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A DOUBLE-STREAM MODEL FOR LINE PROFILES

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ABSTRACT

It is shown that gas clouds in a biconical shape may produce profiles similar to those produced in a spherical geometry. The profile shape depends on the radial velocity field, the projection angle, and most importantly, the shell luminosity distribution. If the conical region extends over a large range of radial distance, the resultant profile may be symmetrical with logarithmic wings, otherwise apparent may be observed. It is shown that the double-peaked Hβ profile in Akn 120 can be modeled with a double-stream model.

Subject headings: galaxies: nuclei — galaxies: Seyfert — line profiles

I. INTRODUCTION

The broad emission lines observed in extragalactic objects can often be approximated with a logarithmic profile ($f_\lambda \propto \log|\lambda - \lambda_c|$, where λ_c is the peak wavelength of the line, and λ is not too close to λ_c) by assuming a spherical ensemble of cloudlets accelerated outward by the continuum radiation (Blumenthal and Mathews 1975). Capriotti, Foltz, and Byard (1980) further show that other radial velocity fields can produce similar profiles. The most commonly adopted geometry is spherical. Recent observations, however, have provided evidence that the line profiles in many active galactic nuclei are not logarithmic and show significant departures from single-peaked symmetry. For example, at least two components which vary with time have been identified in the Hβ profile of the Seyfert galaxy Akn 120 (Peterson *et al.* 1983; Peterson *et al.* 1985; Alloin, Boisson, and Pelat 1988). Peterson *et al.* (1990) find that the net change in the Hβ profile of NGC 5548, during variation events, is a pair of displaced components which vary.

It has been suggested that composite line profiles imply a complex structure in the broad-line region (BLR), and many forms of geometry have been discussed. In order to explain the double-peaked emission-line features, Gaskell (1983) suggests a supermassive binary in the core and a time scale for its line variations between 10 and 100 yr. Nonspherical BLR structures have also been proposed. For instance, Foltz, Wilkes, and Peterson (1983) suggest that a counterjet may explain the observed double peak in Akn 120. Netzer (1987) proposes a two-component BLR model in which the primary component is in a biconical shape and the other is roughly spherical.

Insights into nonspherical structures can be found in extended narrow-line regions which have now been imaged for many objects. As a recent example, Tadhunter and Tsvetanov (1989) report that the Seyfert galaxy NGC 5252 shows a well-defined biconical structure in the [O III] λ5007 region. Wilson, Ward, and Haniff (1988) find that an extended emission-line region is more often aligned along or near the radio axis than in the perpendicular direction, as shown by long-slit spectroscopic and narrow-band imaging observations. If the broad- and narrow-line regions are powered by the same ionizing continuum, we might also expect that the BLR originates from a double stream. It is therefore necessary to study the line profiles that would result from a biconical structure.

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II. MODEL

The general expression for line intensity is given by Blumenthal and Mathews (1975) and Capriotti, Foltz, and Byard (1980), but only the spherical case has been discussed in detail. Here we calculate the profile produced in a biconical geometry. Such a configuration may be a result of the cloud distribution, and the geometrical and physical conditions of the central source. The UV continuum, for instance, may be preferentially radiated along the axis of a central accretion disk (Pringle and Rees 1972; Abramowicz, Calvani, and Nobili 1980; Begelman 1985; Madau 1988; Acosta-Pulido *et al.* 1990). The jet associated with radio emission may produce a shock wave and line emission in the surrounding regions.

We define the projection angle, θ, as that between the cone axis and the line of sight, i.e. the angle is zero when the ejection is toward the observer. For a time-independent case, the profile can be expressed as

$$f(v) \propto \int_{r_{\min}}^{r_{\max}} \int_{\theta_0}^{\theta_1} L(r, \theta)\delta(v - V(r)\cos\theta)r^2 \sin\theta \, dr \, d\theta ,$$

where r is the radial distance to the center, and $L(r, \theta)$ is the column emissivity of a given line as a function of position. The velocity V is considerably smaller than the speed of light. In what follows we will assume that the luminosity is independent of θ (except that it is zero outside the limits θ_0 and θ_1). For simplicity we assume that the velocity is a function of radial distance only and does not involve rotation. Figure 1 shows the predicted profiles formed by a double-cone structure for different parameter values. The values for the fixed parameters in Figure 1 are set as follows: the projection angle, $\theta = 0°$; the opening angle, $\alpha = 20°$; the radial luminosity function $m = d \log [r^2 L(r)]/d \log (r)$ with $m = -0.5$; the radial velocity field $v(r) = r^p$: ($p = 1$).

The radial grid is logarithmically divided into equal size bins which therefore results in a stronger contribution from the inner region when each bin is given a constant shell luminosity weight ($m = 0$). One of these parameters is allowed to vary in each panel of Figure 1. The solid line represents the profile corresponding to the case of a spherical geometry. Figure 1*a* represents profiles with different opening angles $\alpha = 20$, 40, and 180 (spherical case) degrees; Figure 1*b* to profiles with different projection angles $\theta = 20$, 60, and 80 degrees; Figure 1*c* illustrates different velocity fields with $p = 1.0$, 0.75, and 0.5 while $m = -0.5$; and Figure 1*d* corresponds to different indices of the luminosity distribution: $m = -1.5$, -1.0, and

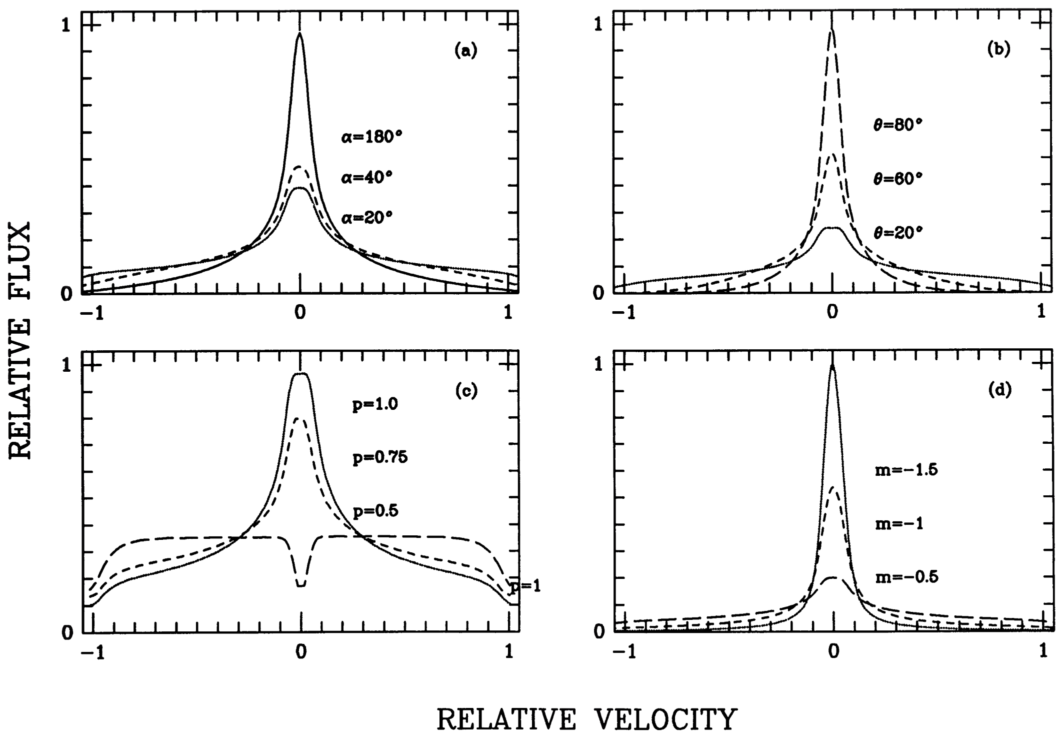

FIG. 1.—Profiles resulting from a biconical BLR. (*a*) At different projection angles; (*b*) at different opening angles; (*c*) with different radial velocity fields; and (*d*) with different luminosity distributions.

−0.5, respectively. In all cases, the ratio of outer to inner radius is 20, and the profiles are normalized such that the total integrated flux remains constant. All plots are smoothed with a bin size of 0.05, in units of the maximum velocity, to represent turbulent velocity or other sources of velocity dispersion. It is seen in Figure 1*a* that the profiles produced by a double-cone geometry bear a strong resemblance to the spherical case, especially in the wings. In many cases, the results for spherical and conical structure show little difference. Thus the conical configuration is able to produce a logarithmic profile like the spherical model. When the projection angle is large (nearly perpendicular to the line of sight), the resultant profile has a well-defined peak similar to that is obtained for a spherical configuration.

The profile shape depends on projection angle, the radial velocity function, and, most importantly, the luminosity distribution. In general, the resultant profile will be nearly Gaussian or logarithmic, depending on the behavior of the covering factor with radial distance. If a BLR extends over a large range of radius and the radial velocity varies significantly, the contribution to the line core from the low-velocity region is important resulting in a logarithmic profile. If the luminosity distribution is not a monotonic function of radial distance, a peak can appear at a displaced velocity and this can result in a double-peaked profile consisting of two Gaussian components one produced by each stream, as shown in Figure 2. Since the physical conditions in each region may not be identical, one profile wing can be stronger than the other which results in a profile asymmetry and/or redshift difference. This result might account for the large number of asymmetrical and shifted BLR profiles that are observed (Sulentic 1989).

Although Figure 1 corresponds to the radial outflow case ($p > 0$), similar profiles will also result from infall. The profile shape depends on the luminosity distribution (proportional to the covering factor) at different radial distances. Therefore the observed steady-state profiles cannot be used by themselves to determine the direction of the radial motion, although Penston *et al.* (1990) suggest that this is possible by studying the far wing. Kallman and Krolik (1986) and Rees, Netzer, and Ferland (1989) suggest that the line luminosity at small radii is considerably enhanced. If so, a profile with a strong core is expected to be formed in an outflow rather than inflow configuration.

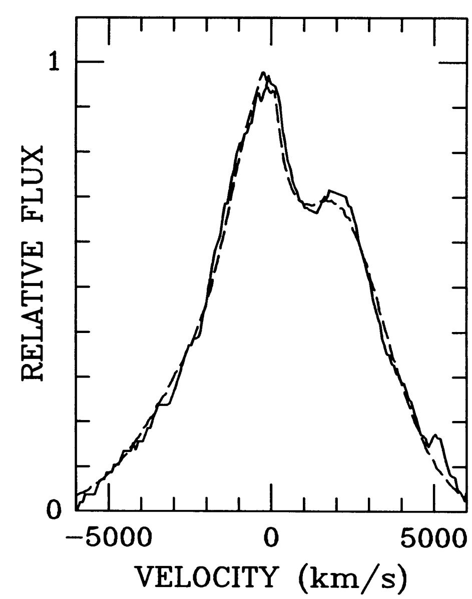

FIG. 2.—A model fit to the Hβ profile of Akn 120

It is interesting to note that the double-stream model can explain not only the double-peak structure but also the very broad features which are often assumed to result from the Keplerian motion. If the velocity difference between the two streams is large enough, the resultant profile may become very broad (FWHM greater than 10,000 km s^{-1}), which is observed in several radio galaxies and QSOs (3C 390.3: Pérez *et al.* 1988; PHL 909: Zheng and Burbidge 1988; Arp 102B: Chen, Halpern, and Fillippenko 1989).

The radial luminosity distribution is a key factor but it remains unknown. Robinson and Pérez (1990) suggest that the range of the radial luminosity distribution is not too large (about 5–10). Current photoionization models (Rees, Netzer, and Ferland 1989) suggest that the density range probably extends from 10^9 to 10^{11} cm^{-3}, thus a range of 10 in radial distance will result in a density range of roughly 50. The luminosity and velocity at different radii may simply be represented as monotonic functions of the radial distance to the center. However, the shell luminosity distribution function, $r^2L(r)$, may take such a form that it peaks at a given radius, resulting in a displaced peak in the line profile. In a spherical case such a displaced peak would have been averaged out over the angular distribution. Therefore the double-stream model may account for the observed double-peak profiles observed in several cases including the Seyfert galaxy Akn 120.

The nonspherical geometry can account for some uncorrelated profile variations. Since the line emission near each peak is formed in different regions individual components do not vary together unless the two streams are nearly perpendicular to the line of sight. In general, the line emission from the stream closer to the observer will show a smaller phase shift with respect to the variation in the continuum flux. Furthermore, if there is an acceleration or deceleration of the flow in the jet a variable peak which shifts slowly in velocity space may be present (Peterson *et al.* 1990) since the peak position is mainly determined by the location of the maximum shell emissivity.

One problem with the double-cone model is the absence or weakness of the core unless a large range of radial distance is introduced. The difficulty, however, is associated not only with this model but with nearly all other models which attribute the line profile to radial motion. Additional assumptions, such as a turbulent or rotational velocity, or a combination of infall and outflow, may be needed to supplement the above cone model. Note that the presence of a narrow line component might also turn the weak core of the broad component into a strong feature. Another problem is that the line component produced in the stream closer to us would be more closely correlated with the continuum than the emission from the other side. It has not been clear, even for Akn 120, if observations reveal such a trend. Despite the problems, the strength of such an approach is that it can potentially account for both red and blueshifts and asymmetries in a natural way.

III. APPLICATION

We apply the model to the double-peak Hβ profile of the Seyfert galaxy Akn 120. The latest measurements (Korista 1990) identify three components in the Hβ profile, at velocities relative to the narrow lines ≈ -200, and ± 1800 km s^{-1}, respectively. Alloin, Boisson, and Pelat (1988) find that the net change of Hα over one line variation event suggests a pair of displaced components, giving strong support to a model invoking the presence of a double-cone structure in this object. In a simple model fit, we assume that a broad component at the narrow line redshift and a pair of streams is producing the displaced components. The maximum radial velocity is ≈ 7000 km s^{-1}, derived from the observed full width at zero-intensity of 230 Å. Stream A, which is moving toward us with an angle of 30° with respect to the line of sight and an opening angle $\alpha = 20°$. The opposite stream B ($\theta = 210°$) is characterized by an intensity which is 60% of stream A. We assume a relatively narrow radial distribution, i.e., the chosen luminosity distribution function, which is a Gaussian distribution, peaks at approximately 0.3 of the maximum velocity and has a standard deviation of about 0.25. The model allows some freedom in the parameter space. The intensities of each cone, for example, need not be identical. Depending on the covering factor and other parameters for each side of the stream, the intensity of any individual line component can be varied. In particular, the variation in the continuum may not be observed directly since the direction of the latter is essentially perpendicular to the line of sight (i.e., we are not able to see this part of the ionizing continuum directly). Peterson *et al.* (1985) report that the velocity of each component has been constant for at least 5 yr. In this period, the stream may have moved a distance of 0.02 lt-yr, which is only a fraction of the estimated BLR size for this object. Therefore this does not result in any detectable shift of the peaks.

It should be emphasized that this fit does not represent a unique solution. Since there are many free parameters, different fits may be equally possible. It appears likely that, in addition to a BLR containing a biconical structure, there also exist other components such as a spherical BLR which would further improve the fit. Since the ratio of radiative to gravitational acceleration is higher for higher densities (Zheng and Sulentic 1990), the BLR gas may flow inward from the outer region and then at some point turn into outflow but with a smaller velocity. If so, the gas in one cone can have both positive and negative radial velocity and it can contribute to both the red and blue part of a profile, giving a chance for an even better fit.

IV. SUMMARY

We have shown that BLRs with a double-stream configuration could account for both the usual logarithmic profile as well as other peculiar features such as double-peaked profiles or broad, nearly "square" profiles, depending on the projection angle and the radial extent of the emitting conical region. We postulate that the BLRs of many extragalactic objects contain both the double-stream and spherical components. The double-stream approach may be able to account for the red and blueshifts and asymmetries frequently observed in the BLR.

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REFERENCES

Abramowicz, M. A., Calvani, M., and Nobili, L. 1980, *Ap. J.*, **242**, 772.
Acosta-Pulido, J. A., Pérez-Fournon, I., Calvani, M., and Wilson, A. S. 1990, *Ap. J.*, in press.
Alloin, D., Boisson, C., and Pelat, D. 1988, *Astr. Ap.*, **200**, 17.
Begelman, M. C. 1985, in *Astrophysics of Active Galaxies and Quasi-Stellar Objects*, ed. J. S. Miller (Mill Valley, CA: University Sciences), p. 411.
Blumenthal, G. R., and Mathews, W. G. 1975, *Ap. J.*, **198**, 517.
Capriotti, E., Foltz, C., and Byard, P. 1980, *Ap. J.*, **241**, 903.
Chen, K., Halpern, J. P., and Filippenko, A. V. 1989, *Ap. J.*, **339**, 742.
Foltz, C. B., Wilkes, B. J., and Peterson, B. M. 1983, *A.J.*, **88**, 1702.
Gaskell, C. M. 1983, in *Quasars and Gravitational Lenses* (*Proc. 24th Liège Int. Ap. Coll.*), p. 473.
Kallman, T. R., and Krolik, J. H. 1986, *Ap. J.*, **308**, 805.
Korista, K. T. 1990, private communication.
Madau, P. 1988, *Ap. J.*, **327**, 116.
Netzer, H. 1987, *M.N.R.A.S.*, **225**, 55.
Penston, M. V., Croft, S., Basu, D., and Fuller, N. 1990, *M.N.R.A.S.*, **244**, 357.
Pérez, E., Penston, M. V., Tadhunter, C., Mediavilla, E., and Moles, M. 1988, *M.N.R.A.S.*, **230**, 353.
Peterson, B. M., *et al.* 1983, *A.J.*, **88**, 926.
Peterson, B. M., Meyers, K. A., Capriotti, E. R., Foltz, C. B., Wilkes, B. J., and Miller, H. R. 1985, *Ap. J.*, **292**, 164.
Peterson, B. M., Reichert, G. A., Korista, K. T., and Wagner, R. M. 1990, *Ap. J.*, **352**, 68.
Pringle, J. M., and Rees, M. J. 1972, *Astr. Ap.*, **21**, 1.
Rees, M. J., Netzer, H., and Ferland, G. J. 1989, *Ap. J.*, **347**, 640.
Robinson, A., and Pérez, E. 1990, *M.N.R.A.S.*, **244**, 138.
Sulentic, J. W. 1989, *Ap. J.*, **343**, 54.
Tadhunter, C., and Tsvetanov, Z. 1989, *Nature*, **341**, 422.
Wilson, A. S., Ward, M. J., and Haniff, C. A. 1988, *Ap. J.*, **334**, 121.
Zheng, W., and Burbidge, E. M. 1988, *Ap. J.*, **328**, 175.
Zheng, W., and Sulentic, J. W. 1990, *Ap. J.*, **350**, 512.

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