ACCRETION DISKS, PRECESSING JETS, AND THE

ASYMMETRIC EMISSION LINES OF QSOs*

(NASA-CR-173632) ACCRETION DISKS, PRECESSING JETS AND THE ASYMMETRIC EMISSION LINES OF QSOS (Texas Univ.) 14 p HC A02/MF A01 CSCL 03A G3/89 N84-27613 Unclas 13639

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*Submitted to the Gravity Research Foundation Essays on Gravitation, April 1, 1983.

SUMMARY

The broad line profiles of active galaxies are consistent with emission from the surface of an accretion disk ionized by an ultraviolet continuum emitted from a linear or point source of continuum above the disk. If the point source is offset from the axis of the disk, then the line peak is shifted from zero velocity in a way that resembles observed cases. This misalignment could result from the Lense-Thirring precession of a rotating black hole.

I. INTRODUCTION

The optical and ultraviolet spectra of active galactic nuclei (Seyfert galaxies and QSOs) show broad emission lines superimposed on a "nonthermal" continuum of roughly power-law form. The broad lines, with full widths at zero intensity (FWZI) of $\sim$4000 to $\sim$20000 km s^{-1}, are seen only in the permitted transitions. In addition, narrow lines (FWZI $\lesssim$ 1000 km s^{-1}) are seen in the forbidden and permitted transitions. The narrow lines agree in velocity with that of the host galaxy when the latter can be measured (Gaskell 1983). The broad lines usually have fairly symmetric profiles that peak at the same velocity as the narrow lines (Osterbrock and Shuder 1982). However, there are a few cases in which the broad line peak is shifted with respect to the narrow line velocity by as much as ±2000 km s^{-1}. Gaskell (1983) has attributed these shifts to the orbital motion of a binary system of supermassive black holes, only one of which has an associated emission-line region. In this paper, I suggest instead that the shifts find their explanation in terms of line emission from an accretion disk illuminated by ionizing radiation emitted from a jet that is tilted with respect to the rotation axis of the disk.

II. ACCRETION DISK LINE PROFILES

Accretion disks around supermassive black holes provide an efficient mechanism for the energy production in active galaxies, and the rotation axis provides a natural way to align oppositely directed jets to supply energy to the double radio lobes that often are observed (Lynden-Bell 1969). Orbital motion in the disk is an interesting possibility to explain the broadening of the emission lines (Shields 1977, 1978; Osterbrock 1978). The circular velocity is

$$v_\phi \simeq (10^3 \text{ km s}^{-1})\ M_8^{1/2}\ R_{18}^{-1/2} \quad , \tag{1}$$

where M_8 is the black hole mass M_H in units of $10^8\ M_\odot$ and $R_{18} = R/10^{18}$ cm. The line profiles require significant contributions of line emission from radii having $v_\phi \simeq 10^4$ km s^{-1} down to $v_\phi \lesssim 300$ km s^{-1}, if only circular motion is involved (Shields 1978). At the radii of interest, the disk surface is rather cool ($\sim 10^3$ K), and the observed line emission must come from a photoionized skin on the disk created by the impact of the X-ray and ultraviolet continuum. If the continuum is generated by nonthermal processes in a jet along the rotation axis, then the width and shape of the line profile is governed by the distribution of continuum emission with height z above the disk, and by the directionality of this emission. For an isotropic point source at $z = H_J$, equal amounts of continuum energy strike the disk inside and outside $R = 3H_J$, so that the ratio H_J/M_H determines the characteristic line width. Observations of the ultraviolet and X-ray continuum of active galaxies (e.g., Penston et al. 1981; Tenant and Mushotzky 1983) indicate that in most cases, variability occurs on timescales of at least several days for Seyfert galaxies of modest luminosity, and on longer timescales for more luminous objects. This is consistent with the idea that much of the continuum is emitted at heights $H_J \approx 10^{17}$ cm above the disk for average luminosities, with some increase with increasing luminosity. Since M_H is likely to increase with luminosity, all this is consistent with the observed line widths of FWZI $\approx 10^4$ km s^{-1} for Seyfert galaxies and QSOs.

Figure 1 shows the computed line profile of a Keplerian disk illuminated by an isotropic point source of ionizing continuum at a height H_J such that v_ϕ = 3000 km s^{-1} at $R = H_J$. Each surface element of the disk was assumed to emit a quantity of line energy proportional to the ionizing continuum energy deposited on it. For such a simple model, the profile is remarkably similar to observed profiles (cf. Osterbrock and Shuder 1982). In particular, the wings fade rapidly enough at high velocity that an effective intersection with the continuum would be fairly well defined; and the illumination of the disk fades gradually enough at large radii to give a centrally peaked profile rather than a central dip as results from insufficient emission from the outer, low velocity regions of the disk (Shields 1978; van Groningen 1983). (Also shown for comparison is the line profile produced by an isotropically emitting line source along the rotation axis with continuum luminosity dL/dz = const at $z \leq H_J$ and $dL/dz \propto z^{-2}$ at $z \geq H_J$. This case also has an inner edge to the line-emitting disk at v_ϕ = 7,000 km s^{-1}, which results in a fairly sharp intersection of the line wings with the continnum, as is sometimes observed.)

III. LINE PROFILES FROM DISKS WITH TILTED JETS

Radio observations of active galaxies give evidence of precessing jets (*e.g.* Gower et al. 1982), and there are theoretical reasons to suppose that jets emitted from the central black hole could be tilted with respect to the axis of the outer parts of the accretion disk (Rees 1978a). For example, an active episode may be triggered by capture of a massive gas cloud by a galactic nucleus (Gunn 1979), and this gas is likely to settle into a plane that is not aligned with the rotation of the black hole. (If the hole grows by disk accretion, it is likely to have nearly the limiting angular momentum, $J_{max} = G\,M^2/c^2$). As the gas in the disk gradually spirals into the black hole, it suffers the Lense-Thirring precession of general relativity on a timescale

$$t_{prec} = t_{orb}\ (J/J_{max})^{-1}\ (R/R_S)^{3/2}\ , \tag{2}$$

where R_S is the Schwarzschild radius (Bardeen and Petterson 1974; Rees 1978). At a radius R_{BP}, this precession occurs on the same timescale as the inward diffusion of the gas; and from R_{BP} inward, the disk is aligned with the equator of the black hole. In the α-model for accretion disks (Shakura and Sunyaev 1973), the radial diffusion speed v_R is $\sim 10^{-5}\ v_\phi$ for likely parameters, and from eq. (2) we then find

$$R_{BP}/R_S \simeq 10^3\ (J/J_{max})^{2/3} \tag{3}$$

and

$$v_\phi(R_{BP}) = (10^4\ \mathrm{km\ s^{-1}})\ \ (J/J_{max})^{-1/3}\ . \tag{4}$$

Thus, the disk is expected to shift from its outer plane to the black hole plane at a radius inside that at which the broad line velocities occur. Since most of the accretion power is released at $R \simeq 10R_S$ (Lynden-Bell 1969; Thorne 1974), the jet presumably will follow the axis of the inner disk and will be tilted with respect to the outer disk.

If the ionizing source is offset from the axis of the outer disk, then the sector of the disk directly under the ionizing source will be most strongly illuminated, and there will be an excess of emission in the line profile corresponding to the radial velocity of this part of the disk with respect to earth. Figure 1 shows the line profile resulting from a point source of ionizing continuum located at a polar angle θ_J away from the axis of the outer disk, and at a disk azimuth ϕ_J measured from the subearth point in the direction of the disk's rotation. For $\sin \theta_J = 0.7$ and $\sin \phi_J = -0.7$ (the median absolute value for random orientations), the line peak is shifted to $v_{peak} \simeq -1500$ km s^{-1}. (The distance of the point source from the black hole is the same as for the on-axis case described earlier.) Thus, the profile peaks quite sharply at a velocity substantially different from zero if θ_J is large. On the other hand, the extreme wings of the line come from a relatively small region near the center of the disk; and since this region is fairly uniformly illuminated, the wings are nearly symmetrical around $v = 0$.

This asymmetric line profile is quite similar to the class of objects discussed by Gaskell (1983). In particular, MRK 876 (Osterbrock and Shuder 1982) and Q1613+658 (Gaskell 1983) have broad line peaks that are shifted by about 2000 km s^{-1} blueward from the narrow line velocity; but, as Osterbrock and Shuder point out, the wings center around the narrow line velocity. Even the fairly linear descent of the line wing that passes through $v = 0$ in the theoretical profile resembles these two observed cases. Gaskell (1983) finds for a modest sample of objects that the broad line peak is equally likely to be shifted blueward or redward from the narrow line velocity; and this is consistent with randomly oriented disks with tilted jets.

How long is the tilt of the jet likely to persist? The Lense-Thirring precession acts to bring the black hole's angular momentum into alignment with that of the outer disk on a timescale

$$t_{BP} = (M/\dot{M})\ (J/J_{max})\ (R_S/R_{BP})^{1/2}\ , \tag{5}$$

$$= (10^6\ \mathrm{yr})\ (J/J_{max})^{2/3}$$

(Rees 1978), where in the latter expression we have assumed that $\dot{M} = \dot{M}_{Ed}$, the accretion rate that gives $L = 0.1\dot{M}c^2 = L_{Ed}$, the Eddington limit luminosity. If, after a new injection of gas into the nucleus, the active episode lasts $\sim 10^7$ to 10^8 years, we might expect a few per cent of the active objects to have black holes that have not yet aligned with the outer disk. This is consistent with the observed occurrence of highly shifted broad line peaks in only a few percent of all broad line objects.

IV. DISCUSSION

The point source of continuum discussed above may have some physical basis in addition to computational convenience. Variability observations and broad line widths indicate continuum emission at radii of order 10^4 R_S, whereas an accretion disk around a black hole generates most of its power at ~ 10 R_S. A mixture of magnetic field and ultrarelativistic particles would suffer severe energy losses from adiabatic expansion before reaching 10^4 R_S; and therefore, by analogy with theories of the radio lobes, one suspects that the energy is transported as bulk kinetic energy in a jet and is converted to continuum emitting form in a shock at $\sim 10^4$ R_S. This might result from impact on the magnetic field of the compact radio source (Camenzind and Courvoisier 1983) or the "Compton heated wind" from the outer disk (Begelman, McKee, and Shields 1983). Alternatively, fluctuations in the ejection velocity of the jet could lead to shocks traveling along the jet in analogy with the discussion of M87 by Rees (1978b). Moving shocks may be consistent with observations of NGC 4151 by Ulrich et al. (1983), which show that new continuum flares may be quickly followed by the intensification of very broad wings of C IV λ1549, as though high velocity gas near the center of the disk were being strongly illuminated.

According to equation (5), the jet should approach the rotation axis of the outer disk on a timescale $\sim 10^6$ years. Thus, the broad line peak should remain shifted to the same side of the narrow line velocity over observable time periods. (However, the amount of the offset could vary if the continuum emitting region changes position along the jet.) This contrasts with the supermassive binary model by Gaskell (1983), in which the peak should show a secular change in velocity on the orbital period of $\sim$ 300 years for a luminous quasar, and possibly a shorter time for Seyfert galaxies. The supermassive binary picture already has difficulty explaining why the extreme line wings are not shifted in the same way as the line peak, whereas this is a natural consequence of the picture given here. Another relevant observation would be to study the line profiles of active galaxies showing evidence for precessing radio jets.

In summary, a model involving an accretion disk illuminated by ionizing continuum emission from an axial jet gives a good fit to typical, symmetric line profiles of active galaxies. Misalignment of the jet with respect to the outer disk can account for the occasional objects with highly shifted broad line peak velocities, and observational tests are possible. Verification of this picture would provide important support for the existence of accretion disks and supermassive black holes in active galaxies and of the operation of the Lense-Thirring precession.

This work was supported in part by the National Aeronautics and Space Administration, the National Science Foundation, by an Alfred P. Sloan Research Fellowship.

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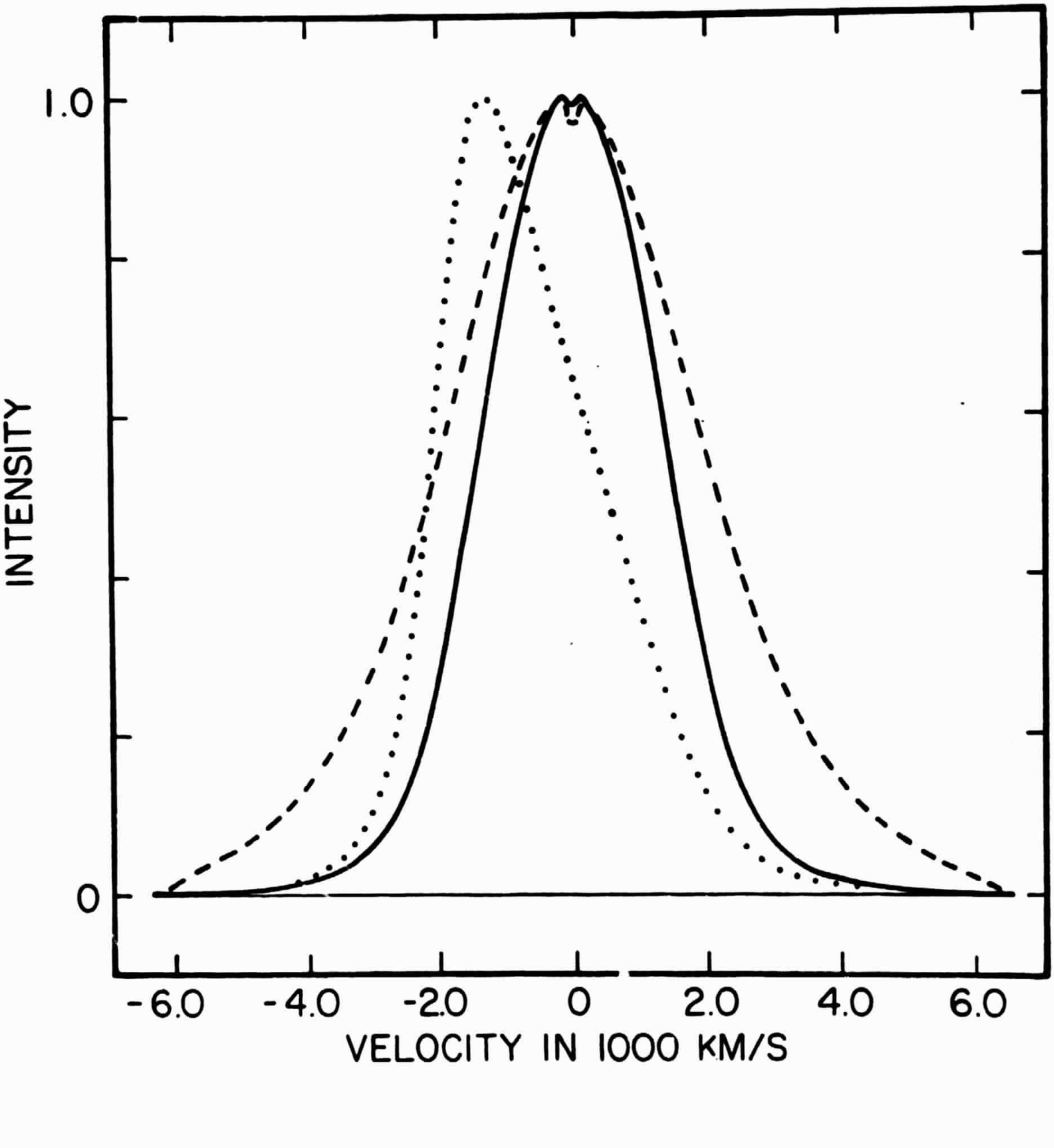
FIGURE CAPTIONS

Fig. 1 - Computed line profile for emission from the surface of a Keplerian accretion disk around a supermassive black hole. Solid line is for a point source of ionizing continuum at height $H_J = G\,M_H/v^2$ with $v = 3{,}000$ km s^{-1}. Dashed line has a linear continuum source that fades as $dL/dz \propto z^{-2}$ abov H_J, and an inner cutoff to the line emission at the radius where $v_\phi = 7{,}000$ km s^{-1}. Dotted line is profile for a point source a distance H_J from the black hole, at an angle $\sin\theta_J = 0.7$ from the rotation axis in azimuth $\sin\phi_J = -0.7$. All models have the rotation axis of the disk at an inclination $\sin i = 0.866$ with respect to the line of sight. The outer edge of the disk had $v_\phi = 200$ km s^{-1}; decreasing the outer radius would give a more prominent central dip in the line profile in the absence of noncircular motions in the outer disk.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