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THE QUEST FOR THE DYNAMICAL SIGNATURE OF ACCRETION DISKS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

The most direct, dynamical evidence for the presence of accretion disks in the central engines of active galaxies comes from observations of very broad, double-peaked emission lines. These "exotic" line profiles are found preferentially in radio-loud AGNs; they occur in about 10% of such objects. Their hosts share a number of common spectral properties which can be understood consistently in the context of a physical model for line-emitting disks. Very recent UV spectroscopy of double-peaked emitters with the *HST* provides very strong additional evidence for an accretion disk origin of the double-peaked Balmer lines. Variability of the line profiles is an independent and complementary approach for assessing the applicability of disk models to double-peaked emission lines. Moreover, once an accretion disk origin is established, the variability of the line profiles will provide a wealth of information on the structure and dynamics of the disk (much like in cataclysmic variables). The dynamical time in the line-emitting part of the disk is expected to be about six months, which is much longer than the light crossing time. Thus the slow variations of the line profiles over time scales of a few years can be used to test models for the dynamical behaviour of the disk. These models include spiral waves in the disk, elliptical disks, supermassive binary black holes, and interactions of the disk with stars or gas clouds in its vicinity. Tests can be carried out using spectra of double-peaked emission lines with high signal-to-noise ratio taken every few months and spanning a baseline of several years.

INTRODUCTION

Our current working scenario for active galactic nuclei (hereafter, AGNs) rests in large part on the properties of the broad emission lines. These are thought to originate in photoionized gas clouds orbiting an intense source of energetic (UV and X-ray) photons, as shown in Figure 1 (*top*). The dynamics of the line-emitting gas, which determine the observed broad emission-line profiles, are poorly understood. The "central engine" (Figure 1, *bottom*) is likely to be powered by accretion of gas, although its detailed nature is obscure. The heart of the AGN central engine is thought to be supermassive black hole (a "monster") which accretes matter from the host galaxy. By analogy with stellar accretion-powered systems such as cataclysmic variables and low-mass X-ray binaries, the accretion flow very close to the monster is thought to form an equatorial accretion disk (see Figure 2). From a theoretical perspective, accretion disks are appealing because they provide an efficient mechanism for dissipating the angular momentum of the accreting matter via viscous stresses (see the widely adopted model of Shakura and Sunyaev 1973). Moreover, they are regarded as an essential ingredient for the production of relativistic jets (Blandford and Znajek 1976; Blandford and Payne 1982; Blandford 1990), which are observed in a considerable fraction of AGNs – not only in the powerful

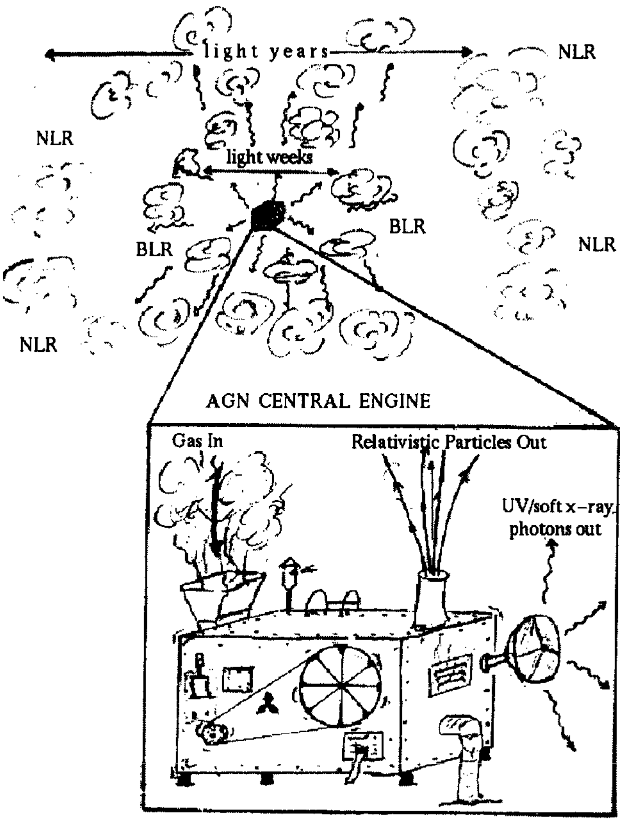

Fig. 1. A schematic representation of the central regions of an active galactic nucleus (top). An enlarged view of the central engine is also shown (bottom).

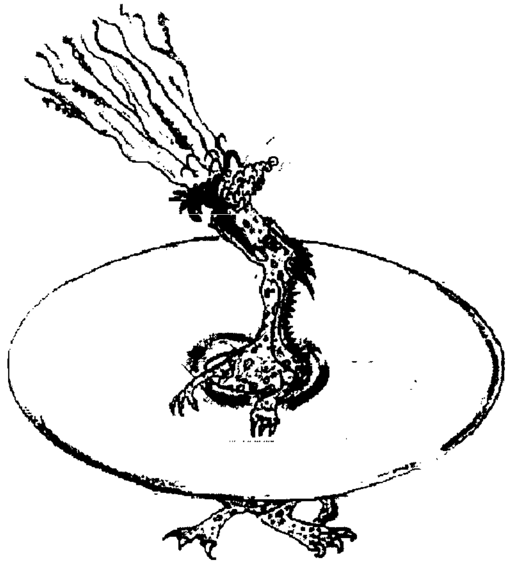

Fig. 2. By analogy with stellar accretion-powered systems, the monster that lives inside the central engine is thought to be fed via an equatorial accretion disk.

radio galaxies and radio-loud quasars (*e.g.*, Bridle and Perley 1984; Miley 1980) but also in a fair number of Seyfert galaxies (*e.g.*, Ulvestad and Wilson 1984*a*, *b*).

The presence of accretion disks had received limited and indirect observational support until very recently. Even though models for the thermal emission from an accretion disk have provided a reasonably good description of the "big blue/UV bump" observed in the spectra of quasars (Edelson and Malkan 1986; Sun and Malkan 1989), the expected Lyman edges and the polarization signature expected from the atmosphere of the disk have proven quite elusive (Antonucci *et al.* 1989; Koratkar *et al.* 1991; Antonucci, 1992; Koratkar *et al.* 1995). The absence of these signatures can be accommodated by invoking a combination of relativistic effects and absorption opacity which wipe out the polarization signature, and Doppler and gravitational shifts which broaden the Lyman edge beyond recognition (Laor and Netzer 1989; Laor *et al.* 1990; but see also the more recent calculations by Blaes and Agol, 1996). The result, however, is not aesthetically pleasing, since observational tests become more difficult. Hard X-ray observations yield additional support for the presence of disks. The X-ray spectra of Seyfert galaxies are described well by a model that includes Compton reflection of the primary X-rays from dense, cool matter, which is interpreted as the accretion disk itself (*e.g.*, Pounds *et al.* 1989; Turner and Pounds 1989; George and Fabian 1991; Nandra and Pounds 1994 – but see also Nandra and George 1994).

All the observations described above provide information about the thermodynamic state of the emitting gas, but tell us very little about its geometry and kinematics. The characteristic kinematic signature of a

Keplerian accretion disk, double-peaked emission lines analogous to those found in the spectra of cataclysmic variables (*e.g.*, Young and Schneider 1980; Young *et al.* 1981; Marsh 1988), was nowhere to be found. It is, therefore, extremely interesting and quite encouraging that several examples of double-peaked emission lines were uncovered very recently in AGN spectra. These examples fall in two broad categories.

(a) *Double-Peaked Balmer Lines in the Optical Spectra of Broad-Line Radio Galaxies*: The current collection of radio-loud AGNs with double-peaked emission lines includes almost 20 objects, most of which were found in the spectroscopic survey of Eracleous and Halpern (1994), although a small number of them were known before this survey.

(b) *Disk-Like Fe Kα Lines in the X-Ray Spectra of Seyfert Galaxies*: With the advent of *ASCA* and the capability for high-resolution X-ray spectroscopy the profiles of the Fe Kα lines in the X-ray spectra of AGNs were found to be extremely broad and asymmetric, with full widths at zero intensity approaching a third of the speed of light (Mushotzky *et al.* 1995; Tanaka *et al.* 1995). In most cases the line profiles can be described very well by models attributing the emission to the inner parts of a highly relativistic accretion disk (Tanaka *et al.* 1995; Nandra *et al.* 1996)

Disk-like emission line profiles provide us with a tool for studying the dynamical behavior of AGN accretion disks. Because of the technological limitations associated with X-ray spectroscopy, and the practical limitations of space-based observations, the optical Balmer lines are much more convenient for studies of this kind. The following sections, therefore, include a review of the observational properties of radio-loud AGNs with double-peaked emission lines and present the case for the origin of these lines in an accretion disk. Included is also a summary of dynamical phenomena in accretion disks that can be studied via the variability of the line profiles and a description of observational efforts in that direction.

RADIO-LOUD AGNs WITH DOUBLE-PEAKED EMISSION LINES

General Observational Properties

The current collection of double-peaked emitters (i.e., radio-loud AGNs whose Balmer line profiles feature double peaks or twin shoulders) comprises 20 objects. A dozen Hα profiles from this collection can be fitted quite well with a model attributing the emission to a relativistic, Keplerian disk, developed by Chen *et al.* (1989) and Chen and Halpern (1989), as shown in the two examples of Figure 3. The studies of Eracleous and Halpern (1994, 1996) establish the latter group of objects, the "disk-like" emitters, as a distinct subclass of radio-loud AGNs *on the basis of a number of additional properties that they possess*, namely:

(a) Their broad Hα lines are, *on the average*, twice as broad as those of typical broad-line radio galaxies and radio-loud quasars (mean full widths at half maximum of 12,800 km s^{-1} *vs.* 5,900 km s^{-1} for all other radio-loud AGNs).

(b) Starlight makes up about half of the nuclear continuum of disk-like emitters in the vicinity of Hα, in marked contrast to a contribution of less than 10% in all other radio-loud AGNs.

(c) The equivalent widths of low-ionization, forbidden lines ([O I]λ6300, [S II]λλ6717,6731) of disk-like emitters are, *on the average*, twice as large as in other radio-loud AGNs.

(d) The oxygen line ratios [O I]λ6300/[O III]λ5007 and [O II]λ3727/[O III]λ5007 are systematically higher in disk-like emitters than in in typical radio-loud AGNs.

Disk-like emitters (and double-peaked emitters in general) are found preferentially among radio-loud AGNs, but they do not have any special radio properties (most, but not all, are powerful, double-lobed radio sources). Their optical spectroscopic properties are reminiscent of LINERs (low-ionization nuclear emission-line regions; Heckman 1980), and in fact, the prototype, Arp 102B, is a certified LINER on the basis of its oxygen line ratios. The association with LINERs has been underscored by the abrupt appearance of broad, double-peaked Balmer lines in LINERs and LINER-like objects that did not previously have them, such as NGC 1097 (Storchi-Bergmann *et al.* 1993, 1995), Pictor A (Halpern and Eracleous 1994; Sulentic *et al.* 1995), and M81 (Bower *et al.* 1996). In addition to the properties listed above, which are observed in all of the members of this class, a small number of well-studied objects exhibit a number of unusual characteristics which are atypical of AGNs. In particular:

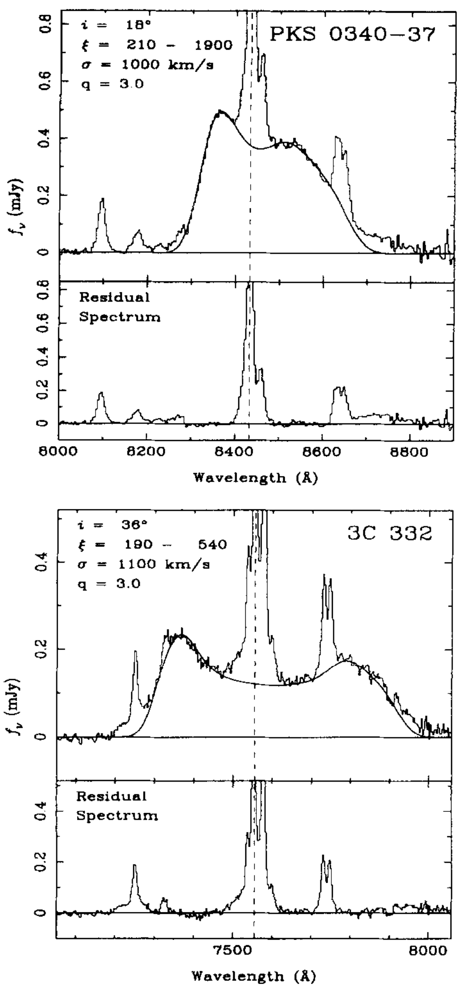

Fig. 3. Examples of double-peaked Hα lines and accretion-disk fits. Galaxy templates were used to subtract the continuum. According to the model in Figure 5, the line emission originates in the outer part of the disk viewed at inclination angle i, between radii r_1 and r_2 (or ξ_1 and ξ_2 in units of GM/c^2). The line emissivity of the disk varies as ξ^{-q}. Local broadening of the line, possibly due to electron scattering or turbulence, is parameterized by a Gaussian of width σ.

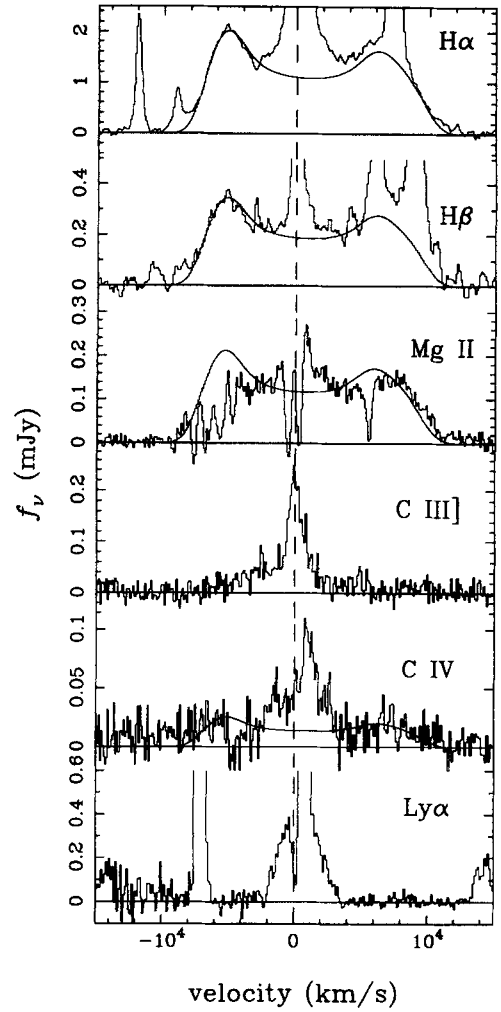

Fig. 4. A compilation of profiles of broad UV and optical lines of Arp 102B. All of the permitted low-ionization lines exhibit extremely broad, double-peaked profiles while the profiles of all high-ionization lines are only moderately broad and bell shaped. Double-peaked Lyα is completely absent. The best-fitting Hα disk-model profile is superposed on the observed profiles of Hα, Hβ, Mg II, and C IV for comparison.

(a) The broad-band spectral energy distributions of 3C 390.3 and Arp 102B do not show the usual blue/UV bump. Rather the peak of the power output of the nucleus is in the infrared, around 25 μm (Golombek *et al.* 1988; Chen *et al.* 1989). The weak optical non-stellar continuum observed in all of the double-peaked emitters is probably a manifestation of the absence of a blue/UV bump.

(b) In the UV spectrum of Arp 102B (observed with the *HST*; Halpern *et al.* 1996) the only line that is as broad as the Balmer lines is Mg II. All of the high-ionization lines, including Lyα, have bell shaped profiles with a width corresponding to about 3500 km s^{-1}, much less than the width of the low-ionization lines (see Figure 4). The absence of a double-peaked profile in Lyα is particularly striking and cannot be attributed to reddenning, since that would be inconsistent with the observed Balmer decrement and Mg II/Hβ ratio.

The spectroscopic properties of disk-like emitters and their preferential occurrence in radio-loud AGNs are among the defining characteristics of this class of object (as important as the double-peaked emission lines themselves) and should be explained by any model or scenario that tries to explain the origin of the double-peaked lines. These unusual properties, and in particular the absence of a disk-like Lyα line in Arp 102B, make a very strong case for the consideration of unconventional models for the line-emitting gas in disk-like emitters. It is no longer reasonable to hope that a single model will account for all broad lines in all AGNs, and especially not those in disk-like emitters.

Accretion Disk Emission as the Origin of Double-Peaked Lines

The accretion disk model of Chen *et al.* (1989) and Chen and Halpern (1989) goes a very long way towards explaining the unusual properties of disk-like emitters. Not only do the predicted line profiles fit the observed lines quite well, but this model also provides a self-consistent framework within which all of the known properties of this class of objects can be understood. In order to balance the energy budget of the line-emitting disk, Chen and Halpern (1989) proposed that the line emission is driven by illumination of the outer disk from an elevated structure that occupies the inner disk. The proposed elevated structure was an ion-supported torus, suggested in the context of AGNs by Rees *et al.* (1982), and resurrected recently as the advection dominated disk by Narayan and Yi (1994, 1995). An ion torus is likely to form at low accretion rates and provides a funnel which can serve to collimate powerful radio jets. This particular feature explains the preferential association of disk-like emission lines with radio-loud AGNs. A schematic representation of the disk structure is shown in Figure 5.

The emission spectrum of an ion torus differs considerably from the thermal spectrum of a "standard", geometrically thin, optically thick accretion disk. Because the main cooling mechanism of the ion torus is the Comptonization of bremsstrahlung and cyclo-synchrotron photons, the emergent spectrum has the form of a hard X-ray power law rather than the usual "big blue/UV bump" (Narayan *et al.* 1995; Di Mateo and Fabian 1996). The absence of the UV bump allows the starlight to make a significant contribution to the optical continuum, in agreement with observations. The UV bump itself is in fact *absent* from the spectra of Arp 102B and 3C 390.3. The unusually strong low-ionization lines can also be understood in this context, as the result of the power-law ionizing spectrum and a low ionization parameter †. Photoionization models of the emission-line spectra of LINERs by Halpern & Steiner (1983) and Ferland & Netzer (1983) show that the relative strengths of the emission lines of LINERs can be reproduced if one assumes a power-law ionizing spectrum and a low ionization parameter. These models are the basis for the interpretation of the narrow-line spectra of disk-like emitters, which are reminiscent of LINER spectra: when the radiation from the torus illuminates the (otherwise normal) narrow-line region it results in the production of unusually strong low-ionization lines, exactly as observed in disk-like emitters.

The remaining unusual properties of the well-studied disk-like emitters can also be understood in the context of the ion torus model, and in fact provide very strong support for it. First, the dramatic difference between the profiles of the Lyα and Balmer lines of Arp 102B can be interpreted with the help of models of photoionized accretion disks by Dumont and Collin-Souffrin (1990*a*, *b*, *c*) and Rokaki *et al.* (1992). Since the emission originates in the dense matter of the X-ray illuminated disk (density of order 10^{15} cm^{-3}, column density of order 10^{25} cm^{-2}), the Lyα photons will have a very large optical depth to resonance scattering.

† The ionization parameter is defined as the ratio of ionizing photon density to electron density at the face of a gas cloud. It is given by $U = \Phi_H/n_e c$, where Φ_H is the number flux of photons which are energetic enough to ionize hydrogen, n_e is the electron density, and c is the speed of light.

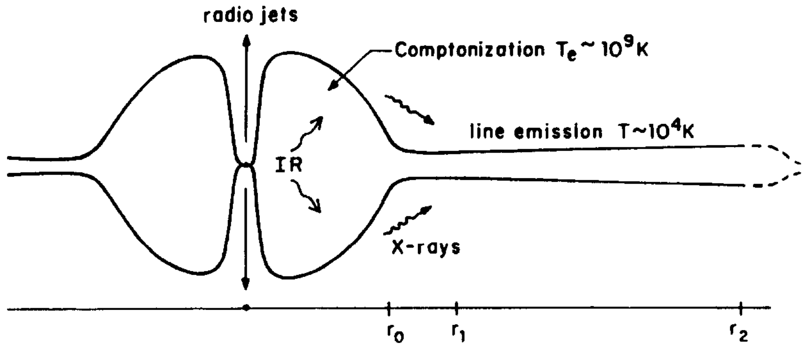

Fig. 5. Proposed model of the accretion disk in double-peaked emitters (Chen and Halpern 1989). The inverse Compton X-ray photons from the ion torus, which occupies the inner disk, photoionize the thin outer disk to produce the broad lines which we observe from $r_1 < r < r_2$. Typical values of r_1 and r_2 are 500 and 2000 GM/c^2, respectively. This disk structure was suggested for radio-loud AGNs by Rees *et al.* (1982) but it was originally considered in the context of accretion-powered binaries by Lightman and Eardley (1974), and Shapiro *et al.* (1976).

They will thus be trapped in the bulk of the disk and ultimately be destroyed by collisional de-excitation and possibly by bound-free absorption from the first excited state of hydrogen. More specifically, the extremely low Lyα/Hβ ratio predicted by these models agrees with the observed upper limit. Second, the observed infrared peak in the broad-band spectra of 3C 390.3 and Arp 102B represents the direct emission from the ion torus. The primary cyclo-synchrotron radiation from the torus has a self-absorbed spectrum which peaks at 30 μm (Begelman 1985; Di Mateo and Fabian 1996; Narayan *et al.* 1995).

In conclusion, we note a reassuring consistency check which makes use of the superluminal motion in the compact radio core of 3C 390.3 (Eracleous *et al.* 1996): the combination of a number of constraints on the orientation of the radio jet in this object yields an inclination angle relative to the line of sight of $i_{\rm jet} = 28^{+5}_{-9}$ degrees, which agrees with the inclination of the axis of the accretion disk obtained from the fit to the Hα profile, $i_{\rm disk} = 26^{+4}_{-2}$ degrees.

On the negative side, the simplest accretion disk models predict very specific profile shapes and cannot fit all of the observed double-peaked profiles (uniform axisymmetric disk models produce double-peaked line profiles with the blue peak always stronger than the red peak because of Doppler boosting). It also cannot account for emission lines with single, broad displaced peaks. These shortcomings can be partly overcome by resorting to more sophisticated, non-axisymmetric models which, for example, allow the disk to be eccentric (*e.g.*, Eracleous *et al.* 1995) or include inhomogeneities (Zheng *et al.* 1991) or spiral waves (Chakrabarti and Wiita 1993*a*). Such features could cause the line profiles to vary with time, as described in the next section, and thus offer a means for testing the models and studying dynamical phenomena in the disks.

Alternatives to Accretion Disk Emission

Even though accretion disk emission is the best developed model for the origin of double-peaked emission lines in radio-loud AGNs, it is not the only game in town. To date, three alternative scenarios have been proposed: (a) emission from a twin broad-line region associated with a binary black hole, (b) emission from a bipolar outflow, and (c) emission from a spherically symmetric broad-line region illuminated by an anisotropic (bipolar) continuum source. All of these scenarios offer an explanation for the double-peaked Balmer line profiles, and can also explain, with a varying degree of success, some of the other properties of the disk-like emitter class, as described below. However, they are much less appealing than disk models both because they cannot explain all of the general properties of disk-like emitters, and because in some cases their predictions are not confirmed by the observations.

The binary black hole scenario was proposed for AGNs by Gaskell (1983) to explain the displaced broad Balmer line peaks of objects such as 3C 227 and Mkn 668 (for which it may still provide the most viable interpretation). A supermassive black hole binary can form as a result of the merger of two galaxies, each with its own nuclear black hole (Begelman *et al.* 1982). If each of the black holes has an associated broad-line region, the orbital motion of the binary will produce Doppler shifts in the emission lines, analogous to what is observed in stellar double-lined spectroscopic binaries. The resulting line profiles will, therefore, have double peaks (or single but displaced peaks if only one of the two black holes has an associated broad-line region). Since the hosts of radio-loud AGNs are elliptical galaxies, which are also the most likely products of mergers, this scenario can also account for the preferential occurrence of double-peaked lines in radio-loud AGNs. In the specific case of the double-peaked lines of the quasar OX 169, Stockton and Farnham (1991) concluded that a binary black hole resulting from a recent merger is the most plausible interpretation. Observational support for the binary black hole hypothesis for 3C 390.3 comes from the recent analysis of a large collection of Hβ spectra of this object, spanning a period of over 20 years, by Gaskell (1996). The blueshifted peak of the line is found to drift in velocity at an almost constant rate during this time. The drift is consistent with the orbital motion of a supermassive binary with a period of about 300 years. The same test yields negative results, however, when applied to two other disk-like emitters: Arp 102B and 3C 332 (Halpern and Filippenko 1988, 1992). The absence of any drift in the displaced peaks of these two objects places rather restrictive lower limits on the total masses of any black hole binaries of 4×10^9 and 2×10^{10} $M_\odot$, respectively. A serious drawback of this scenario is that it implicitly assumes that the line-emitting regions are described by "standard" photoionization models, and hence cannot account for the unusual spectroscopic properties of the disk-like emitters. Most notably, it predicts that all emission lines should have similar profiles, in flat contradiction with the UV spectroscopic observations of Arp 102B.

In the bipolar outflow model, originally proposed by Zheng *et al.* (1990), the double-peaked lines originate in pairs of oppositely directed cones of outflowing gas, presumably accelerated by the passage of the relativistic radio jets through the line-emitting regions or the interstellar medium of the host galaxy. It has been applied to 3C 390.3 and Pictor A by Zheng *et al.* (1991) and Sulentic *et al.* (1995) yielding successful fits to the observed Balmer line profiles. The model is purely kinematic and relies on a parametric description of the geometry, structure, and velocity field of the outflow. As such, it is quite flexible, and it can reproduce a wide variety of profiles, albeit by an *ad hoc* choice of model parameters. Our present physical understanding of the formation and collimation of outflows is rather poor, so the model parameters cannot be computed from a consideration of the detailed physical processes. As a result it is impossible to assess whether the parameters obtained by fitting the line profiles are reasonable or not. This family of models can explain the line profile shapes and the association with radio-loud AGNs, but has nothing to say about the specific properties of the disk-like emitter class (*e.g.*, the Lyα *vs* Balmer line profiles), much like the binary black hole scenario. The suggestion by Sulentic *et al.* (1995) that the double-peaked emitters represent the extreme segment of a population of line emitting outflows in which the line of sight happens to be close to the axis of the outflow is not supported by the data: double-peaked emitters are associated with double-lobed radio sources, suggesting that the line of sight has a considerable inclination to the axis of the jets. Although radial ouflow models as a class are very difficult to constrain, specific versions of such models can be tested observationally. In particular, Livio and Pringle (1996) have pointed out that an accretion disk will obscure the receeding parts of an outflow at small radii from its center (see illustration in Figure 2). This suggests that if double-peaked lines are to be attributed to an outflow, then they must originate in parts of the ouitflow that are far enough from the center of the disk not to be obscured. Morever, if the line emission from the outflow is powered by a central source of ionizing radiation then variations in the luminosity of the source will result in corresponding changes in the flux of the line. The difference in light travel time between the two sides of the outflow and an an observer on the Earth dictates that the red and blue sides of a double-peaked emission line should not respond simultaneously but rather with a delay of the order of years.

The recently proposed model of Goad and Wanders (1996) assumes that a spherically symmetric broad-line region, composed of clouds in randomly inclined Keplerian orbits, is illuminated by an anisotropic continuum source (*i.e.*, a pair of back-to-back beams superposed on a uniform, isotropic "background" radiation field).

This model can produce double-peaked emission lines for a range of orientations of the ionizing beam relative to the line of sight, and it can also account for the dramatic difference of the profiles of the Lyα and Balmer lines in Arp 102B by placing the observer close to the axis of the ionizing beam, and invoking an ionizing spectrum which is a function of the off-axis angle. Similarly, it can explain the weak non-stellar continuum in disk-like emitters by orienting the observer at a large inclination from the axis of the ionizing beam. However, by virtue of the geometry it invokes, this scenario requires that one observes *either* double-peaked Balmer lines *or* a weak non-stellar continuum in an object. This is is contradiction with observations which show double-peaked emitters to possess both of these properties at the same time. One would expect in this context that double-peaked Lyα profiles should also exist in some objects with single-peaked Balmer line profiles, which has never been observed; moreover, this scenario offers no reason why double-peaked profiles should be associated preferentially with radio-loud AGNs.

DYNAMICAL AND THERMAL PHENOMENA IN ACCRETION DISKS AND THEIR TIME SCALES

Rare as double-peaked emission lines may be in AGNs, they can afford clean tests of a number of models of the broad-line region, as described above. They also provide potentially the most direct dynamical evidence for the presence of accretion disks in AGNs, and they offer a means of studying the structure and properties of such disks. The discussion of the previous section shows the line-emitting disk scenario to be the most likely and most promising interpretation of double-peaked emission lines. Thus, this section presents a summary of possible phenomena in the disk that can cause the profiles of the emission lines to vary, and gives estimates of the relevant time scales. Viewed from a different perspective, variability can also be used as a test of different models for the origin of the lines, since different models make different predictions for the pattern of variability.

The most rapid variability is likely to result from the reverberation of a variable ionizing continuum from the disk. The relevant time scale is the light crossing time of the disk, which is given by

$$\tau_\ell \sim \frac{R}{c} \sim 6\ M_8\ \xi_3\ \text{ days}, \tag{1}$$

where R is the radius in the disk and c is the speed of light. This time scale is also expressed in terms of the radius scaled by the gravitational radius: $\xi = Rc^2/GM$ ($\xi_3 = \xi/10^3$, G is the gravitational constant, and M is the mass of the black hole), a quantity that can be inferred from fitting the disk-like line profiles. The mass of the black hole is scaled to 10^8 M$_\odot$, by convention, so that $M_8 = M/10^8$ M$_\odot$. Variability of the profiles on this time scale is discussed elsewhere in this volume and is beyond the scope of this paper. In the opposite extreme, perhaps the longest time scale in a disk is the viscous time, which is given by (Frank *et al.* 1992)

$$\tau_{\text{visc}} \sim 10^6\ M_8^{3/2}\ \xi_3^{5/4}\ \alpha_{-1}^{-4/5}\ \dot{M}_{-1}^{-3/10}\ \text{ years}, \tag{2}$$

where $\alpha_{-1} = \alpha/0.1$ is the Shakura-Sunyaev viscosity parameter and $\dot{M}_{-1}$ is the accretion rate in units of 0.1 M$_\odot$/year. As a consequence, unless the mass of the black hole is of the order of 10^5 M$_\odot$or less, it would be rather difficult to observe viscous phenomena in the outer disk. Observations that can sample the inner disk (*e.g.*, in the X-ray band), are better suited for studying phenomena on the viscous time scale since this time scale is much shorter at small radii.

The time scales of greater interest here are the dynamical, thermal, and sound-crossing times in the disk, which are given by (Frank *et al.* 1992)

$$\tau_{\text{dyn}} \sim \left(\frac{R^3}{GM}\right)^{1/2} \sim 6\ M_8\ \xi_3^{3/2}\ \text{ months}, \tag{3}$$

$$\tau_{\text{th}} \sim \frac{\tau_{\text{dyn}}}{\alpha} \sim 5\ \alpha_{-1}^{-1}\ M_8\ \xi_3^{3/2}\ \text{ years}, \tag{4}$$

$$\tau_{\text{s}} \sim \frac{R}{c_{\text{s}}} \sim 70\ M_8\ \xi_3\ T_5^{-1/2}\ \text{ years}, \tag{5}$$

where c_s is the sound speed and T_5 is the disk temperature in units of 10^5 K. Variations on the dynamical time are the most easily observable. For example, if an inhomogeneity develops in the disk (*e.g.*, through a collision with or the capture of a star or a cloud) it will orbit at the local dynamical time, and could produce a hump in the line profile which will drift on the same time scale. If waves form in the disk (*e.g.*, as a result of a non-axisymmetric perturbation; see, for example, Chakrabarti and Wiita 1993*b*), they will propagate on the sound-crossing time and may produce a periodic modulation of the line profiles if they are long lived. However, the effect of waves may be detectable on time scales shorter than the sound-crossing time by comparing model line profiles such as those of Chakrabarti and Wiita (1994) with observations. Local inhomogeneities in the disk will also decay over a sound-crossing time as a result of Keplerian shear. Disk instabilities, analogous to the dwarf nova instability in cataclysmic variable disks will develop on the thermal time scale, and the associated heating and cooling fronts propagating through the disk can leave an imprint on the line profiles.

A distinct possibility is that a (transient) line emitting disk can form abruptly as a result of the tidal disruption of a star or a cloud by the central black hole. The bound portion of the debris can form an elliptical ring within a viscous time (Syer and Clarke 1992), which would precess because of general relativistic advance of the pericenter. Such an effect is most likely to be observable if the mass of the black hole is low (of order 10^6 $M_\odot$), because low-mass black holes can readily disrupt stars before accreting them, and because the precession period of the elliptical ring is short for a black hole mass of this order,

$$P_{\rm GR} \sim 10\ M_6\ \tilde{\xi}_3^{5/2}\ \text{years}, \tag{6}$$

where $M_6 = M/10^6$ $M_\odot$, and $\tilde{\xi}_3$ is the pericenter distance of the ring in units of 10^3 GM/c^2. The observed profile will therefore vary over an interval of a few years as the disk precesses. Finally, another noteworthy time scale is the orbital period of a supermassive binary black hole,

$$P_{\rm orb} \sim 50 \left(\frac{q}{1+q}\right)^{-1/2} A_{17}^{3/2}\ M_8^{-1/2}\ \text{years}, \tag{7}$$

where M_8 is the *total* mass of the system in units of 10^8 $M_\odot$, A_{17} is the orbital separation in units of 10^{17} cm, and q is the ratio of the two masses (more massive to less massive). This is the time scale on which one may expect to see a drift of the twin peaks caused by the orbital motion of the binary.

OBSERVATIONS OF THE LONG-TERM VARIABILITY OF DOUBLE-PEAKED EMISSION LINES

In order to investigate the range and pattern of variability of double-peaked emission lines, and with the ultimate goal of carrying out the tests described above, we have been accumulating spectra of double-peaked emitters for almost a decade. Our program is aimed at studying the variability of the profiles on time scales of a few months to several years (*i.e.*, time scales at least of the order of the dynamical time), and it therefore involves observations of double-peaked emitters a few times every year. Examples from our data collection are shown in the montage of Figure 6. The spectra presented in this figure demonstrate the different variability patterns that we have observed in disk-like emitters. In the prototype of the class, Arp 102B, the general character of the line profile remains the same, while there are subtle but significant variations in the detailed shape. In the case of 3C 390.3, the data presented here show the variability to be more pronounced than in Arp 102B, and to have the form of small changes in the relative sizes of the two peaks and significant changes in the shape of at least the blue peak. This object is famous for an even more spectacular performance in the late 70s and early 80s, when the relative sizes of the two peaks varied considerably much like what we observe in 3C 332, below (Veilleux and Zheng 1991; Zheng *et al.* 1991). In addition these authors also find a gradual drift the velocity of the blue peak of Hβ (for a possible interpretation of the latter effect see Gaskell 1996). In 3C 332 the variability is quite dramatic. The relative sizes of the two peaks have been changing constantly over the past few years: in its initial state the red peak was weaker than the blue peak, but within the time span of our observations it became stronger than the blue peak and then receded to almost its original strength. In another example of dramatic variability, Pictor A, two broad displaced peaks

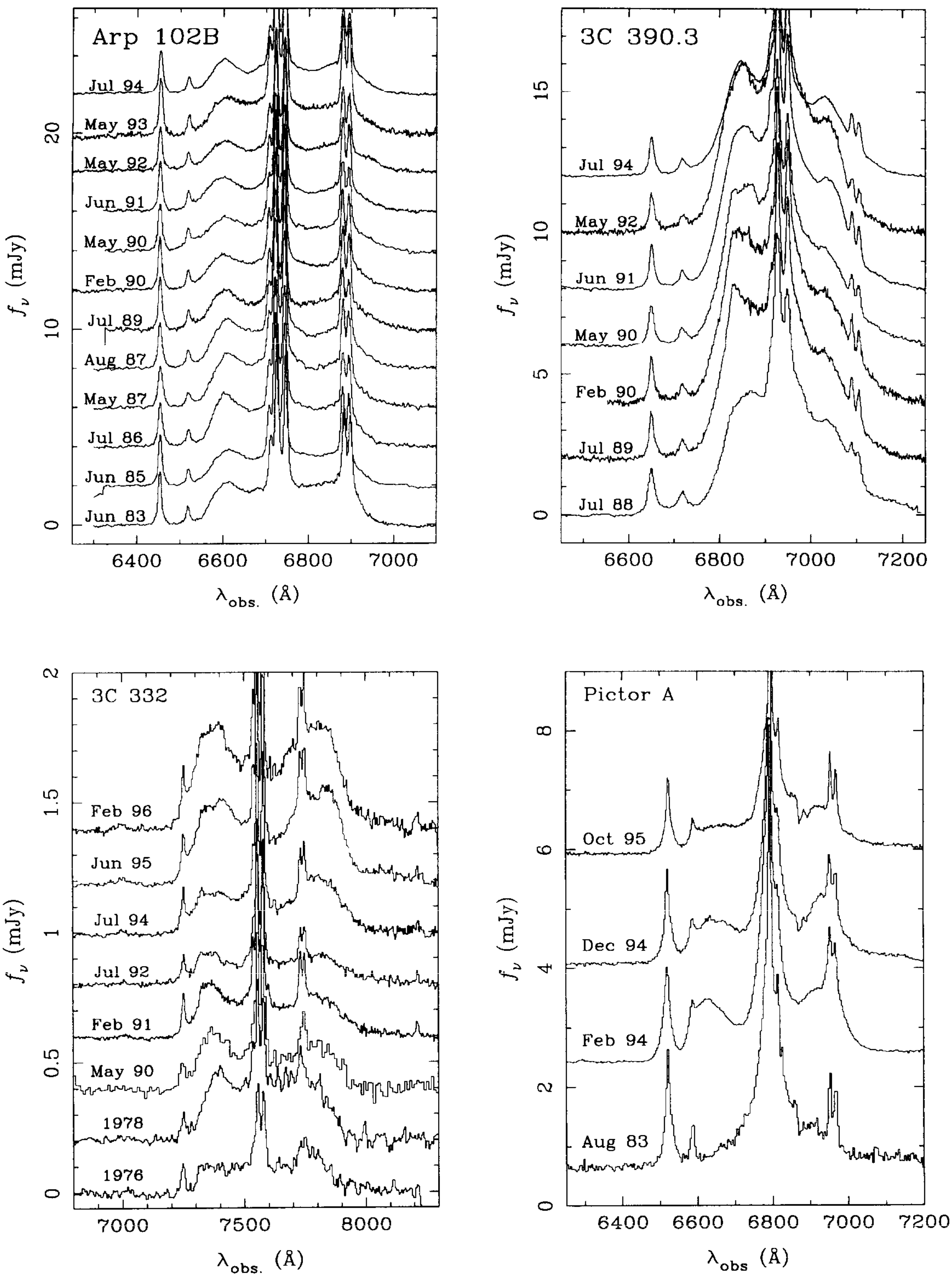

Fig. 6. A compilation of spectra of four double-peaked emitters showing the range of variability of their Hα line profiles. The data presented here are only a subset of the entire collection for each object.

appeared abruptly in the Balmer lines after 1983. The available data suggest that the red peak appeared first sometime between 1983 and 1987, followed by the blue peak sometime between 1987 and 1993 (Halpern and Eracleous 1994; Sulentic *et al.* 1995). The twin peaks have been varying both in intensity and in velocity ever since their appearance.

From the available data one can carry out preliminary tests of some models, and draw at least preliminary conclusions about the cause of the variability of the Hα profiles. The binary black hole scenario can be tested readily by looking for variations in the locations (velocities) of the displaced peaks and using such variations (or their absence) to constrain the mass of the hypothesized supermassive binary. Following Halpern and Filippenko (1988, 1992) we have made measurements of the locations of the two peaks of the Hα line of 3C 332, using the spectra of Figure 6. The radial velocities of the two peaks, and in particular their variation over the past decade, constrain the period of the hypothesized binary and place a rather restrictive lower limit on its total mass of $M > 2 \times 10^{10}$ M$_\odot$, making this scenario unlikely for this particular object. We note that this does not rule out the *existence* of a binary black hole with a mass less than this limit in the nucleus of 3C 332; it constrains the scenario in which the observed emission-line peaks are attributed separately to each of the two members of the binary. The same procedure is now being applied to other objects (see below for Arp 102B), and the results will be presented by by Gilbert *et al.* (1996) along with a refined constraint for 3C 332 itself.

The variations of the Balmer line profiles of Arp 102B have been studied in detail by Newman *et al.* (1996). The binary black hole hypothesis for this object was evaluated using the method described above, which yielded a lower limit to the mass of the hypothesized binary of $M \gtrsim 10^{10}$ M$_\odot$. Newman *et al.* find subtle changes in the Hα profile of Arp 102B, which take the form of regular variations in the relative sizes and velocities of the two peaks over a period of a few years. The observed behavior is best understood in the context of an accretion disk model for the origin of the double-peaked lines. The variations of the Hα profile can be accounted for *in detail* by invoking a "hot spot" in the inner parts of the accretion disk, which has a very small radial extent and enhances the local surface brightness of the disk. The "hot spot" appears to follow a circular orbit very closely for about two revolutions before dissipating gradually. The combination of all observational constraints allows, in the context of this model, a dynamical measurement of the mass of the central black hole of about 2×10^8 M$_\odot$.

We hope that within the next few years we will have put together a large collection of spectra for many double-peaked emitters and will be able to carry out a detailed study of the variability of their profiles. From a preliminary inspection of our data, the most common pattern of profile variability that we observe is a gradual change in the relative intensities of the two peaks with no immediately noticeable changes in their positions (*i.e.*, velocities) or the overall width of the line. The common variability pattern is yet another close similarity between double-peaked emitters, in addition to their similar profiles and the common, distinguishing characteristics of their hosts. The fact that the intensities of the twin peaks do not increase and decrease in concert does not mean that the two peaks "vary independently"; it would, in fact be very difficult (and perhaps impossible) to rule out any causal connection between the variations of the two peaks. Moreover, the observed variability does not contradict in any way the accretion disk model for the origin of the lines: the wide variety of possible phenomena associated with accretion disks described in the previous section makes it very likely that the structure and emission properties of the disk will vary with time and that the resulting line profiles will vary accordingly. The case of Arp 102B illustrates this point quite clearly: although the intensities of the two peaks in the Hα profile do not vary at the same time, they are variations are not "independent".

EPILOGUE

The members of the small but distinct subclass of radio-loud AGNs with disk-like double-peaked emission lines most likely harbor line-emitting accretion disks. The data available on these objects can be explained best in the context of the line-emitting disk model. Alternative models are far less appealing because even though they can reproduce the double-peaked line profiles they do not offer an all-encompassing interpretation for all the other very unusual properties of the hosts. The double-peaked emitters are thus worthy of our study because they offer us a means of exploring dynamical phenomena in AGN accretion disks.

Because models of the variability of double-peaked emission lines abound it is very difficult at present to distinguish among them using snapshots of the observed profiles alone. The variability time scales are usually rather long, and they depend sensitively on the mass of the black hole which is, in practice, unknown (see previous section). It is thus necessary to compare the evolution of the line profiles with detailed model predictions (see, for example, the application to NGC 1097 by Storchi-Bergmann *et al.* 1995, and the application to 3C 390.3 by Zheng *et al.* 1991). This underscores the importance of monitoring double-peaked emitters for variability, a task that we have already begun and intend to continue.

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