Emission Lines in Active Galaxies: New Methods and Techniques
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Emission Lines in Active Galaxies: Outlook for the Future

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Abstract. I briefly outline some of the unanswered questions that have emerged as recurring themes at this conference and offer some speculation about how these will be addressed with new techniques and facilities of the future.

1. Introduction

The first meeting at which quasars appeared as a major item on the agenda was the Second Texas Symposium on Relativistic Astrophysics, which was held in 1964 December (Douglas et al. 1969). During the intervening 32 years, we have made tremendous progress in describing AGNs empirically and refining our observations of the phenomenon. This progress is a natural outcome of improvements in and desemination of technology that has been driven, in fact, largely by requirements for observations of AGNs. Because AGNs are the most luminous known discrete sources and can be observed out to very large redshifts (approaching $z \approx 5$ at the time of this conference), the motivation to understand them is great. The broad-band spectral energy distributions of quasars have necessitated their study all across the electromagnetic spectrum, and consequently AGNs have served as important motivators for the development of multiwavelength astronomy.

2. Why We Study AGN Emission Lines

The fundamental question in AGN astrophysics remains: *what is the nature of the central engine?* Most, but not all, researchers believe that no serious challenges to the black-hole/accretion-disk paradigm have emerged. Nevertheless, we must be cautious: as Blandford (1992) reminded us at the Taipei conference in 1991 March '... it remains true that, even by the lax standards of astronomy, there is no *proof* that black holes exist in AGN, or indeed anywhere else'. While this statement remains strictly correct, the circumstantial evidence for supermassive black holes in the centers of galaxies has become much stronger over the last five years. Specific evidence includes the following:

1. Stellar dynamics (e.g., Kormendy & Richstone 1995).
2. Gas dynamics (e.g., Ford et al. 1994 on M 87.)
3. Megamaser kinematics (Miyoshi et al. 1995 on M 106).

4. Broad-line reverberation results (e.g., Korista et al. 1995 on NGC 5548).
5. Very broad, gravitationally redshifted Fe Kα X-ray emission (Tanaka et al. 1995 on MCG -6-30-15).

Table 1 shows the approximate scale length in units of the Schwarzschild or gravitational radius $R_S = 2GM/c^2$ probed by each of these techniques. We see immediately that the smallest-scale probes are provided by emission lines. At this conference we have heard about recent developments in many of these areas (e.g., Greenhill, p. 394; Maoz, p. 138; Nandra, p. 36).

Table 1. Evidence for Supermassive Black Holes

Observation	Scale probed
Stellar dynamics	$r \gtrsim 10^6 R_S$
Gas dynamics	$r \approx 7.7 \times 10^5 R_S$
Megamaser kinematics	$r \approx 3.7 \times 10^4 R_S$
Broad-line reverberation	$r \approx 600 R_S$
Fe Kα profiles	$r \approx 3$–$10 R_S$

So while the case for supermassive black holes in the centers of AGNs is still not established beyond reasonable doubt, it is hard to envisage other models that are consistent with such highly concentrated mass distributions. And the strongest evidence over the past several years has been provided through novel observations of AGN emission lines.

There are other important reasons for our interest in AGN emission lines. At least in principle, the emission lines provide us with an indirect probe of the ionizing continuum once we understand how the emission-line clouds reprocess the radiation; this is simply a more general application of the Zanstra (1931) method for determining the temperatures of stars embedded in ionized Galactic nebulae. Broad AGN emission lines are also of interest on account of their unique astrophysical characteristics. The broad ranges in ionization level and velocity width indicate that we are observing the radiative cooling of diffuse gas in an extreme environment. Finally, although no convincing observational case has yet been made, the emission-line gas *must* have some relationship to the AGN fueling process. Efficient conversion of potential energy to radiation requires that accreted matter be in a diffuse rather than a condensed (e.g., stars) state within several gravitational radii of the central source, and surely this gas must somehow manifest itself in AGN spectra. Indeed, my own belief is that the most fundamental question we have about AGNs is no longer whether or not supermassive black holes exist in the centers of AGNs, but rather how are these sources fueled?

3. Some Specific Questions Concerning Emission Lines in AGNs

A number of recurring themes emerged during this conference. Here I want to outline briefly my own beliefs about certain of these questions, and describe how I believe they will can be addressed through existing or planned new facilities or techniques. In keeping with the conference theme, I am confining my attention to emission-line issues. Obviously this overlooks some of the most important questions in AGN astrophysics, such as *what is the interaction between the accretion disk and its hot corona?*, which I believe is the single most important theoretical question in AGN astrophysics, and *what is the difference between radio-quiet and radio-loud AGNs?*, which is one of the longest-standing questions.

3.1. What Is the Origin of the Fe Kα Line?

The X-ray spectra of AGNs show the Fe Kα line in emission at $E \approx 6.4\,\mathrm{keV}$ in both Seyfert 1 and Seyfert 2 (Awaki, p. 44) galaxies. *ASCA* observations by Tanaka et al. (1995) have shown this line to be asymmetric and gravitationally redshifted in the Seyfert 1 galaxy MGC–6–30–15, and Nandra (p. 36) now reports that these same characteristics can be seen in a mean spectrum based on several different AGNs, which suggests that MCG–6–30–15 is representative rather than peculiar. The Fe Kα line profile is highly suggestive of an accretion-disk origin, although actual proof is still lacking and other explanations need to be fully explored.

The *Advanced X-Ray Astrophysics Facility (AXAF)*, on account of the high spectral resolution ($R \equiv E/\Delta E = \lambda/\Delta\lambda$) available with its transmission gratings ($100 \lesssim R \lesssim 2000$), will be able to address this problem directly (Kunieda, p. 1; Fabbiano, p. 34). Indeed, it can be expected that *AXAF* will precipitate a qualitative change in the nature of astronomical X-ray spectroscopy in general. The highest spectral resolution that has been routinely obtained in X-ray astronomy is $R \approx 50$ with *ASCA*. This is high enough that the strongest AGN spectral features can be seen in the raw data, but it is still sufficiently low that spectral modeling is the preferred method of analyzing the data, i.e., spectral models are convolved with the instrumental response and fitted to the raw data. With the advent of high spectral resolution with *AXAF*, it will be possible to identify spectral features readily *without* modeling, and it will be possible to produce flux-calibrated data that can be analyzed in a model-independent fashion, as in UV, optical, and IR astronomy. The consequences of improving spectral resolution from $R \approx 100$ to only a factor of a few higher are dramatic for AGNs. This can be seen by examining some of the early optical spectrophotometry of AGNs. Yee & Oke (1981) show several $R = 100$ spectra of the broad-line radio galaxy 3C 390.3 (see also Dietrich et al., p. 163) obtained with Oke's multichannel spectrophotometer. The strong emission lines are clearly visible in the data, but Hβ and [O III] $\lambda\lambda$4959, 5007 and other lines that are close in wavelength are too badly blended to be identified individually. With a modest improvement in resolution to $R = 700$ with the Lick Observatory IDS (Osterbrock, Koski, & Phillips 1976), the narrow components of all three lines are separated and the broad component of Hβ can be easily seen as well.

Improved X-ray spectral resolution will make it possible to measure the wavelength-dependent variability of the Fe $K\alpha$ line in a model-independent fashion — reverberation-mapping techniques can then be used to determine the structure and velocity field of the $K\alpha$ line-emitting region. Certainly, this will be more complex than the reverberation studies that are done with the UV/optical broad lines because the simplifying assumption that the continuum arises in a point source will not be valid on the scale over which the $K\alpha$ line is produced. The *interpretation* will thus be more model-dependent than are other reverberation results, but the observations should still show clearly enough whether or not the $K\alpha$ line arises in the inner several gravitational radii of an accretion disk. This X-ray spectral monitoring should in the same way be able to reveal the location and geometry of the Compton reflection component in the 10 keV spectral region and of the soft X-ray absorbers and their relationship to UV absorption features (Elvis et al., p. 236; Crenshaw, p. 240).

3.2. What Is the Nature of the Broad-Line Region?

What are the emission-line clouds? Are they somehow related to the accretion flow? Are they perhaps the extended atmospheres of stars (Alexander, p. 207), or do they perhaps originate in the extended regions of the accretion disk (Rokaki, p. 56)? How is the broad-line region (BLR) related to other AGN components?

We are still unable to answer these simple, basic questions despite the fact that during the last decade, major advances in our exploration of the BLR have been made through reverberation mapping. I believe that this method still holds great hope for further progress. At this time, the principal successes of reverberation mapping have been (Maoz, p. 138):

1. Measurement of scale lengths (or time lags) for multiple lines in multiple objects. The BLR has been found to be quite small, typically of order a few light days to a few light weeks in Seyfert 1 galaxies.

2. Confirmation of radial ionization stratification of the BLR. The highest ionization lines respond most rapidly to continuum variations, showing that they arise in the broad-line gas that is closest to the central source.

3. Demonstration of the lack of predominantly radial flows within the BLR. The BLR cloud motions seem to be primarily orbital, although it is still not clear whether the cloud velocities are organized (as in a rotating disk) or random.

Important unanswered questions remain. The origin of line-profile variations remains unknown, although it is now clear that at least the large-scale changes occur over dynamical rather than light-travel time scales and are thus not reverberation effects (Wanders, p. 183). Also, the number of data points obtained in reverberation studies has not yet been sufficient to yield a unique and unambiguous solution for the emission-line transfer function. The first hints of structure in transfer functions are beginning to emerge (Wanders et al. 1995; Done & Krolik 1996), and these only hint at the BLR geometry and kinematics.

Future reverberation-mapping programs will need to be even more intensive than the massive programs that have been undertaken already. High sampling rates (i.e., time resolution less than a day) for long duration (several weeks or months) will be required to make truly significant progress. Such a program is currently being attempted by the International AGN Watch monitoring consortium (Alloin et al. 1994) during this final summer of *IUE* operations. The target for this project, which is being carried out at the time of this conference, is the Seyfert 1 galaxy NGC 7469. *IUE* will observe NGC 7469 virtually continuously for at least 30 days with a time resolution of 1–2 hours. These observations will be complemented by concurrent *XTE* observations that will provide several observations per day during most of this period. A search for very rapid, low-level UV/optical variations will also take place during this period; *HST* FOS spectra will be obtained for several hours with a time resolution of about one minute. And, as usual, the space-based campaign will be supported by observations at several ground-based observatories. The hope is that the large number of spectra produced by this project will lead to determination of the transfer-function structure, which will in turn provide a strong constraint on BLR models. It is worth reiterating, however, that reverberation mapping *cannot* produce a completely model-independent map of the BLR, since it provides only two parameters in a six-dimensional phase space. Models will be compared to two-dimensional transfer functions (in the time-delay/radial-velocity plane) to determine whether or not they are viable.

The future of AGN monitoring beyond this project is questionable. The loss of *IUE* is a terrible blow to multiwavelength science and monitoring programs in particular. Reverberation-mapping experiments will be extremely difficult in the post–*IUE* era. The next qualitative improvements in reverberation mapping will require significant fractions of dedicated space or ground-based facilities. But the return is likely to be worth the investment.

3.3. How Do AGNs Affect Gas on Spatially Resolved Scales?

Major questions that have appeared repeatedly in this conference include:

1. What is the relative importance of direct photoionization and collisional ionization? (See Wilson, p. 264; Viegas & Contini, p. 365; Pogge, p. 378; Bicknell et al., p. 382; Evans et al., p. 386; Metz et al., p. 390, Allen et al., p. 392.)

2. What is the nature of the 'obscuring torus' and to what extent are unification models valid? (See Goodrich, p. 445; Storchi-Bergmann, p. 302)

Observational attacks on these issues will require improved high spatial-resolution imaging spectroscopy in the UV, optical, and most importantly, the infrared. The sharp, high surface-brightness regions and velocity discontinuities that are the signatures of shocks will require observations with high spectral and spatial resolution and high dynamic range. Fortunately, many new developments are imminent, including:

1. The *Space Telescope Imaging Spectrograph (STIS)*, which is expected to be installed on *HST* in the next servicing mission, currently scheduled for in 1997 February. *STIS* will provide long-slit spectra from the far-UV to the near IR.

2. The *Near Infrared Camera and Multi-Object Spectrograph (NICMOS)*, also to be installed on *HST* during the next serving mission, will provide near-IR imaging capability and at least rudimentary grism spectroscopic capability ($R \approx 200$).

3. The *Space Infrared Telescope Facility (SIRTF)*, planned for launch in 2001, will be a major advance for IR astronomy. *SIRTF* will produce $R \approx 50$ spectra in the 5–40 μm range and $R \approx 600$ spectra in 10–40 μm range.

On the longer term, adaptive optics on the new generation of very large ground-based telescopes are likely to play a rôle as well.

3.4. What Do Emission Lines in Very High-Redshift Quasars Tell Us About the Universe?

Since the earliest days of AGN astronomy, it has been recognized that very high-z quasars are the earliest evidence of the formation of discrete structures in the Universe and thus provide important observational constraints for models of galaxy formation. Recently there has been increased emphasis on determining elemental abundances in high-z quasars (Hamann et al., p. 96) since the very existence of heavy-element lines in quasar emission spectra provides information about the earliest nucleosynthesis beyond light elements.

Progress in the study of high-z objects is being made by today's frontline facilities, mainly very large ground-based telescopes such as Keck, and *HST*. However, to probe anything but the very high end of the AGN luminosity function at very high redshift (say, $5 \lesssim z \lesssim 10$) will require IR spectroscopy of very faint objects. It is worth pointing out that there is little motivation to emphasize observations of the UV and optical spectra of such objects, since the number of Lyman-limit absorption systems per unit redshift is about $dN/dz \approx 0.25$ (Stengler-Larrea et al. 1995) and the spectra of most very high-z objects will be cut off somewhere shortward of redshifted Lyα. Observations of the rest-frame UV and optical spectra of these sources will require large space-based infrared telescopes. Recognition of the importance of such facilities led Dan Weedman, former Director of the Astrophysics Division at NASA Headquarters, to assert at an AGN science meeting in Baltimore in 1990 July that 'in the future, we are all going to have to become infrared astronomers'. For the study of AGNs and the early Universe, this is becoming increasingly apparent to many of us, and indeed some appropriate long-range planning is taking place. An example of a concept under consideration is the *Next Generation Space Telescope (NGST)*, which is currently being studied by NASA and the Space Telescope Science Institute. The baseline design mission at the time of writing is an 8-m telescope in high-Earth orbit, operating in the range 0.5–20 μm. If this concept receives support, a launch sometime in the 2005–2010 window is possible.

Those of us who concentrate our research efforts on relatively nearby, easily studied AGNs should never forget the importance of high-z objects. Low-redshift AGNs are a mere remnant of what was once a larger population of active objects, as shown in Fig. 1. The epoch corresponding to $2 \lesssim z \lesssim 4$ was truly the 'age of quasars' and much of their importance to astronomy as a whole is as probes of the distant past history of the Universe.

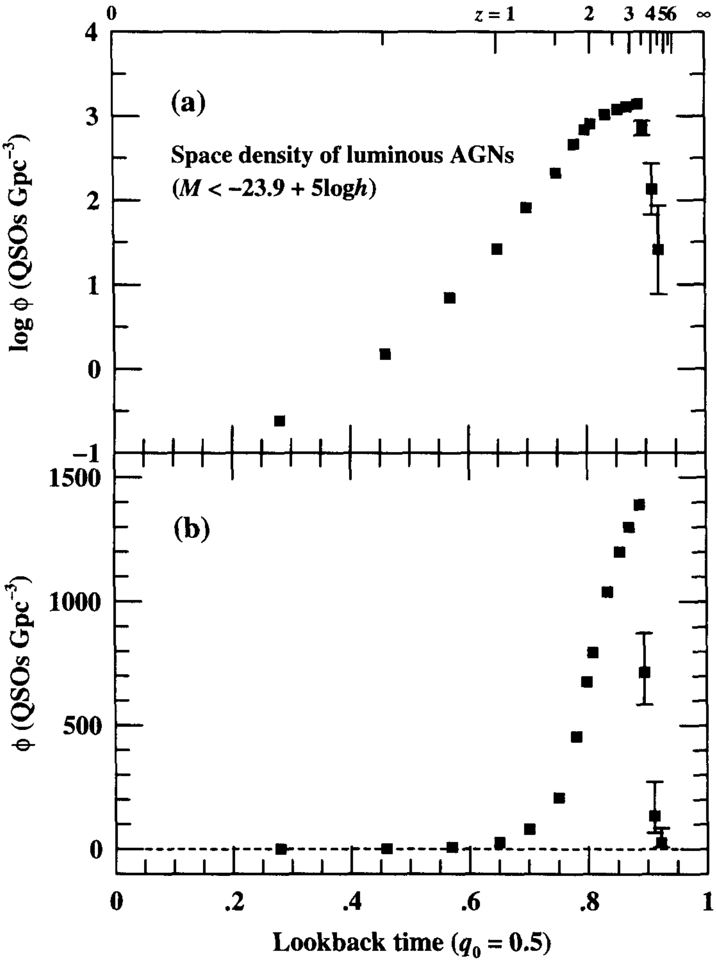

Figure 1. The comoving space density of high-luminosity AGNs as a function of lookback time (in units of the age of the Universe). Redshift is shown on the upper horizontal axis. The top panel (a) shows the space density plotted logarithmically, in the conventional fashion. The space density is plotted linearly in the lower panel (b) to demonstrate the dramatic difference in the space density of bright AGNs between $z \approx 3$ and the present. Based on data from Warren, Hewett, & Osmer (1994).

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4. Final Comments

One of the things that struck me at this conference is the realization that the field of AGNs is demographically dominated by younger people[1]. This is an excellent measure of the health and promise of the field — it shows that there are still good research problems available that one can hope to attack in meaningful ways with existing or imminent facilities. The first half of the 1990s saw some dramatic steps forward in AGN research, with many important advances resulting from the new methods, techniques, and capabilities that have formed the backbone of this conference. As the new capabilities described above become available, we can expect that further consolidation of current work will occur, that there will be some important qualitative improvements in how AGN astronomy is done, and, most exciting of all, that we will encounter surprises that will radically change some of our ideas about AGNs and the Universe.

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[1] Although my friend M. Gaskell has indelicately pointed out to me that my perception is colored by the fact that I am growing older.

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