The Structure and Energetics of Active Galactic Nuclei

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Abstract. The black-hole/accretion-disk paradigm for active galactic nuclei (AGNs) is now reasonably secure, but there are still important unresolved issues, some of which will require the capabilities of an 8 to 10-m class UV/optical space-based telescope. Imaging spectroscopy with a diffraction-limited large telescope will be required to measure AGN black-hole masses from stellar dynamics for direct comparison with reverberation mapping-based masses. High spectral resolution in the UV is required to determine the mass and kinetic energy of the outflows observed in the absorption spectra of AGNs and to understand the energetics of the accretion process. As with ground-based astronomy, however, effective use of a large UV/optical space telescope requires complementary smaller facility instruments; a meter-class UV spectroscopic telescope, for example, can fit into a Medium Explorer budget.

1. Key Questions in AGN Astrophysics

Not long after the discovery of quasars, it was realized that the fundamental source of energy for these objects must in fact be gravitation, and fairly straightforward arguments led to the long-standing paradigm of a supermassive black hole (SMBH) surrounded by an accretion disk. Observational evidence has been rather ambiguous, although there were early strong clues, such as the near-UV/optical “big blue bump” (Shields 1978; Malkan & Sargent 1982) and the rapid X-ray variability, that supported the model if only because they defied other explanation. But it is only within the last several years that the circumstantial evidence has accumulated to the point that few doubters remain. While there is now general, though not unanimous, agreement about the fundamental nature of AGNs, we cannot claim any real understanding of the quasar phenomenon until we successfully address a number of key questions, including the following:

1. What are the masses of AGN black holes? As described below, we are making progress, but there are still areas where our understanding is dangerously incomplete, especially with regard to the magnitude of possible systematic errors.

2. What are the energetics of the accretion process? In particular, for the various types of AGNs what are the accretion rates and radiative efficiencies and how do these scale with luminosity? How much of the output is
in the form of kinetic energy (e.g., jets and absorbing gas) as opposed to radiation?

3. _How does the AGN mass function evolve over time?_ Does the accretion process contribute significantly to black-hole growth, and how do black-hole demographics evolve with time?

4. _What is the nature of the line-emitting and absorbing gas in AGNs?_ There is good reason to believe that these are somehow related to the accretion process, but there is no standard paradigm for the origin and role of these components in AGNs. This is one of the remaining outstanding mysteries in AGN structure.

2. _Masses of Black Holes in AGNs_

Ironically enough, the first reasonably secure SMBH masses were not measured in AGNs, but in quiescent galaxies, in which stellar or nuclear gas dynamical methodologies were employed (see Kormendy & Richstone 1995). The first and still highest precision AGN SMBH mass was determined from megamaser motions in NGC 4258 (Miyoshi et al. 1995). It was the fortuitous combination of source geometry and inclination that made this possible and, unfortunately, the method is not generally applicable to a broader range of AGNs. Most SMBH mass determinations in AGNs are based on emission-line reverberation mapping (Blandford & McKee 1982; Peterson 1993, 2001), which at this stage remains a rather crude tool; these masses are systematically uncertain to at least a factor of a few, and more accurate determination of these masses is an important current problem in AGN astrophysics.

2.1. _Reverberation-Based Black-Hole Masses_

Reverberation mapping makes use of the natural variability of AGNs to probe the central structure. The broad emission lines that dominate the UV/optical spectra of AGNs vary in response to changes in the continuum flux with a time delay, or lag, \( \tau \) that reflects the light-travel time across the broad-line region (BLR). If gravity dominates the dynamics of the BLR, then by combining the size of the BLR \( c\tau \) (as measured in a particular emission line) with the Doppler width \( V \) of the line, we can make a virial estimate of the central mass

\[
M_{\text{BH}} = \frac{k c \tau V^2}{G},
\]

(1)

where the constant \( k \) depends on the structure, kinematics, and projection (inclination) of the line-emitting region. It is the factor \( k \), and thus the level of possible systematic uncertainties in the reverberation method, that remains unknown.

While the fundamental assumption that the gravitational field of the SMBH determines the BLR gas dynamics is unproven, there are nevertheless good reasons to believe that the reverberation-based black-hole masses are meaningful and that the systematic errors are not large enough to render the method useless. First, different emission lines within an individual source give consistent
virial mass estimates, i.e., the emission-line time lags and line widths show a virial relationship, \( \tau \propto V^{-2} \). This has now been demonstrated for four AGNs (Peterson & Wandel 1999, 2000; Onken & Peterson 2002), and constitutes the best evidence to date that the BLR motions are determined primarily by gravity. The relationship is surprisingly tight given that the line-emitting regions for the high-ionization and low-ionization lines are not necessarily expected to have similar geometries. Second, AGNs follow the same relationship between black-hole mass and stellar bulge velocity dispersion that is seen in quiescent galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), constituting a strong demonstration that reverberation-based masses are comparable to stellar-dynamical masses in accuracy.

There are two important things that need to be done to secure our understanding of black-hole masses in AGNs and their relationship to the black holes in quiescent galaxies:

1. More intensive reverberation-mapping experiments that will allow determination of detailed two-dimensional transfer functions for multiple emission lines. This will lead to an understanding of the geometry and kinematics of the BLR and thus allow us to assess the magnitude of possible errors in reverberation-based masses from less well-sampled experiments. The data requirements for such experiments are well-understood (Horne et al. 2002) and there is still much that can be done with smaller facilities.

2. Direct comparison of stellar-dynamical and reverberation-based masses by applying both methods to common AGNs. This is in fact a very challenging exercise that can be attacked with an 8-m class diffraction-limited optical telescope, as described below.

### 2.2. AGN Black Hole Masses from Stellar Dynamics

A useful criterion for obtaining an accurate stellar-dynamical black-hole mass is spatially resolving the black-hole radius of influence

\[
\text{FWHM} = \frac{1.22 \lambda}{D} < \frac{r_s}{d},
\]

where \( D \) is the telescope aperture and \( d \) is the distance to the AGN. We can eliminate \( \sigma \) from eq. (2) by using the now well-known relationship between black-hole mass and bulge velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000a). The parameterization of Ferrarese (2002) gives

\[
\frac{M_{BH}}{M_\odot} = 1.66 \times 10^8 \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.58},
\]
and by combining eqs. (2) and (4), we obtain the criterion

$$\frac{M_{\text{BH}}}{M_\odot} > 1.1 \times 10^6 \left[ \frac{d(\text{Mpc})}{D(\text{m})} \right]^{1.78}. \quad (5)$$

This is the smallest black-hole mass that can be measured by stellar-dynamical methods as a function of distance $d$ and telescope diameter $D$. The strong dependence on distance favors measurement of nearby lower-mass black-holes over higher-mass distant black holes.

We plot eq. (5) in Figure 1 for two cases, (a) for Hubble Space Telescope (HST) with $D = 2.4$ m, and (b) for an diffraction-limited 8-m telescope. SMBH masses above these respective lines are large enough to be measurable by stellar-dynamical methods. Also plotted on this diagram are masses and distances for reverberation-mapped AGNs. This diagram shows that no more than two reverberation-mapped AGNs, NGC 3227 and NGC 4151, are even possible candidates for measurement of their central masses by stellar-dynamical meth-
ods with \textit{HST}. On the other hand, with a diffraction-limited 8-m telescope, a half-dozen or so AGNs are amenable to stellar-dynamical measurements of their SMBH masses. This is a marginally large enough sample to compare the stellar-dynamical and reverberation-based masses in a definitive way and to allow a reasonable assessment of the currently unknown systematic errors in the reverberation-based masses.

We note that attempts have been made to observe both NGC 3227 and NGC 4151, the two reverberation-mapped AGNs in which the black-hole radius of influence might be resolvable with \textit{HST} (Gary Bower, PI). Neither attempt has been successful, in both cases because at the time the AGN was observed it was in an anomalously bright state, swamping the Ca\textsc{ii} triplet absorption lines in the host-galaxy spectrum. Spatially resolved spectroscopy of both of these sources should be re-attempted with \textit{HST}, but perhaps on a target-of-opportunity basis when the active nucleus is in a relatively faint state.

An obvious question to ask is why must these measurements be made from space, since the Ca\textsc{ii} triplet is accessible from the ground? The main reason is that the strong contamination by the point-like nuclear source requires a truly diffraction-limited optical system. Ground-based adaptive optics systems are inadequate because of their low Strehl ratios (ratio of core intensity relative to a diffraction-limited point-spread function). Even in the low-luminosity AGNs, the weak stellar absorption features are completely washed out by the bright nuclear light. A second reason to observe from space is that at a fairly low redshift ($z \gtrsim 0.06$), the Ca\textsc{ii} triplet lines are redshifted into the strong telluric water vapor lines, thus making an already very difficult observation virtually impossible.

It is also worth noting that it is only Type 1 AGNs (i.e., those with prominent broad lines in the UV/optical) that are amenable to reverberation mass measurements; on the other hand, of course, this is an important method that needs further development since it can be applied to Type 1 AGNs at arbitrary distance. Black-hole masses can be measured by megamaser motions in only very special cases. Thus direct measurement of the central masses of most local galaxies, including many AGNs and related objects (e.g., Type 2 AGNs and LINERs), will require stellar-dynamical studies. These, we see from Fig. 1, are capable of measuring SMBH masses for $M_{\text{BH}} > 10^8 M_\odot$ out to a distance of $\sim 100 \text{ Mpc}$.

Comparison of stellar-dynamical and reverberation-based masses is of critical importance. Once this has been effected, we will be able to employ (a) reverberation-mapping methods to distant AGNs and (b) secondary methods that are tied to reverberation (e.g., Wandel, Peterson, & Malkan 1999, Vestergaard 2002) to estimate with confidence masses of the black holes in distant quasars and thus address how the quasar mass function evolves with time.

3. X-Ray/UV Absorption

During the last decade, largely because of moderate-resolution, high-sensitivity UV spectroscopy with \textit{HST} and soft X-ray spectroscopy with \textit{ASCA}, it has been recognized that UV and X-ray absorption features are ubiquitous properties of low-luminosity AGNs (e.g., Crenshaw et al. 1999). The origin of the resonance-
line and ionization-edge absorption features is poorly understood. In many instances, a strong case can be made that the UV and X-ray features arise co-spatially. The absorbing gas is always blueshifted relative to the emission lines, and multiple velocity components are often identifiable in the UV lines. The large column densities indicate that the flows are massive and in some cases can involve kinetic energy fluxes similar to the radiative output of AGNs. These properties suggest that they are the analogs of the polar outflows seen in young stars, i.e., they are a by-product of the accretion process. They may be somehow related to the much more massive outflows seen in about 10% of high-luminosity AGNs, those known as broad absorption line (BAL) QSOs. Perhaps most importantly, outflows from AGNs may have a profound feedback effect on star-formation processes in the host galaxies (e.g., Silk & Rees 1998).

The basic questions that need to be addressed are:

1. How much mass and kinetic energy is involved in these outflows, and how does this compare to the radiative output of AGNs?

2. How do the properties of the absorbers vary with other AGN properties, especially mass, luminosity, and radio loudness?

Only a very large space-based telescope can address these questions, as the sources are faint and high spectral resolution observations are required. Spectral resolution must be high enough to resolve the individual velocity components at their thermal width (\( \sim 10 \text{ km s}^{-1} \), or \( R = 30,000 \)), and the most important features are the UV resonance lines of abundant elements, notably C\textsc{iv}, Si\textsc{iv}, N\textsc{v}, and O\textsc{vi}. It is only in the lower-luminosity, lower-redshift objects that the individual velocity components are distinguishable from one another; we cannot address the same question simply by observing similar systems at higher redshift, as the absorption systems seen in the higher-redshift, higher-luminosity BALs are virtually continuous in velocity, making physical analysis extremely difficult and model dependent.

Variability of absorption lines in lower-luminosity AGNs, which occurs on time scales as short as a day, and detection and measurement of weak fine structure lines afford useful probes of physical conditions (mainly particle density) in the absorbing gas. Large collecting apertures are key to acquiring data of sufficient quality to utilize these tools.

4. Space Astronomy Infrastructure

A generally recognized principle in ground-based astronomy is that to make efficient use of new-technology very large telescopes, we must off-load essential work that can be done with smaller telescopes. During the early years of HST, the International Ultraviolet Explorer (IUE) served in this capacity. At the present time, only HST and the Far Ultraviolet Spectroscopic Explorer (FUSE), which do not have overlapping capabilities, are operational. By no later than

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\(^1\)This conclusion is dependent on the assumed “covering factor”, but this must be of order unity since absorption is present in virtually all nearby well-studied AGNs.
2010, there is likely to be no UV spectroscopic instrument generally available to the community. Even optimistic launch dates for an 8-m class UV telescope might mean a long hiatus during which no UV observations are possible and hard-won expertise in UV spectroscopy begins to evaporate. Moreover, once an 8-m UV/optical telescope becomes operational, either it will spend some fraction of its time doing truly critical UV observations that might equally well be done on a smaller, cheaper telescope, or this important work simply will not get done.

NASA’s contribution to astrophysics has been fantastically successful; in many areas of astronomy, and active galactic nuclei constitute only one example, UV data are simply too critical to do without. Large areas of astrophysics opened by UV astronomy cannot be allowed to die or languish when HST reaches the end of its lifetime. Certainly the case put forward at this meeting tells us that there are many frontiers in which we can progress significantly with an order-of-magnitude increase in collecting area and a factor of a few improvement in angular resolution. However, in our planning, we need to recognize the need for smaller workhorse facilities as part of the space astronomy infrastructure. These do not need to be glamorous telescopes laden with superlatives or science programs designed to address in a definitive way one of the handful of current big mysteries of the Universe. Neither would they be expensive; indeed, a 1-m class UV spectroscopic telescope fits into a Medium Explorer funding envelope (∼$200M) and expendable launch vehicle (e.g., Delta II with a 3-m fairing). In other words, we are fully capable of solving this problem essentially with existing resources because new funding lines would not necessarily be required. If we fail to solve this problem, we have no one but ourselves to blame.

5. Summary

The most dramatic impact that an 8-m space-based UV/optical telescope would have on AGNs would be to enable stellar-dynamical mass measurements out to a distance of ∼100 Mpc, a volume large enough to include several AGNs with reverberation-based mass measurements. The increase in collecting area relative to HST will enable far more detailed studies of the poorly understood, but energetically important, massive outflows seen in AGN spectra. The order-of-magnitude improvement in spatial resolution afforded by HST relative to ground-based observations has provided us with a wealth of information on the inner structure of AGNs (e.g., Pogge & Martini 2002) and on the evolution of AGN host galaxies. Certainly, another factor of a few improvement in resolution and the much larger collecting area will allow us push these frontiers forward.

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