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A Low-Resolution View of High-Resolution Spectroscopy

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ABSTRACT. The enormous cost of even relatively simple focal-plane instruments for 8±2-meter telescopes is, inevitably, acting as a driver to produce very general-purpose spectrographs for each of them. Somewhat unexpectedly, the result seems to have been a convergence on very similar, cross-dispersed, $R=\lambda/\Delta\lambda\sim 10^5$ echelles for nearly every such telescope in use, under construction, development, or consideration. Such spectrographs are well matched to studies of small numbers of relatively bright point sources (stars or QSOs) directed at understanding either the sources themselves or intervening gas responsible for absorption lines. They are much less well suited to studies of extended objects (nebulae, galaxies) and to studies of populations of stars or galaxies, including those in clusters, and to studies of very faint objects, where accurate sky subtraction is vital. Adaption of the existing and contemplated instruments to long-slit, multi-slit, and multi-object use apparently carries high prices in lost photons, increased noise, and increased exposure time.

1. INTRODUCTION

The three sponsors of the workshop NOAO, UCO, and McDonald are all operating or building optical telescopes in the 8±2-meter regime: NOAO = two 8 meters called Gemini in cooperation with the United Kingdom, Canada, Argentina, Brazil, and Chile, for which ground has been broken; UCO = two segemented 10 meters called Keck telescopes in cooperation with California Institute of Technology, University of Hawaii, and NASA, with one in operation and one under construction; McDonald = Hobby-Eberly Telescope, a 9–11 meter, depending on source location, in collaboration with Pennsylvania State University, Stanford, and the Universities of Munich and Göttingen, with site preparation under way. This adds up to five.

Other organizations whose members spoke at or attended the workshop and which are more or less committed to similar telescopes are: ESO = four 8 meters called the Very Large Telescope, with a site largely developed in Chile; the National Astronomical Observatory of Japan = 8 meter called Subaru, under construction in Hawaii with University of Hawaii cooperation; University of Arizona = a rebuilding of the Multi-Mirror Telescope as a 6.5-meter monolith, with the blank paid for and cooling, plus an attempt to go ahead with the Columbus project of two 8.5-meter telescopes under the name Large Binocular Telescope, the former effort in collaboration with Smithsonian Astrophysical Observatory; Observatories of the Carnegie Institution of Washington = one 6.5 meter called Megallan, with funding in place for a Chilean site; and, less officially, the consortium of Spanish observatories hoping to install an 8 meter in the Canary Islands. This is an additional ten large telescopes, and if all should come into operation, the world astronomical community would have rather more square inches of glass per person than ever before in its history. "Glass" should, of course be liberally interpreted to include various ceramics; and the precise names and partnerships of some of the telescopes and their sponsors are still subject to modification.

Under the circumstances, a gathering of the clans to discuss focal-plane instrumentation, in this case focused on high-resolution spectroscopy, seems a natural development. In retrospect, the author is somewhat surprised that there hasn't already been more effort, formal and informal, to make use of the expertise achieved in building the first Keck telescope and its HIRES spectrograph, the only one of these facilities currently in operation.

2. WHAT IS HIGH RESOLUTION?

In advance of the workshop, I had asked this question by trying to sort out what you can learn at logarithmic steps upward in $R=\lambda/\Delta\lambda$. For instance:

$R=1$. Source counts, which are not to be despised. For, while Herschel and Kapteyn counting stars "discovered" that we are at the center of the Milky Way, the Cambridge radio source counts (properly understood) were the first firm evidence that the universe could not be in a steady state, and the source counts of gamma ray bursters are clearly trying to tell us something very important, though nobody knows what.

$R=10$. *UBV* and other broad-band photometry. This suffices to plot a color–magnitude (HR) diagram and to distinguish elliptical from spiral galaxies, at least in their $z=0$ incarnations.

$R=10^2$. Narrow-band colors, achieved with interference filters and such. At this point you can develop metallicity indicators (and remember that in the 1970's disagreement between the photometrists and spectroscopists over the metallicity scale for globular clusters, the photometrists turned out to be right), perhaps separate age from composition effects in elliptical and dwarf spheroidal galaxies, and (if you hadn't known about them before) pick out strong emission-line objects like quasars and supernova remnants.

$R=10^3$. This is roughly the resolution of the original Robinson–Wampler scanner and of Annie J. Cannon's HD survey of spectral types. It enables you to measure redshifts, do two-dimensional spectroscopic classification (based on ratios of lines from ionized and neutral metals, not on linewidth as your log *g* signature), and recognize what once

were called "stationary lines" in the spectra of spectroscopic binaries, that is, to discover the interstellar medium.

$R=10^4$. This was the standard resolution of prime focus and Cassegrain spectrographs of an earlier generation of 3–5-meter telescopes. It permits good orbits for spectroscopic binaries, recognition and study of quasar absorption lines, determination of the abundance of individual relatively common elements, and the study of moderate values of rotational velocity and magnetic fields in stars, as well as reasonable mapping of velocity fields in things like novae and planetary nebulae that do not expand quite so fast as supernovae.

$R=10^5$. Here we enter the regime achievable only with Fourier Transform spectrometers and cross-dispersed echelle spectrographs. It permits detailed measurement of line profiles for study of stellar winds and disks and signatures of convection, the measurement of abundances of elements with nothing but weak lines nearly blended with those of less rare elements, and recognition of the enormously complex velocity structure present in both interstellar and intergalactic absorption lines, as well as searches for long-period and low-mass binary companions and the measurement of velocity dispersions where they are only a few km s^{-1} in star clusters and dwarf spheroidals.

$R=10^6$. This regime is currently occupied by only one spectrograph, developed at University College London and operating on the Anglo-Australian Telescope, whose light-gathering power is not quite equal to feeding it, except for very bright sources. Combined with larger mirrors, this sort of resolution permits searches for planetary companions of stars, the measurement of isotope ratios, Doppler mapping of stellar disks (and interesting effects might also be seen in the reverberation mapping of quasar broad emission lines within detailed line profiles and their changes), and the tracing of stellar line profiles to look for slow rotation, weak magnetic field effects, and other contributors to line broadening, including micro- and macro-turbulence and unexpected pressure effects. It is at least possible that interstellar gas clouds and quasar absorption-line clouds will reveal still further structure at this level, but conceivable that they may not.

3. HIGH RESOLUTION MEANS $R=10^5$

This was a consensus that seemed gradually to develop in the course of the workshop. It was motivated at least partly by the certainty that you continue to find exciting new science up to this level, but possibly not much beyond, apart from special-purpose applications. What I mean becomes clear upon a comparison of run-of-the-mill publications that display spectra at various resolutions such that an inch or so on a journal page may equal 30 or 3 or 0.3 Å.

The interested reader is invited to compare (a) Frye et al. (1993), who show a QSO Lyman-alpha forest at $R=4300$, observed with the Oke–Gunn spectrograph on the 200-in. Hale telescope, (b) Crotts (1988), who shows a complex of [C IV] absorption lines in a quasar at $R=15,000$, observed with the Cassegrain echelle on the KPNO 4 m, (c) Sahu and Blaauw (1994)—yes, the Blaauw you are thinking of—presenting interstellar Na I at $R=100,000$, recorded with the Coude Echelle and Coude Auxiliary Telescope at ESO, (d) LaGrange (1994), who shows an ultraviolet Fe II line from the disk of Beta Pic at $R=80,000$, achieved with the Goddard High-Resolution Spectrograph on *HST* (where you need the little tick marks provided by the authors to decide which substructure in the lines is real), (e) Nissen et al. (1994), who display a very interesting failed search for ^{6}Li in HD 76932 at $R=115,000$, recorded with the ESO 3.6 m and Coude Echelle (they discover that an instrumental asymmetry in all weak lines puts some extra absorption in the right wing of the 6707.8 Å line just where the ^{6}Li component would fall), and (f) Crawford et al. (1994), who again show us the Beta Pictoris disk, but now at $R=900,000$, so that it is instantly clear which are the real structures and also that they change significantly in months, obtained with the UCL UHRF at the AAT.

With this choice in mind, we can then ask just what is meant by $R=10^5$? By analogy, an angular resolution of 1 arcsec means that you expect just to be able to separate two stellar images of equal brightness whose centers are 1 arcsec apart. But you can determine the centroid of one such image to 0.1 or 0.01 arcsec or even better (otherwise ground-based astrometry could never be done), and the various optically selected coordinate systems imply that absolute positions can be found also to rather better than 1 arcsec.

At 5000 Å, $R=10^5$ means 0.05 Å (or, of course, 3 km s^{-1} at any wavelength) resolution. This does seem to mean that you can recognize as separate two lines that far apart or measure independent fluxes that far apart in a single broader line. The implication of remarks by various speakers is that you also expect to be able to find line centers to 0.3 km s^{-1} (but not much better) and do not expect either absolute wavelength determination or wavelength stability even at this level without special effort.

4. DESIGN COMPROMISES

Two thoughts arise in contemplating trade-offs between high wavelength resolution and all the other things you want—wide wavelength coverage, high signal to noise, good angular resolution, multi-object and extended-object capability, and so forth. The first is that (at least for absorption spectra) most of the information is contained in the pixels with the fewest counts, hence this is where you should measure your S/N. The second is a quote from a senior instrumentalist: "The two important properties of a physicist are his power output and his signal-to-noise ratio."

Given an 8±2-meter telescope with the f ratios that are currently being built, it seems that you can devise an $R=10^5$ spectrograph that will cover one to four octaves (e.g., 0.3–1.1 or 1–5 μm) in "a few" exposures on existing CCDs and InSb arrays with sampling fairly close to the ideal of 2–3 pixels per resolution element. The efficiency (meaning number of photons detected or electrons counted per photon that hits the first mirror) of most systems is near 0.1, where a factor of three is lost in the telescope itself and a second factor of three in the spectrograph. This is, of course, an enormous improvement over the efficiency of one silver iodide grain per 10^3 incident photons from photographic methods; but most of the improvement has, of course, been in the detectors, not in the rest of the spectrograph, except that echelle configurations allow you to open up the slit to match the seeing, thereby making use of more of the light, without significant loss of wavelength resolution.

The price paid for high resolution and reasonable wavelength covered in a finite number of exposures is a relatively high and complex one. First, there is not much blank sky available for accurate sky subtraction for faint objects or for studying extended objects, because slit lengths are limited to about 10 arcsec. *A fortiori*, you cannot do more than one or two objects at a time. Because each echelle order is a fairly short wavelength bite, establishing an accurate continuum level may be a problem. And for some designs, the direction of constant wavelength is not perpendicular to the dispersion direction, which considerably complicates both sky subtraction and velocity measurements.

Some of these difficulties can be evaded by isolating one or a few orders with filters. This costs you another 20%–30% of the light and most of your wavelength coverage, but permits multi-slit (two-dimensional) and multi-object spectroscopy. It was not clear that any of the designs discussed at the workshop contemplated actually doing this sort of thing. Other add-ons that may be necessary, but cost still more in either exposure time or signal to noise include image rotators, polarimeters, and atmospheric dispersion correctors.

Discussion focused almost entirely on echelles (two gratings or grating plus prism, in either order), with only a single source of gratings currently available. Brief mentions of Fourier transform spectroscopy and Fabry–Perot interferometry (especially for two-dimensional astronomical objects) left me wondering whether they might not still be the approach of choice, particularly if detectors as good as the echelle CCDs could be employed.

The high-resolution spectrographs under discussion are, by intention and of necessity, general-purpose instruments. They give, nevertheless, a strong impression of being optimized for certain kinds of projects and, correspondingly, rather inefficient at others. The winners are point sources (fairly bright and in modest numbers), which are individually interesting either for their own astrophysics or for the sight lines to them. This includes stars and QSOs, intrinsically and as probes of intervening gas. The losers are extended objects of all kinds, where the variation of properties from place to place is of interest, and clusters of stars and galaxies, whether your interest is in composition or kinematics.

A final, curious point remarked upon by one or two speakers is that all of the existing, growing, and planned facilities will be in a relatively narrow longitude range from 70° to 160° west. This precludes continuous coverage of rapidly changing targets of the kind that has proven so valuable in the study (with smaller telescopes!) of cataclysmic variables (the Whole Earth Telescope) and the Sun (the Global Oscillation Network). In the southern hemisphere, sites in Australia and South Africa could largely remedy this defect. In the northern hemisphere, one thinks (along with the Spanish observatories) of the Canary Islands and, conceivably, the Tibetan plateau or Asiatic parts of the former Soviet Union.

5. SCIENCE

The majority of speakers addressed work already complete or under way, with the possible extensions to come with more photons and/or more resolution. Guided by their remarks, I approach this section in the spirit of a child writing to Santa Claus, rather than one who has come to understand that Mummy and Daddy and Uncle Sam have to be able to pay for it all. Most of the topics are being worked on with existing instrumentation. They seem, however, capable of yielding up additional secrets, given larger telescopes, higher resolution, and, in many cases, one or more of the following additional items: (1) continuous temporal coverage, (2) wavelength stability, (3) signal to noise in excess of 100 or so, (4) low noise contributions from readout and dark current (or the equivalent for other sorts of detectors), (5) multi-object capability, (6) long slits, and (7) multiple slits or authentic two-dimensional coverage.

5.1 Stars

Astroseismology comes immediately to mind, given item (1). My only idiosyncratic thought is to urge that the words "astronomy" and "astrology" already tell us that the correct combining form of "aster" is "astr" or "astro" not "astero." Thus, the first word of the first sentence is not misspelled. I hope it will persuade workers in the field to pronounce their subject in a way that makes clear its connections with stars, rather than stereo.

Other stellar projects include (B) Doppler mapping of stellar surfaces, spots, and disks (given 1 and 2); (C) measurements of weak, localized, or variable surface magnetic fields; (D) isotope ratios, even the elusive ^{6}Li/^{7}Li, given (3); (E) searches for low-mass companions (2); (F) determination of star-cluster and dwarf-galaxy velocity dispersions (2,5); (G) wind structures and changes and momentum transport in objects like T Tau and Beta Pic (1,4); (H) abundances of rare elements with lines in awkward places, like Li, Be, B, Th, F, and r-process products; (I) line profiles, line bisectors, and wiggles at the bottoms of saturated lines as signatures of convection, low-level convection, slow rotation, and pole-on rotation (4); (J) recognition of mild composition anomalies; (K) projects that can be done quickly at small S/N for large groups of objects (4), and (L) population and composition studies for stars in distant and/or crowded fields (5 and adaptive optics also needed).

5.2 Intervening Gas

Absorption lines imposed upon stellar and QSO spectra tell us about multiple velocity components for disk, halo, and extragalactic gas; kinematics of the gas, including galactic rotation and clustering of clouds along and between lines of sight; and weak lines as diagnostics for temperature, density, ionization, abundances of rare elements (moving into the r- and s-process regime, still not well studied even for the gas of our own galaxy), and depletion.

5.3 Emission Lines and Extended Sources

Efficient pursuit of these topics requires long-slit, multislit, or two-dimensional capability. Given these, one can examine the kinematics, composition (including rare elements) and place-to-place composition variation in planetary nebulae, nova ejecta, supernova remnants, and other H II regions at home and abroad. Gassy galaxies provide an opportunity to look for non-circular motions associated with spiral arms, galactic fountains, and so forth, though this is one regime where it is very hard not to believe that a Fabry–Perot spectrometer is a better bet. (There has been interesting European work along these lines.)

The emission regions of quasars and other active galaxies normally appear point-like, and the lines tend to be broad. But reasonably high resolution within the line profiles permits separation of the broad, narrow, and intermediate line regions and determination of the kinematics, temperature, electron density, and chemical composition of each.

6. LOOKING AHEAD AND BEHIND

It is the traditional prerogative of the last speaker at a conference to thank the sponsors (NOAO, UCO/Lick, and McDonald), and the local organizers, ably headed by Tom Kinman. It is a sign of the remarkable smoothness of the meeting that I never had occasion to talk with any of the people in back of the registration desk long enough to become acquainted.

What were the goals of the workshop, and did it meet them? Clearly, the primary purpose was to bring together people designing and building spectrographs (who are also users, and often very skilled ones) with the more numerous class of users who appear after the devices are working. You will remember that the Little Red Hen had no difficulty in finding collaborators for the final task of eating the bread. This was, to a certain extent, frustrated by the talks having been tightly grouped by topic (not to mention the competition from the WIYN telescope dedication). Many of us would like to see a similar gathering a year or two downstream, but with instrumental, stellar, and extragalactic talks somehow mingled.

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