

A Unified View of How the Study of Emission Lines Furthers Our Knowledge of AGN

Julian H. Krolik

*Department of Physics and Astronomy, Johns Hopkins University,
Baltimore, MD 21218, USA*

Abstract. A global view is given of how emission lines have been, and may in the future, be used to enhance our understanding of AGN. Lines from the microwave to the X-ray bands all contribute. Although we have a deep understanding of the physical processes by which line photons are generated, when the circumstances of line emission are complicated, models become too unreliable to provide strong inferences about the rest of the AGN system. At present, the lines which appear the most promising for helping answer the most important questions about AGN are the 22 GHz H₂O rotational transition and the 6.4 keV Fe K α fluorescence.

1. Overview

We have seen many presentations in this conference illustrating the enormous richness of emission-line phenomenology in AGN, as well as the great progress which has been made in understanding their excitation mechanisms and locating their excitation regions. In this contribution, I wish to step back for a moment and ask what the study of emission lines has gained us with respect to answering the most fundamental questions about AGN. Innumerable proposals requesting support for AGN emission-line work have been justified by the assertion that these lines may, much as emission lines from fusion plasmas do, serve as diagnostics of the entire system. I wish to examine to what extent this assertion has been borne out so far, and evaluate the prospects for success of this program in the foreseeable future.

The natural place to begin is to list the most important questions of AGN studies. To my mind, there are six that stand out clearly as being truly fundamental:

1. What is the power source? Is it really accretion onto a massive black hole?
2. What triggers nuclear activity in galaxies? Put another way, what regulates the accretion flow? Why was powerful nuclear activity so much more common at $z \approx 2-3$ than it is today?
3. Why is the continuum emission so broad-band? What balances the emission so that (to order of magnitude) the flux is constant per logarithmic frequency from the mid-infrared through hard X-rays?
4. How are jets accelerated and collimated? Why do they exist at all?

5. How can we relate the different varieties of AGN? What controls the choices in type of activity? For example, what creates the correlation between host morphology and radio (i.e., jet) power?
6. Does the existence of an active nucleus affect the evolution of the host?

Despite more than thirty years of intense activity in this field, most of these questions remain almost as open today as they were decades ago. We do have partial answers to questions (1) and (5), and emission-line studies have contributed significantly to providing those answers, but we have made little headway with the others. The central issue before us is how emission-line studies may be used to provide more complete answers to all these questions.

My review of the contributions of emission-line work will be ordered from the outside in, moving from the narrow-line region inward toward the black hole's event horizon.

2. Narrow Lines

Historically most of the effort devoted to analyzing narrow emission lines has been devoted to inferring the physical conditions in which they are excited. However, those details have told us little about other, more important issues. It is, rather, the shape of the region from which they are emitted that has revealed the greatest information. As reviewed, for example, by Wilson (1994), in a great many Seyfert galaxies the narrow-line region is a double cone whose apex coincides with the galactic nucleus. The edges of these cones are often so sharply defined and so straight that we can imagine hardly any other explanation for them but the projection of light rays (a particularly clear example is displayed in Fig. 1). That is, the existence of these cones tells us that there is a sharp-edged toroidal collimating structure close to the nucleus which permits ionizing photons to escape only within a certain angle of a preferred axis.

Several important conclusions follow immediately. The first is that AGN appear very different, depending on one's viewing angle. If an observer's line of sight lies within the favored cone, a strong ionizing continuum can be seen; if outside, the ionizing continuum (and likely the non-ionizing optical continuum also) will appear much weaker. Thus, there must be categories of AGN which are separated by empirical classification schemes but are intrinsically the same. Some of the now almost-universal support for the unification of type 1 and type 2 Seyfert galaxies (Antonucci 1993) stems from these observations of conical narrow emission-line regions.

Another conclusion is that the surprisingly weak impact AGN appear to have on their hosts is due in part to the collimation of ionizing photons so close to the nucleus. If the absorbing structure obscures $\sim 3/4$ of solid angle (as indicated by both the opening angles of the cones and the statistics of type 1 and type 2 Seyferts), then most of the host galaxy is protected from exposure to the AGN's ionizing continuum.

We are beginning to have some grounds for hope that narrow emission lines may also help us learn about the dynamics of the accretion flow at distances $\sim 100\text{--}1000\text{ pc}$ from the nucleus. Nelson & Whittle (1996) have discovered a

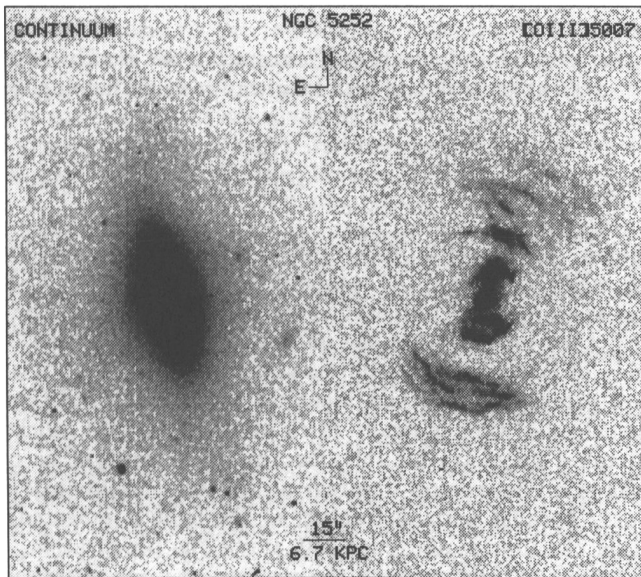


Figure 1. The ‘ionization cone’ in the type 2 Seyfert galaxy NGC 5252 (courtesy Z. Tsvetanov). *Left:* Continuum image of the galaxy *Right:* An image in a filter centered on redshifted $[\text{O III}] \lambda 5007$. The line emission is entirely within a sharp-edged double cone canted at an oblique angle with respect to the galactic axis.

strong correlation between the integrated width of the narrow lines and the velocity dispersion in their hosts' bulges. This correlation strongly suggests that narrow-line dynamics are dominated by gravity, although the spatial separation between the narrow-line region and the portion of the bulge where the stellar dispersions are generally measured makes the nature of this connection somewhat obscure. Detailed images of the line profiles, as provided, for example, by Fabry–Perot spectroscopy (Cecil et al. 1990), have the potential to reveal more about the nature of the forces directing gas towards the center.

Care will be necessary to successfully carry out this program, however. If one wishes to interpret gas kinematics as solely due to gravity, it is vital to omit those regions for which the character of the emission lines suggests shock excitation rather than photoionization. Contrasting the gas kinematics with the kinematics of adjacent stars should go a long way towards helping us make these distinctions.

3. Reflected Lines

In a classic paper, Antonucci & Miller (1985) demonstrated that broad Balmer emission lines, while invisible in the total flux of the classic type 2 Seyfert galaxy NGC 1068, are as strong in its polarized spectrum as in any type 1 Seyfert. Based on this finding, they inferred that the nucleus of NGC 1068 (and by the astronomical version of mathematical induction, the nuclei of most, if not all, other type 2 Seyfert galaxies) are in fact identical to the nuclei of type 1 Seyferts but for the accident of very optically thick obscuration that blocks our line of sight. The simplest geometry for this obscuration is toroidal, as confirmed by the conical shape of the narrow-line region. We see the intrinsic spectrum of the nucleus only because a small fraction of the light is reflected our way by electrons within the illuminated cone but above the obscuration, thus having unencumbered lines of sight to both the nucleus and our telescopes. The polarization created by the asymmetric disposition of these electrons on the sky allows us to identify the light as coming from the nucleus. Clearly, the presence of strong broad emission lines in the polarization spectrum served in this case as a marker of nuclear reflected light.

Many others (again, see the review by Antonucci 1993) have told the story of how polarized emission lines showed us the path to unification of the different Seyfert types, as well as (more speculatively) FR 2 radio galaxies and radio-loud quasars. Here I wish to emphasize a less well-known way in which emission lines from the mirror tell us more about AGN. Because the primary scattering mechanism is electron scattering, the profile of any reflected emission line with line-center frequency ν_o is both broadened [by $\delta\nu \approx \nu_o(kT_e/m_e c^2)^{1/2}$] and shifted [by $\delta\nu = \nu_o(\vec{v}/c) \cdot (\hat{n}_f - \hat{n}_i)$], where T_e is the electron temperature, \vec{v} the electrons' bulk velocity, and $\hat{n}_{i,f}$ are the initial and final directions of the scattered photons. Thus, the detailed profile properties of the polarized emission lines function as diagnostics of the physical properties of the mirror gas. For example, in NGC 1068, Miller, Goodrich, & Mathews (1991) were able to show that $T_e \approx 3 \times 10^5$ K, and that the H β line is shifted 600 km s^{-1} from systemic in the sense that the scattering medium is moving outward.

X-ray spectroscopy of the mirror gas has the potential to tell us even more. When our line of sight is in the equatorial plane of the obscuration, we see the mirror gas by virtue of its intrinsic emission and its reflection of the nuclear light (the specific spectrum predicted by a particular model is shown in Fig. 2). When this gas is warm (i.e., $T \approx 10^5\text{--}10^6$ K as in NGC 1068), electron scattering is the only scattering mechanism effective in the optical and ultraviolet bands, but numerous resonance lines enhance the gas's albedo in the soft X-ray band (Band et al. 1990; Krolik & Kriss 1995). Exactly which lines are present, and at what strength, depends on details of the physical conditions. In particular, we have good reasons, both observational (the line shift seen in NGC 1068 described in the previous section) and theoretical (Krolik & Begelman 1986, Balsara & Krolik 1993) to believe that this gas is flowing outward supersonically. In such a state, the gas absorbs somewhat more heat from radiation than it emits, so its temperature is not exactly the one given by thermal balance at a fixed ionization parameter. Consequently, to specify its ionization state one must define both the ionization parameter and the temperature. Dynamical models (e.g., the two papers just cited) suggest that Ξ (the ionization parameter defined as a ratio between radiation and gas pressure) is ~ 10 and the temperature is between 10^5 and 10^6 K. That is, the gas is slightly to the net heating side of the equilibrium curve near the region of that curve where it is marginally stable with respect to isobaric perturbations.

In Fig. 2, the spectrum has been smoothed with a Gaussian filter having a fractional frequency width of 0.05 in order to illustrate the richness of the structure which might be seen when X-ray spectrographs are able to obtain both resolution on this scale, and adequate signal-to-noise ratio (S/N) to make use of it. The features seen are actually blends of numerous lines, both intrinsic and reflected, whose shapes and strengths depend strongly on the state of motion of the mirror gas. Supersonic motion has an especially powerful effect on the reflected lines because it can move them from the flat part of the curve-of-growth to the linear part: the ratio between the velocity width of a line formed in a supersonic flow and the velocity width that line would have in a static gas is $\Delta v_{\text{wind}}/\Delta v_{\text{thermal}} \approx A^{1/2}\mathcal{M}$, where A is the atomic mass of the ion and \mathcal{M} is the Mach number of the flow. For those ions with resonance lines in the soft X-ray band, A is typically a few tens, so a supersonic velocity gradient can widen their lines by an order of magnitude.

A polar view of the mirror (and nucleus) provides us with a different view that is potentially equally informative in a complementary way. In this case, the features are more likely to be absorption than emission. Because the gas is only partially ionized, photons are removed from the nuclear continuum both by photoionization (true absorption) and by resonance scattering (as just discussed). Because the mirror covers at most $\sim 1/4$ of the solid angle around the nucleus, re-emission by radiative recombination and scattering from other lines of sight into ours replace only a small part of the photons removed by absorption and scattering. Viewed down the axis, then, the mirror acts as an absorption filter in the soft X-ray band.

It is fair to ask whether these predicted absorption features have ever been seen. If the mirror covers most of the solid angle left open by the obscuration, they must occur in many, if not most, type 1 Seyfert galaxies. Estimates of the fraction of the nuclear light reflected (e.g., Miller et al. 1991) indicate a

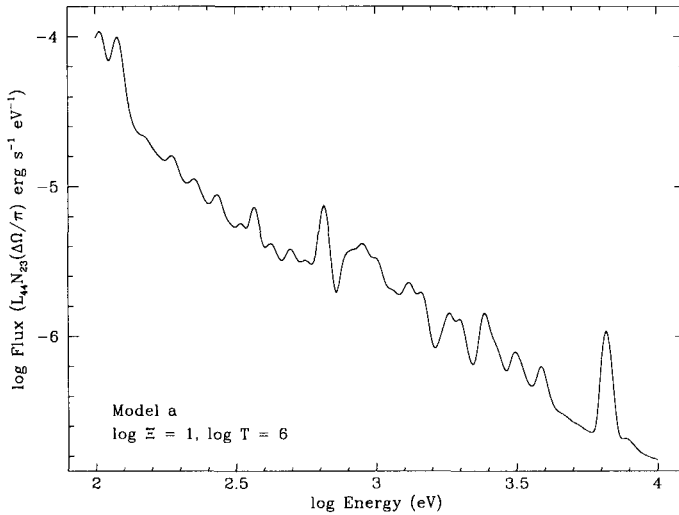


Figure 2. The EUV through X-ray spectrum of an obscured AGN, including both intrinsic emission from the mirror and resonance scattering, as predicted by a plausible model for its physical conditions (Krolik & Kriss 1995). The velocity distribution was assumed to be a Gaussian with a characteristic width equal to the sound speed.

column density $\sim 10^{22}$ – 10^{23} cm^{-2} , and, as we have seen, other measurements and theoretical arguments suggest a temperature in the range 10^5 – 10^6 K and an ionization parameter slightly larger than the value at which marginally stable thermal equilibria are found. When radiative-equilibrium models are fit to warm absorber spectra, very similar column densities and temperatures are found, and the ionization parameter is estimated to be very close to the marginally stable value (e.g., Netzer 1997). The mirror is, therefore, an excellent candidate to be the warm absorber. X-ray absorption-line studies may then provide another vehicle for learning about the character of the reflection region.

4. The Obscuring Torus

Emission lines from the obscuring material are also useful. Covering 3π of solid angle, it should be a source of substantial Fe $K\alpha$ emission if its column density is $\sim 10^{24}$ cm^{-2} or more (Krolik et al. 1994; Ghisellini et al. 1994). Since much of the obscuring matter is located 1–10 pc from the nucleus (for Seyfert-scale luminosities), the flux in Fe $K\alpha$ produced in the obscuring torus can only change on time scales of at least a few years. Therefore, very long-duration (10 yr or more) reverberation-mapping experiments might be able to map out the location of $K\alpha$ -emitting material in much the same way as shorter-duration reverberation mapping has given us much information about the location of broad emission-line gas (Maoz 1997). In at least one object (NGC 2992), incomplete time sampling

shows line and continuum variations of just the sort that could be used for this kind of experiment (Weaver et al. 1996).

The obscuring torus houses a still more powerful emission-line diagnostic in the form of 22 GHz H₂O masers (Braatz et al. 1996). Because interferometric techniques are so well developed at radio frequencies, and the angular scale of these masers is comparatively great (relative to other AGN structures), we are able to obtain genuine *images* of their location, without any sort of inferential guesswork. In the case of NGC 1068, we can see them outlining the inner edge of the obscuring torus (Greenhill 1997)!

Combining direct positional information with line-of-sight velocities, we can conduct detailed investigations of the torus dynamics using these maser spots. When, as in the case of NGC 4258 (Miyoshi et al. 1995), those dynamics are simple, it is possible to make very robust and precise inferences about the overall gravitational potential. Because the maser spots in that object are very closely confined to a thin (albeit slightly warped) plane, the spots travel in orbits that are very close to circular, and the magnitude of their orbital speed scales $\propto r^{-1/2}$, it is very hard to escape the conclusion that their motions are simple tracers of a point-mass potential created by a central mass of $3.6 \times 10^7 M_{\odot}$ whose size must be rather smaller than 0.1 pc.

On the other hand, there are also examples, such as NGC 1068 (Greenhill 1997), in which the dynamics are complicated. Interesting inferences may still be made, although the arguments are much less clean. In that case, there is a very large velocity dispersion at the innermost radii, and the upper envelope of the line-of-sight velocity scales rather more slowly with radius than $r^{-0.5}$; in fact, it is more like $r^{-0.3}$. If one nonetheless makes the simplistic assumption that the motions are due primarily to gravitational forces, the orbital speed at the innermost radius may be used to yield an order-of-magnitude indicator of the central mass, i.e. $M \approx rv^2/G \approx 10^7 M_{\odot}$. Compared to the bolometric luminosity of 10^{45} ergs s⁻¹ (Pier et al. 1994), this means that the luminosity relative to Eddington is ~ 0.6 . Inside the torus, the spectrum peaks in the mid-infrared where, for a normal dust-to-gas ratio, the opacity per unit mass is about ten times the value for Thomson scattering. Since the radiation force is the flux times the opacity, these observations demonstrate that radiation force *must* be important to the dynamics of the torus, as predicted by Pier & Krolik (1992).

These arguments illustrate an important general principle: simple sub-systems (e.g., the maser spots in NGC 4258) can be so thoroughly understood that they may be reliably used for inferences about the larger system in which they are embedded. But complicated systems (e.g., the maser spots in NGC 1068) are never well-enough understood that they may be used as springboards for inferences about larger issues. Inevitably we find ourselves fully occupied refining what we know about their *intrinsic* properties. That activity may be fascinating and well worth the effort, but it does not lead to information bearing on larger questions.

5. Broad Lines

Having said that, we are now equipped to consider the role of broad emission-line studies in the context of the broad sweep of AGN work. These lines offer a tremendous wealth and quality of data. In any one object, there are numerous different lines; the flux and profile of each one may be measured, and they vary in time in a way which is correlated with the continuum. At the same time, because the atomic physics of optical and ultraviolet line emission is well understood, it is possible to make very detailed calculations modeling their excitation and have some fair confidence that the results are meaningful. By comparing the relative strengths of different lines, one may infer the ionizing flux and pressure of the region where the lines are made; using the methods of reverberation mapping one may also constrain the distance from the central continuum source to the line-emitting region, thereby fixing all the unknowns of the problem. The pressure in the line-emitting regions might be taken as a measure of the pressure in the surrounding gas, which, if we were lucky, might be identified with the accretion flow through that range of radii. The line profiles give measures of bulk velocities; again, with good fortune, we might hope that these velocities indicate at least something about the velocities of surrounding matter. On this basis, many people have long expected that the study of AGN broad emission lines would cast a bright light on the field as a whole.

Unfortunately, there are numerous obstacles that may prevent us from ever reaching these goals. Reverberation-mapping experiments (again see the review by Maoz 1997) have shown that the broad-line region is a very complex place. The material responsible for individual lines is spread over at least an order of magnitude dynamic range in radius, and maybe more (Done & Krolik 1996). The ranges of radius corresponding to different lines are systematically offset from each other by sizable amounts (e.g., Clavel et al. 1991, Krolik et al. 1991). And the whole structure may change in time scales as short as a few years (Wanders & Peterson 1996).

Moreover, even obtaining a believable reverberation map is subtler than might be apparent at first sight. The effective S/N for a monitoring experiment is *not* the ratio of mean flux to rms error, but rather the ratio of rms flux change (that is, compared to the long-time mean of the flux) to rms error. In most monitoring experiments so far this ratio has been only a few; even in the best (measurements of the total flux in the C IV $\lambda 1549$ line in the *HST* campaign on NGC 5548 reported by Korista et al. 1995), it rose only to ~ 40 . Blending is frequently a problem, corrupting otherwise easily measured lines. It is particularly frustrating that N V $\lambda 1240$ almost always strongly contaminates Ly α .

Even when the data are very clean, inversion of the line and continuum time series to obtain the response function *requires* insertion of some *a priori* information in order to achieve numerical stability. This automatically means that *all* response functions are model-dependent on some level (Fig. 3). It is possible to make this model-dependence relatively benign, but it is always present. As Fig. 3 makes plain, while there are certain features that are robust with respect to changes in the model assumptions, there are definitely others which are clearly model-dependent.

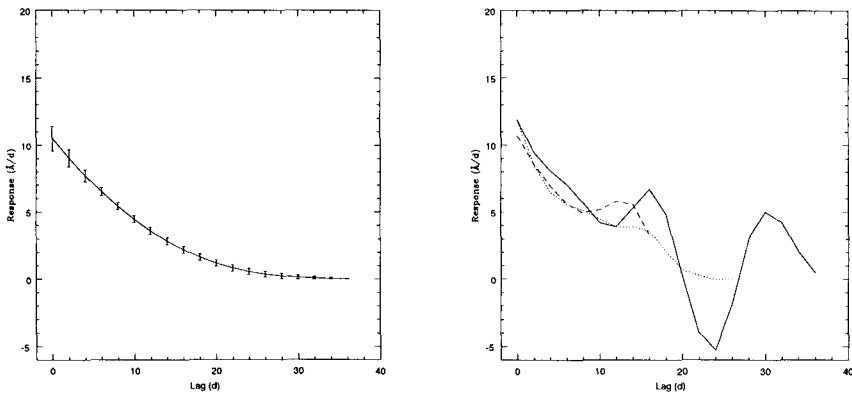


Figure 3. The model-dependence of response functions. *Left*: A solution for the total C IV flux data from the NGC 5548 *HST* campaign which was tuned to yield the smoothest response function consistent with the data. *Right*: Response functions obtained from the *same* data, but for a range of maximum lengths, and reducing the relative weight given the smoothness constraint so that it has no more weight than the data.

To go from the 1-d map given by the response function to a true 3-d picture of the emission-line region one inserts far greater model-dependence. A response function is no more than a projection of the marginal response of line emissivity onto the surfaces of constant delay *relative to our line of sight*. We certainly cannot expect our line of sight to be a symmetry axis for any but a tiny minority of AGN, so we must make some choice about the real symmetry in order to transform the response function into a 3-d description. This procedure is obviously highly non-unique.

The potential pay-off from reverberation mapping becomes still greater when separate maps are made not just for different emission lines, but for different portions of the lines, separated by line-of-sight velocity. There is no change in the technical issues; the only respect in which velocity-resolved reverberation mapping is more difficult than integrated-flux reverberation mapping is the reduction in S/N due to chopping up each line into several segments. What makes the scientific yield so much more interesting is that the solution provides a constraint on the *kinematics* of the line-emitting gas, which we may hope will ultimately provide clues about their *dynamics*.

Unfortunately, the remarks made above about non-uniqueness are underscored by the current state-of-the-art in velocity-resolved reverberation mapping. Four dramatically different models for the NGC 5548 C IV $\lambda 1549$ response have been put forward, all claiming qualitative consistency with the data (in order of publication, Wanders et al. 1995; Done & Krolik 1996; Chiang & Murray 1996; Bottorff et al. 1997). The first argues that the velocities are all random, but

that a 'shelf' exists in the total-flux response similar to that appearing in the solid curve of Fig. 3b. They interpret this shelf as due to strong anisotropy of the ionizing continuum, rejecting the numerous other possible interpretations of such a feature. The second finds no evidence against spherical symmetry and isotropy in the emission. On the other hand, while their analysis shows (like that of the first paper) that the line's red and blue cores respond similarly, they differ from Wanders et al. in discovering that the red wing responds significantly more quickly than the other line segments, especially the blue wing. On this basis they suggest that the line motions are predominantly random, but there is a net radial infall. The third posits a rotating wind driven off a flat accretion disk by radiation pressure, and argues that the anisotropy of line emission in this sort of situation creates leading response in the red wing despite the outflow. The fourth also favors a disk wind, but driven by rotating magnetic fields.

The only hope we have to break this degeneracy is to impose the twin thresholds of physical self-consistency and quantitative (e.g., as measured via a statistic such as χ^2) consistency with the data. None of the above models passes both tests fully: the first two are physically *ad hoc*, while the second two are based on incompletely worked out dynamical models; only the second has even computed the χ^2 for its predictions.

Let us suppose that over the next few years we are able to arrive at a generally accepted picture of the kinematics of the broad-line region. How much will we be able to learn then? For a number of years, it has been commonplace in the literature to assume that the dynamics of the line-emitting material are dominated by the gravitational force of a massive central object, and that its mass could be estimated simply by computing rv^2/G . Unfortunately, these statements have as yet little or no justification.

First of all, we do not yet have any clear indication regarding which forces dominate the broad emission-line gas. In any gas that is optically thick over much of the continuum bandwidth, the ratio between the mean outward radiation force and the inward gravitational force due to the central object is

$$\frac{F_r}{F_g} \approx \frac{L/L_E}{\tau_T},$$

where L/L_E is the luminosity in Eddington units and τ_T is the optical thickness of the gas in Thomson units. We do not know with any confidence either of the two dimensionless numbers taken in ratio on the right-hand side of this equation. Both have been suggested to lie anywhere in the range 10^{-3} to ~ 1 . We can hardly state with confidence, therefore, that radiation force is clearly negligible relative to gravity.

Other forces may also play a role. While we have good reason to believe that the broad emission-line gas occupies only a very small fraction of the volume of its region, we have no idea what sort of gas fills the rest of the volume. Friction against this other gas could be very important to the emission-line gas. Similarly, we have even less idea about the state of magnetic fields running through the region, so we have no sensible way to even begin to limit $(\nabla \times \vec{B}) \times \vec{B}$ relative to gravity (see, for example, Rees 1987 or Emmering et al. 1992).

Indeed, contrary to what is often said, rv^2/G does not even provide a limit. If other forces dominate gravity, the number it gives for the central mass is an

overestimate; if other forces are comparable to gravity and partially cancel it, this number gives an underestimate.

Even if in the future we are able to eliminate significant roles for forces other than gravity, there are several complications that stand between us and using broad-line kinematics to measure the mass of the central black hole. First of all, it is essential to have a complete picture of the kinematics, not just measures of the characteristic size and velocity. As we have just finished discussing, one of the most important results of the reverberation-mapping program has been to demonstrate that emission-line material exists over a very broad range of radii. Simply inserting some sort of weighted-mean radius and (differently) weighted-mean velocity in the formula rv^2/G can be extremely misleading. In fact, one way we might some day demonstrate that the motions are due to the gravitational force of a point-mass would be to use velocity-resolved reverberation maps to verify that $v \propto r^{-1/2}$ (intriguingly, Done & Krolik 1996 suggest that the scaling of v with r is a good deal slower than this). Furthermore, although rv^2/G does provide an order-of-magnitude estimator of the central mass in the event that the motions are purely orbital, it is no better than that without additional information about the shapes of the orbits. When the orbits are exactly circular, the central mass is exactly rv^2/G ; but if the velocities at any given location are distributed randomly in direction, the central mass is three times greater.

Finally, if, as has long been hoped, we are to eventually use the broad emission lines as accretion diagnostics, we must find some way to relate the gas which emits them to the accretion flow. If the broad emission-line material is *not* moving inward, it cannot itself be taking part in the accretion process, although it might perhaps be nearby. Learning how to draw this relation is unlikely to precede a clear understanding of the line-emitting matter's dynamics. On the other hand, if the broad-line material is going in, we might speculate that it comprises the accretion flow, or is at least a part of it. To feed a typical Seyfert galaxy with a luminosity $\sim 10^{44}$ ergs s^{-1} , an accretion rate of $\sim 0.02L_{44}(e/0.1)^{-1} M_{\odot} \text{ yr}^{-1}$ is needed, where e is the accretion efficiency in rest-mass units. If one interprets the reverberation mapping of NGC 5548 as showing net inflow, the associated mass inflow rate is

$$\dot{M} \approx 0.001 N_{22} r_{10} v_{1000} \left(\frac{dC/d \ln r}{0.1} \right) M_{\odot} \text{ yr}^{-1},$$

where the (not well-determined) column density of the gas has been scaled in units of 10^{22} cm^{-2} , the radius in units of 10 lt-d, the velocity in units of 1000 km s^{-1} (roughly the best-fit number for the net radial speed found by Done & Krolik 1996), and C is the covering factor of the gas around the central source of radiation. Thus, even if one accepts the net inward-flow interpretation of the reverberation mapping, the line-emitting stuff may not be more than a small part of the total accretion. If that is so, we are still faced with the problem of understanding its dynamics well enough to know how to use it as a tracer of the bulk of the accretion.

Broad emission lines, therefore, despite (or perhaps because of) their phenomenological richness appear to be a prime example of the general principle enunciated in the previous section. They are so complicated that we may never

go beyond studying their *intrinsic* properties; using them to answer fundamental questions about the global AGN system may forever be beyond our reach.

6. The Accretion Disk

Finally we come to the innermost observable portion of any AGN, the accretion disk. By far the strongest emission line that we can expect to be emitted from the accretion disk is the Fe K α fluorescence line, but numerous other, weaker lines are also possible, mostly with energies ~ 1 keV (e.g., as described by Życki et al. 1994). Improvements in both the energy resolution of X-ray spectrometers and their *S/N* might eventually allow us to study the weaker lines, but in the meantime, the Fe K α line, which has an equivalent width that is commonly a few hundred eV, is already very informative (Nandra 1997). The discovery, enabled by the *ASCA* satellite, that this line commonly has a FWHM between 20,000 and 70,000 km s $^{-1}$ is a dramatic signal that relativistic motions are taking place deep inside AGN. That the profile is frequently offset to the red also suggests a significant gravitational redshift, and the plausible supposition that those relativistic motions are simply orbital motions in a relativistically deep gravitational potential.

Moving from qualitative to quantitative results will take a great deal more effort, however. Several detailed calculations must be performed in order to adequately model the K α emission in these circumstances, and we do not yet know how to carry out every step in these calculations.

First, the line is excited by fluorescence, so this entails a radiation transfer calculation of modest scope to determine how many K-edge photons reach how deep into the material. If the opacity of the material to K-edge photons were independent of ionization state, this would be a straightforward calculation. However, because a significant part of the opacity at energies above 7.1 keV (the edge energy for neutral Fe) is due to other elements, one must also calculate the ionization structure self-consistently. This, in turn, requires a model of the underlying disk structure.

Unfortunately, we do not yet have a satisfactory description for the equilibrium state of accretion disks around black holes. The standard Shakura–Sunyaev (1973) equilibrium is thermally unstable when the accretion rate is more than $\sim 10^{-3}$ of the Eddington rate (Shakura & Sunyaev 1976), and we do not know what other equilibrium replaces it.

Nonetheless, if one assumes a model for the (un-irradiated) density and temperature in the disk, it is possible to then compute in a self-consistent manner its density, temperature, and ionization structure when irradiated by X-rays (see, for example, Ross & Fabian 1993 and Życki et al. 1994). It is important to know the ionization distribution of Fe as a function of depth because the energy of the K α photon depends on ionization state. The dependence is weak until the atom is mostly stripped, but can be significant if highly ionized stages are reached: the K α line in H-like Fe has $\sim 8\%$ greater energy than the line emitted by neutral Fe, a difference comparable to the frequency shifts expected from relativistic effects.

An important uncertainty in any such emission model is the Fe abundance. Several opacity processes compete with Fe K-shell photoionization, so the frac-

tion of the photons in the Fe K continuum which actually photoionize Fe is considerably less than unity. If the Fe abundance is solar and the material is weakly-ionized, the sum of photoionization opacities due to lower- Z species is about equal to the Fe opacity at 8 keV. The Compton opacity is also comparable to the Fe opacity, so a fraction of the Fe K continuum photons can be reflected without being absorbed by any atom. Clearly, in these circumstances the ultimate $K\alpha$ yield is quite sensitive to the Fe abundance, which could easily differ from solar by factors of a few.

After the spectrum of the initial photons is calculated, one must next find the angular distribution and spectrum with which they emerge from the disk surface. Note that the angular distribution with respect to the system axis may be different from the angular distribution with respect to the local surface normal if the disk surface is curved. Some of the line photons may be absorbed by photoionizing lower- Z atoms before escaping from the disk, others may change direction and energy as a result of electron scattering. With the quality of modern X-ray spectroscopy, the last effect is significant: Compton recoil losses are about 1% per scatter, and thermal broadening is about $7(T_e/10^7\text{K})^{1/2}\%$ per scatter. If the abundance of Fe ionization stages with L-shell vacancies is significant, resonance scattering can also occur. In the ionization stages with at least one L-shell electron, the $K\alpha$ photon has a high probability of being lost as a result of resonance scattering because the excited atom is more likely to de-excite by Auger ionization than by re-radiation. The net result of all these processes is moderately strong limb-darkening, but the degree of limb darkening is a strong function of photon energy (Matt et al. 1996).

Thirdly, the relativistic effects must be evaluated (as in Matt et al. 1993 and Laor 1991). There are several. The photon energies and directions must be transformed from the rest frames of the disk's fluid elements to the observer's frame. In addition, if we are considering regions not far outside the black hole's event horizon, the photon trajectories suffer substantial bending by the gravitational field. All these effects clearly depend strongly on the initial directions of the photons, a fact which emphasizes the importance of a good calculation of their fluid rest-frame angular distribution.

Finally, each of these previous steps is implicitly a local calculation. Each must be performed separately for different rings in the accretion disk, and then added with weights appropriate to the run of emissivity with radius. That distribution is, obviously, almost totally unconstrained *a priori*, so our procedure will usually be to guess some simple form, compute its predictions, and compare to the data.

To date, there is no model calculation in which all these elements have been combined. Perhaps the single most complete is that of Matt et al. (1996), in which the ionization balance as a function of depth, local angular distribution, and relativistic effects are all computed for two sample emissivity laws. However, even in such a complex model there are still unresolved issues that can be expected to change the predicted profiles at the order unity level. First, of course, is the underlying disk model — they chose the standard Shakura–Sunyaev solution, despite its instability. Second, the ionizing radiation transfer is treated in the diffusion approximation, despite the fact that few ionizing photons penetrate to Thomson depths of more than ~ 1 . Finally, their relativistic calculation is limited to the Schwarzschild geometry, whereas realistic black holes are likely

to be much better described by the Kerr metric. The line profiles and angular distributions predicted by the two metrics are substantially different when there is much line emission from within a few gravitational radii (Laor 1991). Thus, it is still a bit premature to expect quantitative conclusions from fits of measured line profiles to disk-emission models.

Another line of approach may offer additional insight: variability analysis in the spirit of reverberation mapping. If the line emission comes from a region comparable in size to the continuum source (as would be predicted by the disk models), one of the key assumptions of ordinary reverberation mapping — that the line-continuum delay depends only on the position of the line-emitting material — is no longer valid. The continuum source distribution is also important because the light-travel times from different parts of the continuum source to a particular part of the line source are significantly different. Nonetheless, it is still possible to work out relationships between light-travel times and source sizes that are analogous to those used in conventional reverberation mapping. With adequate data, constraints may then be put on the source size and geometry.

The difficulties in carrying out this monitoring program have to do with the very short time scales that are relevant. If the Fe $K\alpha$ photons are emitted from within 10 gravitational radii of the black hole, the light-travel times across the system are only $\sim 10^3(M/10^7 M_\odot)$ s. Because X-ray variability power spectra are generally rather 'red', the amplitudes of variations on such short time scales are quite small. Even the very large effective-area detectors on *XTE* may provide only marginal S/N on even the brightest sources. The much smaller effective area of *AXAF* at 6 keV will severely handicap its use for such studies. Moreover, the low-Earth orbit in which many X-ray telescopes are placed in order to avoid radiation backgrounds poses another problem: most sources are occulted by the Earth for ~ 3000 s out of every 5400 s. A window function of this sort makes observations of variability on 1000 s time scales extremely difficult. Only if a sufficiently bright source can be found near enough the pole of the orbit to be continuously in view does this sort of experiment become feasible.

7. Scorecard

From this quick survey of the achievements of AGN emission-line studies we may extract a list of how the different sub-areas have propelled us along the path toward a fundamental understanding of AGN. Ironically, the greatest qualitative advances have come from two areas in which efforts to date have been comparatively small scale: maser-spot kinematics, and Fe $K\alpha$ spectroscopy. Study of the former has yielded by far the cleanest measurement of a central mass concentration in a galactic nucleus, as well as the tightest upper bound on its size. Work with the latter technique has produced the strongest evidence we have for the existence of relativistically deep potentials in AGN. We may hope for more quantitative results from Fe $K\alpha$ spectroscopy in the future, but they will require improvements in both data and models. A variety of other uses of emission lines — maps of the region radiating the narrow emission lines, spectropolarimetry revealing reflected emission lines — have been of great aid in the construction of unification models for otherwise apparently dissimilar classes of AGN. Now that we realize that AGN can look very different depending on the observer's viewing

angle, the presence of broad emission lines can be used as a crude indicator of our angle relative to the system axis. However, despite the enormous amount of work lavished on studies of broad emission line flux ratios, profiles, and variability, and the substantial advances in our knowledge of how and where these lines are produced that have come from these studies, we have not gained from them any significant information bearing on the most important questions of AGN research. It remains to be seen whether further efforts can break through the restraints imposed by the complexity of their emission, and reach our true goals of solving the problems posed in §1 of this review.

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