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Articles

Quasars at 25

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In the quarter century since the first optical identification of a "radio star" (3C 48), astronomers have come to general agreement that the underlying quasar energy source is accretion onto a massive black hole. There is much less agreement on the detailed physics of the processes by which this energy is converted to the forms observed, but this has not prevented the objects from serving as valuable probes of the universe at distant times and places.

ON THE LAST DAY OF 1960, ALLAN R. SANDAGE PRESENTed a late paper at the 107th meeting of the American Astronomical Society, reporting the first identification of a compact radio source (3C 48) with a starlike optical object, whose spectrum showed a blue continuum (suggestive of synchrotron radiation) and broad emission lines at rather puzzling wavelengths. These remained puzzling until spring 1963, when Maarten Schmidt (*1*) showed that a similar pattern in 3C 273 corresponded to ordinary hydrogen lines, redshifted by 15.8%. The 3C 48 pattern then implied a still larger redshift, $Z = 0.3675$.

The discoverers dubbed the objects quasi-stellar radio sources, and the common name, quasar, apparently arose from an attempt to pronounce the acronym QSRS. We shall here follow the purists' custom and restrict the word to radio emitters, calling the larger group of compact, broad emission line, highly redshifted, but radio quiet, objects QSO's (for quasi-stellar objects). Smaller related groups include the BL Lac's (named for the prototype and lacking conspicuous emission lines) and the optically violent variables or OVV's.

Catalogs (*2*) now contain more than 2000 of these compact objects, with redshifts between 0.1 and 3.80, though the largest and smallest values are rare. Careful surveys of small regions of the sky find at least 20 QSO's per square degree brighter than 20th magnitude; thus a million more remain to be pinpointed.

The Distance Scale

Essentially everything else one might want to discuss about QSO's—luminosities, energy content, energy sources, lifetimes, and relationships to normal galaxies—depends on knowing how far away they are. If the distances are the large ones implied by the redshifts and an observed linear relation between redshift and distance called Hubble's law, then many QSO's exceed the luminosities of bright galaxies by factors of 100 to 1000. In addition, observed rapid changes in brightness and morphology require both enormous energy densities and bulk gas motions at speeds very close to that of light. Nevertheless, this interpretation has gradually won out over ideas involving smaller distances and unconventional physics to account for the redshifts.

An early argument against the local hypothesis (*3*) was that discrete, identified radio quasars and galaxies already accounted for 20 to 25% of the total radio flux reaching us. Thus, to prevent the sum of all sources in the universe from contributing much more than we see, either the known objects must sample a large fraction of the volume of the observable universe, or we must live in a region with many more sources than average—and near the center, since the flux is quite isotropic. The situation for the x-ray background and known x-ray emitting QSO's is quite similar (*4*). This line of reasoning cannot tell us that all QSO's are at large distances, but its great strength in demonstrating that most of them must be is still not, perhaps, fully appreciated. The fact that numbers of QSO's rise very steeply with decreasing apparent brightness also says either that we live near the center of a special region or that the faint QSO's must be far enough away that the average properties of the universe have changed since the light we see left them.

Two later important steps were the identification of a small group of normal-looking galaxies around a bright QSO with the same redshift (*5*) and the study of diffuse emission around QSO's at low enough redshift for their parent galaxies to be seen on the cosmological hypothesis (*6*). One of the clearer cases is 3C 48, in which there is no doubt about the existence of spectral features due to starlight whose redshift is the same as that of the QSO (Fig. 1). The observed brightness of what seems to have been a supernova in the host galaxy of QSO 1059+730 (*7*) leads also to a distance close to that implied by the redshift.

Recent additional evidence has come from absorption lines in the spectra of QSO's close in the sky to (but differing in redshift from) a galaxy or second QSO. If distance is a monotonic function of redshift, then one might see absorption due to the lower-Z object in the spectrum of the higher-Z one, but never the converse; but, if redshift is not a distance indicator, then both kinds of absorption should occur with equal probability. One QSO-galaxy pair (*8*) and four QSO-QSO pairs (*9*) all show absorption in the sense required by cosmological redshifts.

The Central Engine

All (cosmological) quasar models have recognized the need for a copious energy source confined in a volume small enough to vary on time scales of days or less. Early efforts invoked both nuclear and gravitational energy sources and both collections of small objects (supernova chain reactions; stellar collisions in dense clusters) and single large ones (supermassive objects stabilized by rotation or collapsed to black holes).

Recent models have largely concentrated on single black holes of 10^6 to 10^{10} $M_\odot$ ($M_\odot = 2 \times 10^{33}$ g, the mass of our sun). These can

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supply continuous gravitational energy either by accretion of gas from their surroundings or by magnetic extraction of their rotational kinetic energy. Reasons for accepting this basic picture (*10, 11*) include: (i) the extreme compactness required by variability as rapid as that of the BL Lac object H0323+022 (*12*), which increased its x-ray luminosity by some 10^{45} erg $\sec^{-1}$ in less than 30 seconds; (ii) occasional outbursts with total energy exceeding Mc^2 (where M is mass and c is the speed of light) of a single star; (iii) sharp central cusps in surface brightness and velocity distribution of the (presumably) similar, but smaller scale, Seyfert and radio galaxies; (iv) the constancy of the radio symmetry axis over many orders of magnitude in size scale in some objects, implying that 3C 276, for instance, has been ejecting material in a single direction for more than 10^8 years; (v) rapid changes in radio structure on millisecond-of-arc scales, which require relativistic potential wells to channel the ejecta; (vi) the inevitability of black hole formation from dense star clusters or other compact collections; and (vii) the lack of credible alternatives. This last is quite powerful, given the enormous number of theorist-hours that have gone into the problem.

The mass of the black hole grows with time as accretion fuels it, and so provides a measure of the active lifetime of QSO's. If many QSO's have flared up and died over the age of the universe, then most bright galaxies should contain a relic black hole at the low end of the possible mass range. If, on the other hand, only a few QSO's form and live billions of years, perhaps fading away as Seyfert galaxies, then relic black holes should be rare but very massive. Available data seem to favor the first possibility.

One Seyfert galaxy, NGC 1566, exhibits occasional outbursts in its emission line flux, with about 10^{51} ergs per outburst in Hα alone and a characteristic time scale near 1300 days (*13*). These outbursts can be modeled as a limit cycle in the object's accretion disk, driven by an S-shape in the curve of stable disk density versus inflow rate (*14*). The model fits the data only for a narrow range in ratio of luminosity to mass of the central black hole, implying much less than $10^9 M_\odot$. NGC 1566, at least, cannot have had a previous career as a QSO that spanned the age of the universe.

A much broader-based, but also model-dependent, argument comes from considering several independent probes of black hole mass (*15*). These are total luminosity (assumed to be a constant fraction of the Eddington luminosity, the maximum permitted before radiation pressure prevents accretion), the velocity widths of both broad and narrow emission lines (assuming the gas that produces them is in bound orbits in the volumes implied by the gas density), and the time scale of x-ray variability (which sets an upper limit to the size of the region that confines the very hot emitting gas and thus a limit to black hole mass). The surprise is that these independent determinations yield masses for a number of objects that are well correlated over a range from $10^{10} M_\odot$ for the brightest QSO's down to $10^6 M_\odot$ for the faintest Seyferts.

The implications are that the kind of activity we see depends at least partly on black hole mass, and that the activity probably disappears in much less than the age of the universe, new QSO's replacing dying ones on time scales $\lesssim 10^8$ years.

The Nature of the Host Galaxies and QSO Formation

Which galaxies form QSO's and when? The definitive observations are difficult. QSO nuclei greatly outshine starlight, and associated winds and shocks greatly perturb galactic gas (Fig. 2). Figure 2 is an image of 4C 37.43 in the light of the 5007-Å line of

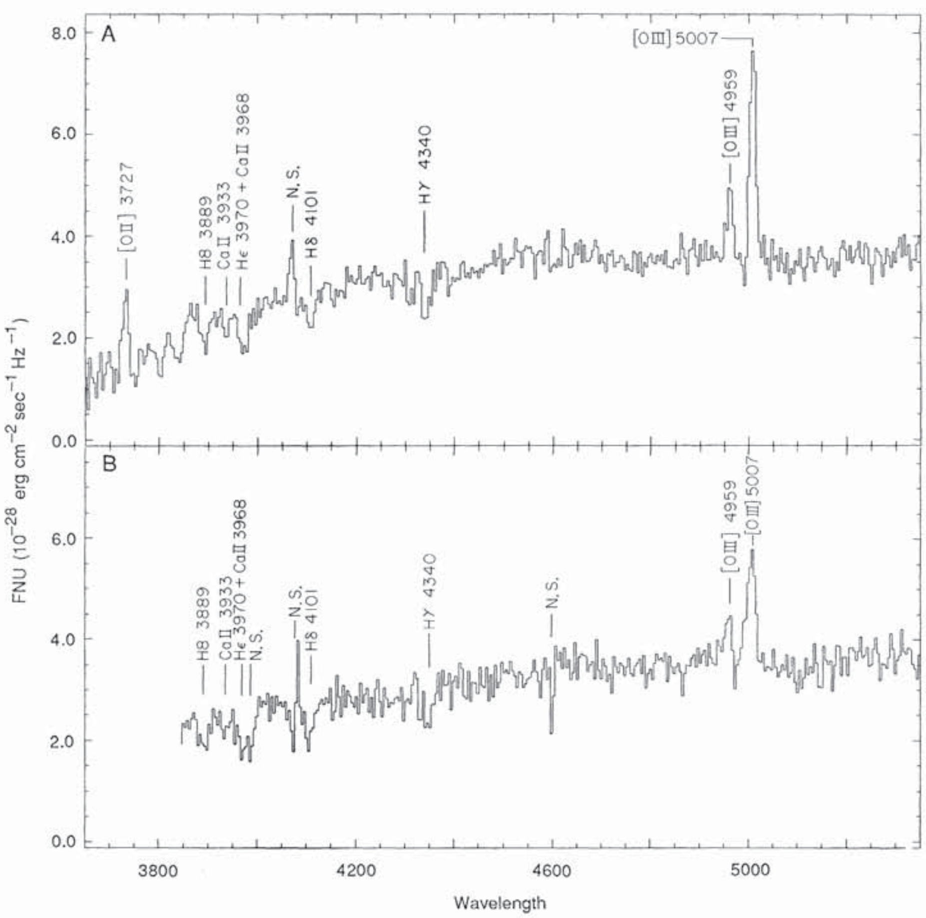

Fig. 1. Spectrograms of the nebulosity ("fuzz") north (A) and south (B) of the quasar 3C 48. Emission lines like those seen could be produced by gas in many different contexts, but the absorption lines labeled Hγ, δ, ϵ, and 8 and Ca II indicate the presence of stars, and so a host galaxy. Lines marked N.S. are produced in Earth's atmosphere (night sky). Vertical axis is flux in the units indicated. [Courtesy of T. Boroson (University of Michigan) and J. B. Oke (California Institute of Technology)]

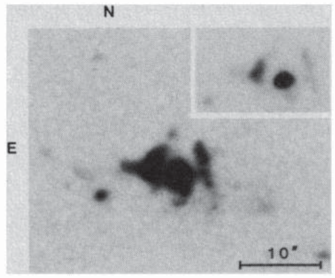

Fig. 2. Image in the light of [OIII] of the quasar 4C 37.43. The inset is a lower contrast version of the same image. The image is the sum of two 45^m exposures on the Canada-France-Hawaii telescope (CFHT) through a 3-Å FWHM (full width at half maximum) interference filter centered at λ5007 in the rest frame of the quasar ($Z = 0.371$). The compact galaxy roughly 10" east and a little south of the QSO has essentially the same redshift, and deep continuum images show that it is clearly interacting with the host galaxy of the QSO. Whether the extended, ionized gas component should be blamed on the interaction or on the QSO itself remains uncertain. [Photograph courtesy of A. N. Stockton (Institute for Astronomy, University of Hawaii)]

[OIII] and bears little resemblance to the gas distribution in normal spiral or elliptical galaxies.

The stellar distribution should be more robust, and numerous recent studies (*6, 16*) indicate that the diffuse emission mentioned in the first section consists of starlight from recognizable galaxies. These host galaxies are brighter than average ones, though generally not so bright as first-ranked members of rich clusters, and seem to be ellipticals for radio-emitting quasars and BL Lac's and spirals for the radio-quiet QSO's, though the brightest nuclei conceal even the type of the host. There is modest evidence (*17*) that hosts at large redshift were brighter and more often spirals than those here and now.

Active galaxies have more than their fair share of companions, sometimes with evidence of tidal interaction. The standard interpretation is that gravitational perturbations drive gas toward the central black hole, enhancing accretion (*18*).

QSO's apparently turn on when galaxies form central black holes and begin drizzling gas onto them. As we have described, this has probably been happening over most of the age of the universe. QSO's of small redshift are, however, rare in the catalogs, and the usual interpretation is that average space density, or luminosity, or both, have declined precipitously and continuously from $Z = 2$ to $Z = 0$ (*19*). There are, however, selection effects against finding objects near $Z = 0.6$, arising from variability in brightness and from the wavelength distribution of emission lines. These must be taken into account in any detailed calculation of the evolution of QSO numbers and their cosmological implications (*20*).

Looking far back into the past, we find that cataloged QSO's at $Z \geq 3$ are also rare (*20a*). Most astronomers agree that the rarity is real: that is, existing survey techniques would have discovered large redshift sources if they were as common as QSO's at Z's of 1 or 2 and had the same optical and radio properties. No one survey method can pick up all the objects, but early biases against the red colors and line distributions expected at large Z have largely been overcome (*21*). There is a good deal less agreement on the meaning of what we see (or rather do not see).

Perhaps the most obvious interpretation, and the most exciting as well, is that we really are looking back to the era when massive black holes (and maybe even their host galaxies) first formed. To establish this, however, requires rejecting two other possibilities, both of which are, in fact, fairly plausible.

First, dust in an intergalactic medium that was denser at $Z \geq 3$ than it is now, or dust in intervening galaxies, might keep us from seeing the QSO's by dimming and reddening their light more than we expect from redshift alone. This can be accomplished without excessively distorting the colors of the QSO's we do see at large Z according to Ostriker and Heasley (*22*), who propose as a definitive test the search for very highly reddened objects at the positions of otherwise unidentified x-ray and radio sources. A portion of the test has been carried out with a radio survey of steep-spectrum, compact sources (*23*). These are moderately common in quasars with redshifts of 2 to 3 and the survey was sensitive enough to have seen the same amount of emission at $Z = 3$ to $Z = 4$. But most of the sources in the survey have already been identified with objects in the lower redshift range; thus, there cannot be a large number of steep-spectrum core quasars obscured by dust at the higher redshifts.

Second, high redshift QSO's might exist but not look like nearby ones. This seems to be so. Objects found by Hazard *et al.* (*21*) in the range $Z = 2.5$ to $Z = 3.8$ have Lyman α (Lyα) emission lines with equivalent widths around 25 Å, much weaker than those in QSO's with $Z = 2$. This implies a strong selection effect—lines a bit weaker would not have shown up at all in the objective prism surveys.

The missing emission lines could have been absorbed by foreground gas (*21*), but the assumption that they are genuinely not being emitted suggests an attractive unifying hypothesis (*23, 24*). Suppose, as seems likely, that young galaxies are richer in gas than contemporary ones. The gas will tend to block the beams of relativistic particles or radiation that must flow from the neighborhood of the massive central black hole to energize emitting regions further out. Thus, first, we lose extended radio emission, even in contemporary spirals, then, looking back in time, the broad emission line region, and then, still further back, the beams will fail even to produce regions that can emit compact optical and radio synchrotron continua, and we will see no quasars, though the parent galaxy and central engine may both be there. Some confirming evidence for this model comes from the correlation of quasar radio morphology with Z. Near us, bright sources tend to look symmetrical and regular; only faint ones show shape distortions suggestive of interaction with an ambient gas. But at larger Z, even the bright sources are distorted, as if by a larger gas density (*23, 25*).

Relativistic Beaming and the Unified Scheme

The appearance of rapid changes in flux from 3C 273 not long after its discovery (*26*) threatened quasar emission regions with a Compton catastrophe. The regions had to be so small, and the photon density in them therefore so large, that relativistic electrons would quickly lose all their energy by inverse Compton scattering low-energy photons to x-rays of far greater intensity than we see (*27*). Relativistic bulk motion of the emitting plasma (*28*) provides a way out by allowing radiation from a larger volume to vary on a given time scale.

The predicted rapid changes in quasar core structure were seen in due course (*29*) and often looked like the rapid ejection of compact blobs from the core, along a reasonably stable direction, typically aligned with the larger radio structure of the object (*30*). These changes were soon labeled superluminal motions, because the blobs seemed to be moving out at $V \approx 3$ to $10\ c$. Calculations correctly incorporating special relativity show, however, that the apparent motions can be reproduced by real motion with $\gamma = (1 - v^2/c^2)^{-1/2} = 10$, aimed to within an angle $\theta \sim 1/\gamma$ radians of the line of sight. These are the same sorts of γ's needed to resolve the inverse Compton problem.

Against this background, two questions are frequently asked. (i) Are there jetlike ejecta only on the one side of the core where we see superluminal motions, or do jets feed the extended emitting regions on both sides, but we see only one because of Doppler enhancements? (ii) How many other properties of QSO's and their relatives can be accounted for as geometrical projection effects in objects where the main energy transport occurs in collimated, relativistic beams?

On the issue of one- versus two-sided jets, there seems to be no easy way around the conclusion that some of each exist. For 3C 273 itself, no counterjet has been seen down to a brightness level 1/5500 that of the jet (*31*). For this to represent Doppler boosting of a symmetric, two-sided configuration would require a considerably larger value of $\gamma/\cos\theta$ than is permitted by the superluminal motions. This jet must be truly one-sided. A similar conclusion may perhaps be drawn from the study of quasars with the largest extent on the plane of the sky (*32*). These must necessarily be the ones we see face-on, which permits no Doppler boosting, yet some display distinctly one-sided jets.

On the other hand, a modest number of two-sided jets have been resolved at millisecond-of-arc scales (*33*), though they are rare, and in no case has detectable motion occurred on both sides (*34*). In addition, the frequent occurrence of two-sided structure on larger scales seems to require bilateral energy transport of some sort in most objects (*35*). Either a second jet that emits little until it encounters ambient gas (because the energy is all carried by protons) or a single jet that flip-flops between sides (*36*) could account for most of what we observe.

An extreme form of the answer to the second question is called the unified scheme (*37*). It postulates that the orientation of a relativistic jet (or jets) relative to our line of sight is the main parameter determining a wide range of properties, including radio luminosities, spectra, and structures, motions, and optical variability line widths. Some systematic trends of observed quantities are well fit by such a model, for instance the correlation of optical line widths (assumed to reflect the projected rotation velocity of a collimating disk perpendicular to the jet) with the ratio of compact to extended radio emission (which should be largest when the jet points at us) (*38*). Many other trends are unexpected and difficult to explain with such a model (*32, 39*), including the correlation of radio and x-ray luminosity, since only the former should be enhanced by a jet pointing at us (*40*).

Rejection of the unified scheme would, however, be premature. First, jets with a spread in both θ and γ bring many of the predictions into much better accord with observations (*11*). Second, there is a statistical problem still not resolved among the superluminal sources, which must have jets nearly along our line of sight. Two recent surveys of well-defined, complete (though small) quasar samples (*41*) have found superluminal motions in about 10% of the sources, more than one expects for an intrinsically rare orientation. In addition, some of the superluminal sources have low radio core luminosities, implying jets not beamed toward us on larger scales.

Conversion of Energy to the Forms Observed

As a general rule, the closer we look to the central engine of QSO's the less well we understand what we see. The extended radio emission is, unambiguously, incoherent, polarized, power-law spectrum, synchrotron radiation. In at least some sources, energy must be continuously supplied to bright spots where the electron energy lifetime is considerably shorter than the travel time from the central galaxy. Of many mechanisms proposed for accomplishing this renewal, the sole survivor appears to be jets that are the extensions of those discussed in the previous section (*42*).

Moving inward, we reach the zones emitting, first, relatively narrow forbidden lines, then, broader permitted lines. There is a considerable body of accumulated wisdom on the densities, temperatures, degree of dustiness, filling factors, bulk velocity dispersions, and energy inputs needed to account for these lines (*43*). An interesting recent development is the discovery of a tight correlation among ionization potential of the lines, their widths (velocity dispersions), and the density of the gas producing them (*44*). The implication is that, although the broad- and narrow-line regions are different in a well-defined way, we see a continuous gradation from high temperature, density, and velocity near the center of QSO's to lower values farther out.

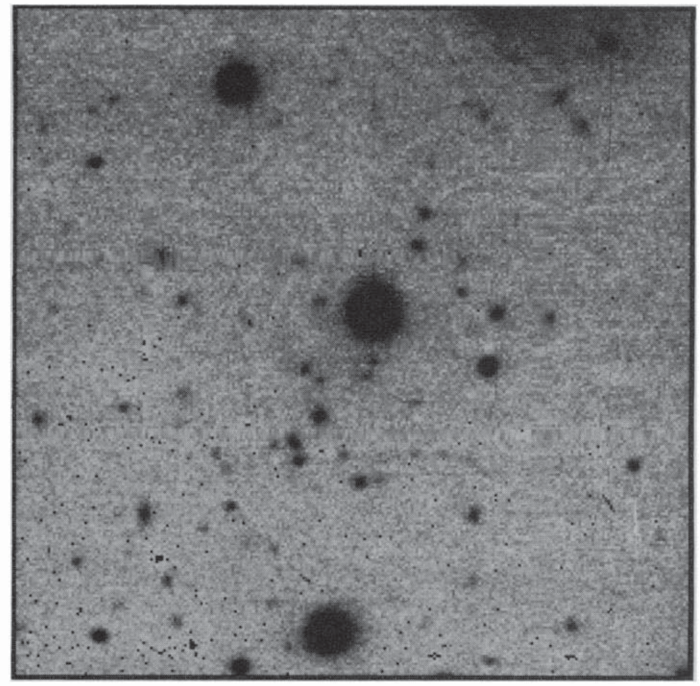

Fig. 3. Deep CCD (charge-coupled device) image of the quasar 3C 263 ($Z = 0.652$), taken with the prime-focus camera of the Canada-France-Hawaii 3.6-m telescope. The quasar is the bright, centrally located image (remember Figs. 2 and 3 are negatives). Other circular, sharp-edged images are foreground stars in our galaxy. The fuzzy ones are galaxies, and are far more numerous here than in other, random, areas of sky. The implication is that we are seeing a rich cluster, one of whose members is the quasar host galaxy. [Photograph courtesy of H. K. C. Yee (Université de Montreal) and R. C. Green (Kitt Peak National Observatory)]

The location of the gas responsible for producing the broad absorption lines seen in a minority of QSO's could be either close in, near the narrow-line region, or much farther out in the galactic disk. Presence of broad absorption lines is, however, associated with reduced large-scale radio emission (*45*) and with optical emission line peculiarities (*46*), suggesting a location near enough the core to interfere with energy transport.

The optical (including infrared and ultraviolet) continuum emission region lies still nearer the center and is less well understood. In the highly polarized, rapidly variable BL Lac's and OVV's, the continuum is probably largely synchrotron. For common, ordinary QSO's with modest variability and polarization, either synchrotron or thermal emission from outer parts of the accretion disk is possible, and both may be present. Although accretion disks play a vital role in most QSO models, the question of whether we ever see light coming directly from them has yet to be resolved (*47*). A recent workshop devoted specifically to continuum emission from active galactic nuclei (*48*) was unable to reach any more definite conclusion.

Still closer in, and beginning to mingle with the compact radio source region and superluminal jets, are the zones emitting x-rays. Both the rapid variability of x-ray flux in many QSO's and the need for a deep potential well to confine high-energy particles imply that these cannot fall much outside 10 Schwarzschild radii. One surprise is that the x-ray flux in most QSO's, despite passage through the various line regions, shows little sign of absorption ($N_H \lesssim 3 \times 10^{20}$

atoms per square centimeter), meaning that we have a clear sight line almost down to the central engine (*49*). Despite this, it has not proven possible to choose among several possible x-ray emission mechanisms, including Compton upscattering of photons by a hot, but subrelativistic, plasma, and Compton boosting by relativistic electrons of their own synchrotron photons. The situation is further complicated by the different time scales on which hard and soft x-rays vary (*50*).

Finally, we come to the very center and ask (i) how is energy extracted from the central black hole and imparted to particles and fields; (ii) how is it collimated into jets or beams; and (iii) what are these made of?

Three extraction mechanisms have been proposed: (i) gradual heating of and radiation by gas in a viscous accretion disk; (ii) a modification of the Penrose process (*51*) in which an ambient magnetic field removes the requirement for relativistic breakup of the incident particle (*52*); and (iii) electromagnetic extraction, in which a magnetic field threading a rotating black hole and anchored to its accretion disk induces an electric potential difference sufficient to produce an electron-positron cascade and thus a force-free magnetosphere a considerable distance away from the black hole (*53*). Once energy is available, many processes known from studies of solar flares, pulsars, and supernova remnants can be invoked to transfer it efficiently to relativistic electrons (*54*).

The composition of the beam, as long as it is a relativistic fluid, does not matter for many purposes. Suggested alternatives to normal electron-proton plasma include low-frequency electromagnetic radiation (*55*) and an electron-positron plasma. Protons are useful for transporting energy over large distances, but the e^+e^- combination requires less total energy and has the advantage of not depolarizing the radio emission we see from the jets. Collimation of the jets probably occurs in two stages, and a number of different phenomena (gas, magnetic, and radiation pressures; deLaval nozzles; aerodynamic forces and others) can contribute (*56*).

With three or four possibilities at each stage of the jet production process, one can easily imagine 100 or more combinatorial models. Virtually all of them have probably been published by someone, and each may well apply at least approximately to some particular object. Clearly, we are very far indeed from having a single model of quasar structure in the way we can be said to have a model of stellar structure and evolution.

Quasars and QSO's as Probes

We have already alluded to the possibility that the rarity of QSO's with $Z \geq 3$ may be a signature of the epoch of galaxy formation and to contributions of quasars and QSO's to observed backgrounds of radio and x-ray radiation. This section addresses several other topics pertaining to applied, rather than pure, quasaronomy. These include (i) QSO's as locators of high redshift galaxies and clusters, (ii) existence and distribution of dark matter implied by gravitational lensing of QSO's, (iii) existence and meaning of QSO clustering, and (iv) various hints about intra- and intergalactic gas derivable from QSO absorption lines.

Yee and Green (*57*) have imaged regions around a complete sample of quasars with redshifts of 0.4 to 0.8. They find that 30 to 40% of quasars with $Z \leq 0.55$ occur in rich clusters of galaxies, versus 5% at $Z = 0.4$ (Fig. 3). The quasars are sometimes, but not always, at the centers of their clusters and are significantly brighter than the other members. In addition, Yee and Green have constructed the luminosity distribution, $N(L)$, of the cluster galaxies, on the assumption that each is at the distance indicated by the redshift of its hosted quasar. The resulting $N(L)$ has the same bent shape as the local one, but the bend occurs about one magnitude brighter. This rapid change of environment with time suggests both the importance of tidal interactions as an activity trigger (*18*) and rapid flaring up and dying away of many generations of QSO's over the age of the universe.

Galaxies at still larger redshifts can be found by using narrow band filters, suitably tuned to emission lines. Djorgovski *et al.* (*58*) have found a $Z = 3.218$ galaxy as companion of a $Z = 3.209$ quasar and are actively searching for others.

Gravitational lensing of quasars was first invoked as a general phenomenon to explain their great brightnesses and rapid variability (*59*). The seven or eight (*60*) cases of gravitationally lensed QSO's now generally recognized present a number of problems. In several, no trace of the lens has yet been seen; for most of them, the number of images detected is even rather than odd, as expected for reasonable lens geometries (*61*), although additional faint images of both QSO and lensing galaxy continue to turn up (*62*); and in no case does a simple point or spheroidal lens fit the observed combination of image separations and brightness ratios (*63*). The subject is widely regarded as having enormous potential for probing the large- and small-scale mass distributions within the lenses and possibly for determining H_o and q_o as well (*64*). At present, the main reasonably firm conclusion seems to be that every lens so far identified must include a considerable percentage of nonluminous matter, which is distributed differently from the luminous material (*63, 65*).

Quasars might be more or less clustered than nearby galaxies, depending on how they form. In addition, the degree of clustering could depend on redshift, being arguably larger in the past if structure in the universe originated from pancake-like structures that later fragmented (top down), and smaller in the past if structure has grown hierarchically by the gravitational clustering of smaller units (bottom up). What one sees depends on the angular scale examined. An absence of perceptible clustering on scales less than or equal to sizes of galaxy superclusters ($\leq 30'$ at typical redshifts) has persisted for more than 20 years (*66*).

On smaller angular scales, three recent studies (*67, 68*) concur in finding a statistically significant excess of pairs with separations less than $10'$, indicative of three-dimensional clustering on scales up to about 10 megaparsec (Mpc), the size of rich clusters and small superclusters, given $H_o = 50$ km sec^{-1} Mpc^{-1} and the Z's of 1 to 2 found in the surveys with measured redshifts (*67*). The total number of matching redshift pairs is only 11 and 20 in these two samples, but it constitutes a 3σ excess over what would be expected for a random distribution and is twice the number of pairs expected if QSO's were distributed like nearby bright galaxies.

In addition to the modest number of pairs involved, there are two other reasons to refrain from drawing the obvious conclusions that distant QSO's are more strongly clustered than nearby galaxies and, therefore, that the universe has evolved in a top-down fashion. First, known gravitational lenses account for 7 of the 20 pairs in one sample, and additional pairs in all three could be images rather than separate objects. Second, if QSO-like behavior is enhanced by tidal interactions, active galaxies should be more clumped than ordinary ones at each redshift. Additional complete surveys, high angular resolution maps of close pairs, and Hubble Space Telescope images of clusters around distant QSO's can deal with these three problems in due course.

Finally, we can probe the medium between us and the QSO's through absorption imposed on their spectra. That we see high-Z objects at all says that most of the intergalactic medium is not opaque in either dust or Lyα (*69*). The absorption we do see is concentrated into line systems—broad ones with redshifts generally close to that of the QSO's emission lines, and narrow ones whose absorption line redshift, Z_a, can be very different from that of the emission lines, Z_e (but where the difference is large, $Z_a < Z_e$ always). Broad lines, discussed earlier, exist in QSO's of all redshifts (*70*) and are, therefore, believed to be intrinsic to the sources. Narrow ones become rapidly more numerous with increasing redshift, as expected for absorption by intervening objects, whose space density should scale as $(1 + Z)^3$ owing to expansion of the universe.

The narrow absorption line systems, in turn, come in two classes, those displaying a range of lines produced by heavy elements and a much more numerous group showing only Lyα absorption (and, sometimes, other Lyman lines). These latter can be seen only when one is able to look shortward of 1216 Å in the rest frame of the source, but then become so numerous as to constitute a "Lyman α forest" in many QSO's. Gas densities and compositions derived for the two classes suggest that they really represent different portions of a continuous distribution of cloud sizes and metal abundances, ranging from solar composition down to extreme population II values of 10^{-3} to 10^{-4} solar, perhaps to zero (*71*).

The absorption systems with metal lines show line ratios much as one would expect from a normal interstellar mix of elements, temperatures, and densities, in combination with statistical and other properties indicative of galaxies that cluster as galaxies should (*72*). The natural conclusion is that we are, indeed, seeing absorption in the interstellar gas of ordinary galaxies. For those few, low Z_a systems where the galaxy itself can be seen, it looks normal.

Given this intervening-galaxy interpretation, the metallic line absorption systems provide a probe of nucleosynthesis in the past. One implication, because of the large numbers of such systems seen, is that metal-enriched gas must extend 30,000 parsecs or more from the centers of galaxies at $Z = 1$. The current record redshift is $Z_a = 3.552$ ($Z_e = 3.78$) and includes one line of Zn II, implying that a considerable number of stellar births and deaths had already occurred in the galaxy by that time (*73*).

Absorption line systems can also reveal the presence of otherwise undetectable material. Spectra of QSO's whose positions and redshifts place them behind some of the famous cosmic voids ($\lesssim 100$ Mpc wide volumes seemingly empty of luminous galaxies) show a couple of cases of absorption at redshifts indicating that the absorbing clouds are within the voids (*74*). Models of biased galaxy formation can easily accommodate hydrogen clouds. The cases with Si IV and C IV lines are more puzzling, but may still be consistent with galaxies too faint to be seen by the surveys that found the voids.

Absorbing clouds extensive enough to produce detectable metal lines are, as a rule, also optically thick in the Lyman continuum, and are thus able to eliminate all photons at wavelengths shorter than $(1 + Z_a) \times 912$ Å. About half of all QSO's with $Z_e = 1.0$ to $Z_e = 2.5$ looked at systematically have their spectra thus truncated (*75*). Presumably by $Z \gtrsim 3.5$ nearly all will be so afflicted. As the cutoff moves into the visible part of the spectrum, it dims and reddens QSO's and will contribute to the rarity of detectable high redshift objects.

The Lyα clouds are numerous enough to permit statistical studies. The bivariate function $N(N_H, Z)$ provides some information on how the clouds themselves evolve (after eliminating those with Z_a so close to Z_e that the gas is likely to be heated and ionized by the QSO). Early results (*76*) are intriguing. Apparently, from $Z = 3.5$ down to the present, clouds with masses from 10^6 to $10^{8.5}$ $M_\odot$ gradually expand and ionize, presumably dissipating in due course, while those above $10^{8.5}$ $M_\odot$ collapse with time, presumably forming galaxies. Perhaps we can use QSO's as probes of galaxy formation after all, since these collapses must be occurring after those that made the QSO's host galaxies. The straightforward implication that big galaxies form before little ones would be of considerable cosmological importance if true.

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