent story: the Apollo 11, 14 and 15 reflector surfaces are partially obscured by dust ($\sim 50\%$), which both reduces their optical throughput by

the direct absorption of laser ranging photons, and through thermally induced distortions of the CCR FFDP due to the absorption of solar energy near the full moon phase.

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Appendix: Thermal Simulation Details

Setting up the Geometry

Defining the geometry of the problem requires us to define a number of thermal properties for all elements of the 3 dimensional cartesian grid. The CCR are defined in detail in ADL Inc. report (Arthur D. Little, Inc., 1969) and for the purposes of the simulation, we consider the properties defined therein to be a starting point for our simulations. We have a grid of size $51 \times 51 \times 51$ (102 mm $\times$ 102 mm) over which these properties are defined.

While the code as written can be generalized to an arbitrarily shaped cuboid, we work here with cubes for simplicity in view factor calculations later. While we have run the code at different spatial resolutions for testing purposes, all runs for science purposes have been run at a resolution of 2 mm, which makes our simulated box size $102 \times 102 \times 102$ mm. Since the heat

transfer is an explicit finite difference scheme, given the material properties used and for ease of comparison for different runs, we have fixed the temporal resolution at 0.005 seconds for all runs. Since the simulation uses cubic voxels, we have oriented the CCR along the (1,1,1) direction, in order to create smooth planes for the sides of the CCRs. While this results in voxelization of the planar surfaces, the effects on heat transfer are minimal. There are two kinds of numerical effects that might occur as a result of voxelization of a planar surface of the CCR. Firstly, the amount of radiative heat transferred between two elements may be slightly inflated due to the increase in surface area as a result of the voxelization. This effect decreases with a decrease in element size, theoretically going to zero as the size of the voxel becomes infinitesimally small. We tested our setup by creating two parallel slabs oriented along the (1,1,1) direction and prescribed a heat flux on one side of one of the slabs, which then radiatively transferred heat to the other slab. Since this is a problem with an analytic solution, we were able to compare our numerical results with the analytic solution and found them to show reasonable agreement with each other. The second effect we need to be careful about is the amount of incident solar flux illuminating each voxel. We tackled this problem by analytically prescribing the heat flux for the entire voxel by multiplying the incident solar flux with the projected area along the (1,1,1) direction.

We first address the assumptions required to simulate a single CCR instead of an entire retroreflector array. The retroreflector array housing the CCRs on the moon is machined out of Aluminum 1100. One of the primary goals of the design of the reflector array was to provide passive thermal control, since it was understood any thermal gradients would have a significant impact on reflector performance. Thus, the array as a whole was thermally isolated from the lunar environment with multiple blankets, reducing external emissivity to 0.01. Additionally, the CCRs are mounted on Teflon rings and the cavities are recessed into the array to prevent illumination from sunlight unless directly overhead. These designs work well enough that we can treat an individual CCR as a standalone retroreflector for thermal purposes, as we will demonstrate with our simulation. As a result, we have simply replaced the array with an outer layer of aluminum 1100 which we refer to us as the "Shell" in this paper. As we will show, the

absence of the remainder of the array has no impact on the thermal performance of the CCR. Thus, our geometry consists of a fused silica CCR, two Teflon rings, the upper aluminum retainer ring and the outer shell. The material properties for these are described in Table 6.3.

The heat transfer is an explicit finite difference scheme. We first define the array $K_{i,j,k}$, which is total conductance between adjacent cells. So for a cell with indices (i, j, k) and a side length Δx , with thermal conductivity denoted by $\lambda_{i,j,k}$, the conductance with respect to its adjacent cell (i, j, k+1) can be calculated as -

$$K_{i,j,k+1/2} = \frac{\Delta x^2}{\frac{\Delta x}{2k_{i,j,k}} + \frac{\Delta x}{2k_{i,j,k+1}} + R_{i,j,k+1/2}} \quad (6.5)$$

Where $R_{i,j,k+1/2}$ is the contact resistance between adjacent cells. This is zero for adjacent cells with identical thermal conductivity, i.e. in the bulk of the material. For elements with distinct values of thermal conductivity, we prescribe the value of contact resistance based on the total conductance allowed between the respective surfaces. Based on the results of ADL report, the CCRs were designed to have a prescribed amount of total conductance between materials and the testing of the CCRs tried to constrain the total conductance value. For our purposes, we took the values of total conductance given in the ADL report as starting values. For pairs of material where no value was given, we prescribed the total conductance as follows. We calculated the total conductance in two limiting cases. Firstly, when the two adjacent cells have perfect contact and the total conductance comes purely from the difference in thermal conductivity of the two cells, we can set the value of contact resistance to zero. This gives a minimum conductance value. In the other limit, we assume the two contact surfaces are separated by an infinitesimal distance and the "conductance" is a result of only radiative transfer between the two surfaces. This gives us a temperature dependent total conductance value, assuming the temperature difference between the two surfaces is small compared to the absolute temperature. We then calculate this conductance for the expected temperatures on the lunar surface and get an upper limit for the total conductance. For the actual simulation runs, we end up taking the average of these

two conductance values as a starting point. Once we have prescribed the total conductance for a pair of materials, we can then calculate the conductance per element. Knowing the thermal conductivity values, we can then prescribe a value of contact resistance for each element. Thus, prescribing the total conductance between any pair of materials, as designed and tested in the ADL report, gives us a value for the contact resistance between any two elements.

Constructing the View Factor matrix

Once we have defined our geometry, the code then constructs a view factor matrix. We create a matrix of all boundary point elements and compute the view factors for each pair of surfaces using the analytic expressions from Ehlert & Smith. Since our geometry does not change as a function of time, this is a one time calculation performed at the beginning of a run. It can then be saved and retrieved for a subsequent run. This step of the code takes about 20 minutes to run for the full CCR simulation. We checked our view factor calculations for parallel and plane geometry by constructing two slabs in a parallel and perpendicular configuration. We calculate the view factor matrix, and using the view factor matrix, sum the individual view factors to obtain the total view factor for the slabs, which can then be computed using the same expression for a larger slab. We can also check this against simpler expressions for the special case where the slabs are exactly opposite each other with no relative lateral displacement. We find that the view factors computed are consistent when summed with what we would expect for the pair of larger slabs. We also find the consistency does not depend on the spatial resolution of the geometry, as would be expected for an analytic expression for the view factors.

Heat Transfer

Given the conductance between adjacent cells, we can calculate the total heat influx into a cell $H_{i,j,k}$ from

$$\begin{aligned} H_{i,j,k} = & K_{i-1/2,j,k} \cdot (T_{i-1,j,k} - T_{i,j,k}) + K_{i+1/2,j,k} \cdot (T_{i+1,j,k} - T_{i,j,k}) \\ & + K_{i,j-1/2,k} \cdot (T_{i,j-1,k} - T_{i,j,k}) + K_{i,j+1/2,k} \cdot (T_{i,j+1,k} - T_{i,j,k}) \\ & + K_{i,j,k-1/2} \cdot (T_{i,j,k-1} - T_{i,j,k}) + K_{i,j,k+1/2} \cdot (T_{i,j,k+1} - T_{i,j,k}). \end{aligned} \quad (6.6)$$

The change in temperature T in time Δt is given by

$$T_{ijk}^{t+1} = T_{ijk}^t + H_{ijk} \frac{\Delta t}{\Delta x^3 \rho_{i,j,k} C_{i,j,k}}, \quad (6.7)$$

where $\rho_{i,j,k}$ is the density and $C_{i,j,k}$ is the Specific Heat Capacity for the element (i, j, k) . For every boundary point, we also track the temperature at the center of the external surface. In order to check our heat transfer code, we performed a number of tests. Our general goal was to run simulations with analytic solutions in order to have something concrete to compare to. To test the conduction code, we use a single slab and subject it to an incident flux on one side. We then switch off any radiative effects on the boundaries, thus reducing this to a one-dimensional heat transfer problem with a known solution. We can start the simulation run from an arbitrary temperature and let it run until we have equilibrium. In practice, we started approximately 50° away from the steady state temperature value. We compared the temperatures on the front and back surfaces with the analytically calculated expected temperatures. We found our simulation agreed with the analytic solution to well within 0.5% for the coarsest resolution of 1 cm and to well within 0.1% using the finest resolution of 1 mm. We then tested our radiative heat transfer code by adding a second slab in parallel behind the back face of the first slab, with boundary radiative effects switched off. We had an incident flux on one side of the first slab. Now we can analytically compute 4 temperatures on the front and back surfaces of the two slabs as follows.

Assuming the temperatures on the front and back of the first slab are T_1 and T_2 , and that on the front and back of the second slab are T_3 and T_4 , the relevant equations in steady state are

$$Q - \sigma T_1^4 = -k(T_1 - T_2) \quad (6.8)$$

$$-k(T_1 - T_2) = \sigma T_2^4 - F_{23}\sigma T_3^4 \quad (6.9)$$

$$F_{23}\sigma T_2^4 - \sigma T_3^4 = -k(T_3 - T_4) \quad (6.10)$$

$$-k(T_3 - T_4) = \sigma T_4^4, \quad (6.11)$$

where k is the thermal conductivity of the slab, σ is the Stefan-Boltzmann constant, Q is the incident heat flux per incident area on the front surface and F_{23} is the view factor between the back and front surfaces of slabs 1 and 2 respectively. Solving these sets of equations numerically gives only two real sets of values, only one of which is physical (positive temperatures). We calculated these values and found good agreement between the numerically obtained and the solutions to the analytic equations, with the agreement improving with higher numerical resolution.

Chapter 6, in full is a reprint of the material as it appears in *Icarus*, Sabhlok, Sanchit; Battat, James B. R.; Colmenares, Nicholas R.; Gonzales, Daniel P.; Murphy, Thomas W, *Icarus*, 417, 116113. doi:10.1016/j.icarus.2024.116113. The dissertation author was the primary investigator and author of this material.

Chapter 7

Summary and Future Work

In this thesis, I have described my work studying the CGM emission around $z \sim 2$ radio-loud quasars using the KCWI and MOSFIRE instruments on the Keck Telescopes on the summit of Maunakea. In the second half, I have described my work on forward modeled PSF reconstruction for the NIRC2 instrument on the Keck II telescope, and have discussed my work on the PSF reconstruction for the Corner Cube Retroreflectors (CCR) left on the moon by the Apollo astronauts. I summarize my results and discuss future avenues of research briefly.

7.1 The CGM around $z \sim 2$ radio-loud quasars

In Chapter 2, I presented our observations of the quasars 3C 9 and 4C 05.84, where we detect companion galaxies and their own CGM subhalos using spatially and kinematically distinct He II and C IV nebulae. I confirm the continuum emission using HST WFC3 and Keck NIRC2, and the spectroscopic redshifts and nebular emission using Keck MOSFIRE, from the companion galaxies. The kinematics of the large Ly α nebulae around both quasar systems and the biconical He II and C IV nebulae around both quasar host galaxies indicate a 2 component CGM model with an inner and outer component. I distinguish the inner and outer components by considering the extent of the He II and C IV nebulae, since these are expected to be directly ionized by the quasar. In addition to the biconical morphology, the extent of He II and C IV emission was kinematically concurrent with the Ly α emission. Outside of this inner

morphology, the kinematics of the $\text{Ly}\alpha$ emission showed a random structure, likely dominated by the turbulence in the medium. The $\text{Ly}\alpha$ emission from this part of the nebula is more likely to occur due to scattered radiation, since the quasar's ionizing radiation influence is indicated by the extent of the He II and C IV nebulae. I discuss potential future evolution of these systems in the context of the present day population of groups and clusters, and estimate that these systems will likely undergo a major merger on their way to becoming a large group (4C 05.84) or a small cluster (3C 9).

In Chapter 3, I presented our observations of the larger QUART sample and discussed the nebular $\text{Ly}\alpha$, He II, and C IV emission observed using Keck KCWI in the QUART sample. I show the surface brightness and kinematic maps of all sources and discuss the luminosity, physical extent, radial profiles, redshift evolution and asymmetry of the nebular emission around these quasars. I discuss these results in the context of OSIRIS observations of the quasar host galaxies (Vayner et al., 2021b,c), and in the context of previous studies of $\text{Ly}\alpha$ emission in the literature (Cantalupo et al., 2014; Borisova et al., 2016; Cai et al., 2019; Arrigoni Battaia et al., 2019; Lau et al., 2022). The implications of a 100% detection rate in finding He II and C IV emission around radio-loud quasars are discussed. The results are compared to the Extremely Red Quasars (ERQs) that are able to probe the inner regions of the quasar host galaxies CGM.

OSIRIS observations of $\text{H}\alpha$ and [O III] emission from potential tidal interactions with the quasar host galaxies and their satellites in 3C 9 and 4C 05.84 will be explored in a future work. The well studied 3C 9 and 4C 05.84 systems present excellent opportunities to study the transport of dust in potential mergers and AGN episodes. JWST MIRI observations can reveal whether dust is transported out of these galaxies concurrent with OSIRIS observations of outflows and whether this dust survives the ionizing radiation of the AGN. It will be possible to investigate the extent of dust in the CGM and any enhancement in surface brightness in the tidal features of the merger. Additionally, MOSFIRE observations of the quasar 7C 1354+2552 and the surrounding CGM, will be investigated for potential companion galaxies and CGM emission in $\text{H}\alpha$.

7.2 PSF Reconstruction

The Keck All-sky Precision Adaptive Optics (KAPA) upgrade is currently ongoing commissioning and testing on the Keck Telescopes and will be ready for on-sky observations soon. I have presented our advancements on PSF reconstruction for the NIRC2 detector on Keck II. The forward model is equipped to work with changes implemented by KAPA namely the new asterism generated by the laser upgrade and its implications for anisoplanatism. Additionally, the model can also include the updated Real Time Controller (RTC) and will be able to adjust the NGS to be chosen as an infrared star, if needed. Currently, the model requires on-sky data, AO telemetry, DIMM/MASS data, NCPA calibrations and a pupil model. The lack of datasets with *all* the required information has made the testing process difficult and slow. The model has been tested to confirm the inputs are being parsed correctly, and is currently being investigated for the implementation of anisoplanatism in the case of a single NGS.

Future challenges include ensuring the calibration inputs themselves are correct, which given the complexity of the model can be a challenge due to the *large* number of input parameters required, which will grow with the implementation of KAPA. This will require a program with involvement from the observatory's operation, where NCPA calibrations are obtained concurrently with observations of targets with a range of NGS/LGS combinations on nights with good seeing. Improvements in PSF-R will help advance a number of science cases involving gravitationally lensed galaxies, detection of protoplanets, microlensing, and the study of the Galactic Center.¹

7.3 Lunar Retroreflectors and the Moon

The Apollo CCRs continue to function to this day, which is an extraordinary feat of longevity for a mission with an expected lifetime in excess of 10 years, but instead has carried on well past its 50th anniversary. The degradation in their performance allowed a very unique

¹Home of our galaxy's supermassive black hole, Sagittarius A*.

investigation into potential dust deposition on the surface of these CCRs, presented in Chapter 6. I model the heat transfer in the CCR in the lunar environment when illuminated by the sun and when undergoing an eclipse.² I show that a dust obscuration of 50% is most consistent with our observations and detailed link budget calculations. I compare this result with models of dust transport on the moon as studied by lunar satellite missions and dedicated ground-based experiments left on the moon by Apollo astronauts. I find that the most likely mechanism for dust deposition is as follows: The solar radiation charges the dust grains and at the times of lunar sunrise or sunset, the boundaries between illuminated and shaded areas develop a potential difference which can levitate and slowly transport large lunar particles, in excess of 100 μm in size. Over decades, this is sufficient to accumulate charged dust particles on the surface of the lunar CCRs. Future work can refine the thermal model and try to closely monitor the rate of signal improvement during an eclipse, and compare these observations to other dust models with different properties. It is also possible to investigate if the kind of thermal gradients produced if there is no dust on the corner cube surface and heat is generated due to defects caused by solar radiation in the volumetric bulk of the CCR.

7.4 Closing Remarks

At the beginning of graduate school, I had yet to develop an affinity for a particular subject and was open to exploring research avenues. This led to my work with APOLLO, not only on the Lunar Corner Cube Retroreflectors as discussed in this thesis, but also instrumentation work to investigate the APOLLO Avalanche Photodiodes. All of this came with a side of “eavesdropping”³ and visits to the Apache Point Observatory in New Mexico, where I saw the Milky Way for the

²This model is a C program in a single file I wrote entirely on gedit. It is more than 6000 lines long. It has parallel processing. While not very efficient, it works sufficiently well for our requirements here. Having worked with a lab of engineers after joining OIRLab, I now understand this is perfectly acceptable practice.

³Eavesdropping is difficult to describe. For a typical Optical/IR observer on Keck for example, you are driving the telescope and the instrument. For APOLLO, this is Russet McMillan, the on site telescope driver and observation specialist. The *eavesdropper* is a co-pilot who is keeping an eye on everything, keeping a parallel set of logs, and occasionally piping in with a suggestion. This was done over a text chat, no zoom.

first time, but only after confusing it for a cloud.

When it was time to decide upon a thesis topic, my objective was to study galaxies partly because I understood that these were incredibly complicated systems, with physics occurring at a range of length and time scales, and I was attracted to this proposition. While in scope, my work on radio-loud galaxies and their CGM seems restricting and confined to *only* the radio-loud galaxies or *only* the CGM, in reality these systems can not be studied in isolation. Radio-loud galaxies do not occur in a vacuum, but belong to our universe and have traits that make them unique and advantageous as a target when studying how a galaxy interacts with its CGM. Similarly, the CGM is essentially a large volume of space with diffuse hot gas ($> 10^6\text{K}$) and suspended clouds of cold (10^4K) gas, but when studied around a quasar, a host galaxy, with visible outflows and ionizing radiation, allows identification of processes that regulate galaxy growth and evolution. Having joined the lab only a few months before the Covid-19 lockdown, I was initially uncertain regarding how much information can we extract from the spectra of 7 galaxies, with 3 emission lines from each, one of which is $\text{Ly}\alpha$ and is extremely difficult to interpret. However, the key here is the environment. The observations make sense in the context of the larger environment around the host galaxy, but also the inner SMBH and outflows from the galaxy.

The multiwavelength dataset is a complementary approach to studying a large number of galaxies using a single method, instead constructing a small sample and observing it across the entire electromagnetic spectrum. This is what studying feedback in galactic environments at multiple length scales is like: Adaptive optics assisted observations of the quasar hosts spatially resolves their dynamic environments and outflows. KCWI observations allow measurement of the cold ionized CGM emission due to photoionization by the quasar and due to potential scattering in the outer clouds, the kinematics of which are dominated by turbulent motion of the gas. Radio observations show the extent of large radio loud jets, which provide valuable information to distinguish the foreground and the background, Hubble or Spitzer images of potential companion galaxies and then a MOSFIRE search for companion galaxies around the

sources. Lastly, Chandra data is used to look for X-rays not only from the quasar and the radio jets, but from potential Intra-cluster medium, heated up to 10^6K .

In addition to all this, I learned about Adaptive Optics, how it is actually implemented at a telescope and the details required in reconstructing the PSF of a telescope. Forward modelling the PSF successfully is the “holy grail” of ground-based Optical/Infrared astronomy, but progress has been slow and challenging to achieve. Nevertheless, I am currently investigating the code implementation of theoretical models and considering whether these models can be improved or simplified.

The really interesting aspect is that all of these topics, while sounding incredibly different, have individually helped me understand each other. For example, understanding AO is important to understanding how Optical/Infrared data reduction works, but also how the LLR link budget works, since it is deeply connected to the Point Spread Function and Atmospheric Turbulence. The galaxy evolution science case for KAPA has allowed me to explore the importance of the PSF when studying star clusters in high redshift galaxies, which in turn has helped me understand the difference between ground- and space-based observations. ⁴

Lastly, I was allowed to take control of one of the largest optical telescope in the world! Keck, KAPA and APOLLO are each an incredible telescope, project and experiment to work on and it is difficult not to take the incredible data and results they have generated for granted. It has been pretty incredible working on them. ⁵

⁴This thesis is a strange jigsaw puzzle, and it does fit, but only when you consider the larger context of observational astrophysics and the techniques we are currently pushing on to improve it.

⁵And so we beat on, boats against the current, drawn back, ceaselessly into the past.

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