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IMPLICATIONS OF ARP 102B: LINE EMISSION FROM AN ACCRETION DISK?

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ABSTRACT

It has recently been proposed that the low-ionization broad lines in AGN originate directly from a radiating accretion disk. A comparison is made between the predictions of the disk models and the largest available sample of line profile parameters. The comparison, made at three different profile heights, shows little agreement with the theoretical predictions. The models imply that all or most profile asymmetries will be red (i.e., excess of emission on the long-wavelength side of the profile). In fact, many blue asymmetries are observed. Perhaps the most significant conclusion from the comparison is that the disk must be completely or almost completely obscured in most AGN (or not a source of significant line radiation). The data suggest that the remarkable agreement between theory and observations for Arp 102B is either fortuitous or an example of a very rare class of AGN with low-ionization broad-line (LIL) emission arising directly from an accretion disk.

Subject headings: accretion — black holes — galaxies: Seyfert — quasars

I. INTRODUCTION

The observation of redshift discrepancies among emission lines in AGN places a serious constraint on any model of the emitting region. Ordinarily one distinguishes between two emission zones in an AGN: the broad-line region (BLR) which shows permitted features such as the Balmer series, and the narrow-line region (NLR) which shows mostly forbidden lines produced by transitions following collisional excitation. Many AGN (Gaskell 1982, 1983; Wilkes 1984) show significant velocity shifts *among* the BLR lines and also shifts of the BLR *relative to* the NLR lines. A recent reanalysis of the spectra for 61 AGN showed that over one-half have BLR versus NLR velocity differences (Sulentic 1989). All evidence is consistent with small or nonexistent shifts of the NLR with respect to the systemic velocity (determined from 21 cm or absorption line measures).

Systematic *blueshifts* ($\leq 10^3$ km s^{-1}) of the BLR high-ionization lines (HIL) with respect to the BLR low-ionization (LIL) features, in the same object (Gaskell 1982; Wilkes 1984), have been interpreted as evidence in support of a disk origin for the LIL emission (Collin-Souffrin, Dumont, and Heidmann 1980; Collin-Souffrin 1987). In this view, the HIL ($n \leq 10^9$ cm^{-3}) arise from clouds directly illuminated by a UV and soft X-ray continuum, while the LIL ($n > 10^{11}$ cm^{-3}) arise, most likely, from a disk illuminated by backscattered hard X-ray photons. This model is attractive for reasons other than providing an explanation for the kinematic difference between the HIL and LIL: (1) it provides a high-density ($n \geq 10^{12}$ cm^{-3}) environment which might account for the strong Fe II LIL features often observed (Collin-Souffrin and Dumont 1989), and (2) it might solve the energy budget problem [too much LIL emission: $F(\text{LIL})/F(\text{HIL}) \approx 2$] discussed by Netzer (1985) and Collin-Souffrin (1986).

Further support for the idea that we are observing disk LIL emission (at least in radio QSOs) comes from a possible correlation between the FWHM of Hβ and the ratio of core-to-extended component radio flux density (at 5 GHz) (Wills and Browne 1986). If one assumes that (LIL) emission-line gas is confined in a plane perpendicular to the radio axis, such a correlation arises quite naturally from a relativistic beaming model. The radio objects in the Sulentic (1989) sample generally support this correlation in the sense that relatively narrow "S" class profiles tend to be radio core-dominated sources, and broader "A" type profiles are the opposite. There is, however, no general correlation between FWHM(Hβ) and profile type in that sample.

II. DOUBLE-HORNED LOW-IONIZATION BROAD-LINE PROFILES

A particularly interesting profile "subclass" that populates the lower (broader profile) part of the above radio correlation involves those exhibiting double-horned structure. The most striking example of this profile type is seen in Arp 102B which is a weak BLRG (Stauffer, Schild, and Keel 1983). The similarity to the 21 cm profile of an inclined spiral galaxy (or to emission lines in a cataclysmic variable star) is visually compelling. Recently, the broad double-horned LIL features in this object have been modeled assuming a relativistic Keplerian disk ($i = 32°$, inner and outer radii 250 and 1000r_g, where $r_g = GM/c^2$) including effects of Doppler boosting as well as gravitational and transverse redshifts (Chen, Halpern, and Filippenko 1989). The most significant and constraining predictions of the model are (1) the double-horned profile shape and (2) the large redshift of the profile centroid. Further refinements of the initial model (Chen and Halpern 1989) have produced an even more striking fit to the observations. These authors have also calculated the expected LIL profile shape for a number of assumed disk inclinations. The most striking results from this calculation must again be the profile shape and the redshifted profile centroid expected at all viewing angles.

III. IMPLICATIONS OF ARP 102B

The successful modeling of Arp 102B, accepted at face value, suggests that the LIL emission arises directly from an accretion disk. The differences between the LIL and HIL profiles in Arp 102B (as evidenced by Lyα; Chen, Halpern, and Filippenko 1989) also support the contention that the HIL region is kinematically distinct. To the best of our knowledge, no one has proposed that *both* LIL and HIL emission originate from a disk.

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The results of Chen and Halpern (1989) suggest that we can identify those AGNs with LIL emission originating from a disk (*assuming Arp 102B is typical of the class*) on the basis of their (1) double-horned and (2) redshifted LIL profiles. Further, as a result of Doppler boosting, we would expect to observe (1) an enhanced blue horn or (2) a blue displacement near the profile peak if the horns are not resolved. Unfortunately, we observe very few profiles with these properties. No double-horned profiles are seen in the large profile sample of Sulentic (1989). Is it possible that LIL emission arises from disks in many cases but that a double-horned profile is not seen? Is Arp 102B one of an exceedingly rare group of AGN where we are able to see an emitting disk? The unsatisfactory nature of the latter possibility has led to various explanations for the rarity of double-horned profiles: (1) the central depression is filled in by the narrow-line component (Calvani, Marziani, and Padovani 1989) or by some additional source of LIL emission that is kinematically distinct (e.g., multicomponent models; Peterson 1987), (2) one of the peaks is typically suppressed or obscured (Sulentic 1989), or (3) the radius of the emitting region of the disk may typically favor profiles where the separation of the peaks is small resulting in blended single-peaked features (Chen and Halpern 1989; Collin-Souffrin and Dumont 1989).

Without discussing the merits of the above explanations for the rarity of double-horned profiles, we note that a profile redshift is still expected, although, again, its magnitude depends upon the black hole mass and the disk parameters. Certainly models or parameter values that favor a distinct double-horned profile are also the ones that predict a large profile redshift. Do we see any other examples of a double-horned profile? The next most cited example is 3C 390.3. Recently Pérez *et al.* (1988) have attempted to fit an accretion disk profile calculated by Mathews (1982) to 3C 390.3 during its "bright" phase. While the fit to the profile is qualitatively good, their data suggest that the profile shows a 400 km s^{-1} *blueshift* at FWHM or below, with respect to the NLR. Recent higher resolution spectra obtained for 3C 390.3 by one of us (P. M.) confirm this profile blueshift (450 ± 150 km s^{-1}) during a quieter phase. This would seem to rule out a disk interpretation for this object unless an explanation for the blueshift can be found. An unpublished analysis by W. Zheng suggests that the blueshift can approach zero during some phases of the profile variation. Another argument against a disk origin for LIL emission in 3C 390.3 involves the lack of correlation in the variations observed from the two "horns" in that object (Oke 1987; W. Zheng, unpublished). It is also interesting to note that neither Arp 102B nor 3C 390.3 shows evidence for strong Fe II multiplet emission. Of course, Fe II blends composed of lines with profiles similar to the Balmer series in these objects might be difficult to distinguish from an enhanced continuum.

Several other AGN with very broad or double-peaked LIL (3C 382, Akn 120, NGC 5548, and Q1404+285) have been cited as examples of "double-horned" profiles (Filippenko 1987; Collin-Souffrin and Dumont 1989). 3C 382 (Osterbrock, Koski, and Philips 1976) bears little resemblance to Arp 102B in the sense that its Balmer line profiles are essentially triangular in shape with zero or small blueward centroid displacements. The red-displaced peak in Akn 120 and Q1404 is stronger than the blue one. The modeled displaced peaks in NGC 5548 (and Fairall 9; Peterson 1988) do not center on the systemic velocity. If the horns resulting from disk emission are partially "obscured" by emission from another source of BLR radiation, deconvolution should reveal peaks displaced equally to the red and blue. If we argue that Arp 102B is a typical accretion disk, then we expect many double-horned profiles with large redshift. We observe no other case as compelling as Arp 102B.

IV. A COMPARISON BETWEEN THEORY AND OBSERVATION

The above results, particularly the apparent uniqueness of Arp 102B, call into question a disk origin for the LIL emission in any AGN. The conflict between the observations and predictions from disk models has recently been the subject of some discussion (Chen and Halpern 1989; Collin-Souffrin and Dumont 1989; Dumont and Collin-Souffrin 1989). Extensions of the models have been proposed to account for the discrepancies, mostly involving emission from larger disk radii (see previously cited references). The modified models are able to produce profiles closer to those observed, especially after allowance for turbulence. We propose a more general comparison of the *domain* of disk model predictions with that for the data. This is, in principle, more useful than discussing agreement or disagreement between the models and any single AGN. There are at least two useful parameters for such a comparison: (1) the wavelength of the profile centroid at different profile heights [$C(3/4)$, $C(1/2)$, and $C(1/4)$] measured with respect to [O III] λ5007 FWHM, and (2) the profile asymmetry index (here defined as [$C(3/4)$-$C(1/4)$]/FWHM). While the asymmetry index, as defined, is constant for any object, the centroid value can change significantly. Figure 1 presents a comparison of the model predictions for these parameters and the observations. We have used a representative set of model parameters (inner and outer radii, inclination) that should effectively define the domain in shift-asymmetry space. The largest existing data sample (Sulentic 1989) is used for the comparison. This sample included all AGN (1) with published spectra of moderate to high resolution ($\simeq 10$ Å) and (2) with weak/absent Fe II optical emission or corrected for the presence of Fe II emission. The assumption is that this sample is large enough to allow us to characterize the observational LIL parameters for AGN (i.e., Seyfert galaxies, QSOs, and BLRG).

We did not think that any accretion disk model was sophisticated enough to give exact predictions that could be directly compared to observations. We decided to use the simplest approach in evaluating theoretical line profiles since we are mainly concerned with general trends rather than with detailed fits. We therefore decided (rather than using a fully general relativistic treatment [see, e.g., Fabian *et al.* 1989]) to use formula (14) in Chen, Halpern, and Filippenko (1989), which takes into account all relevant general relativistic effects, but is correct only to first order in M/R and for inclination angles greater than $\sim 5°$. Near-edge-on profiles generated from this expression produce a spurious third peak near the systemic velocity. In this way we obtained line profiles for r_{IN}, r_{OUT}, and the inclination angle as free parameters (we fixed the exponent in the surface emissivity power law to be $Q = 3.2$ [see eq. (9) in Chen *et al.*]). Models were also generated with $Q = 2.2$, but they do not alter the conclusions and, therefore, are not shown. From the plots we then evaluated the FWHM, $C(3/4)$, $C(1/2)$, $C(1/4)$, the asymmetry index, the peak ratio and separation. Moreover, in order not to rely on a single model, we did the same for the plots of Hβ presented by Dumont and Collin-Souffrin (1989) for their model of an accretion disk illuminated by a central source of nonthermal radiation. These results for radiation from large disk radii occupy a small part of the total model domain near the origin. Data for both models are

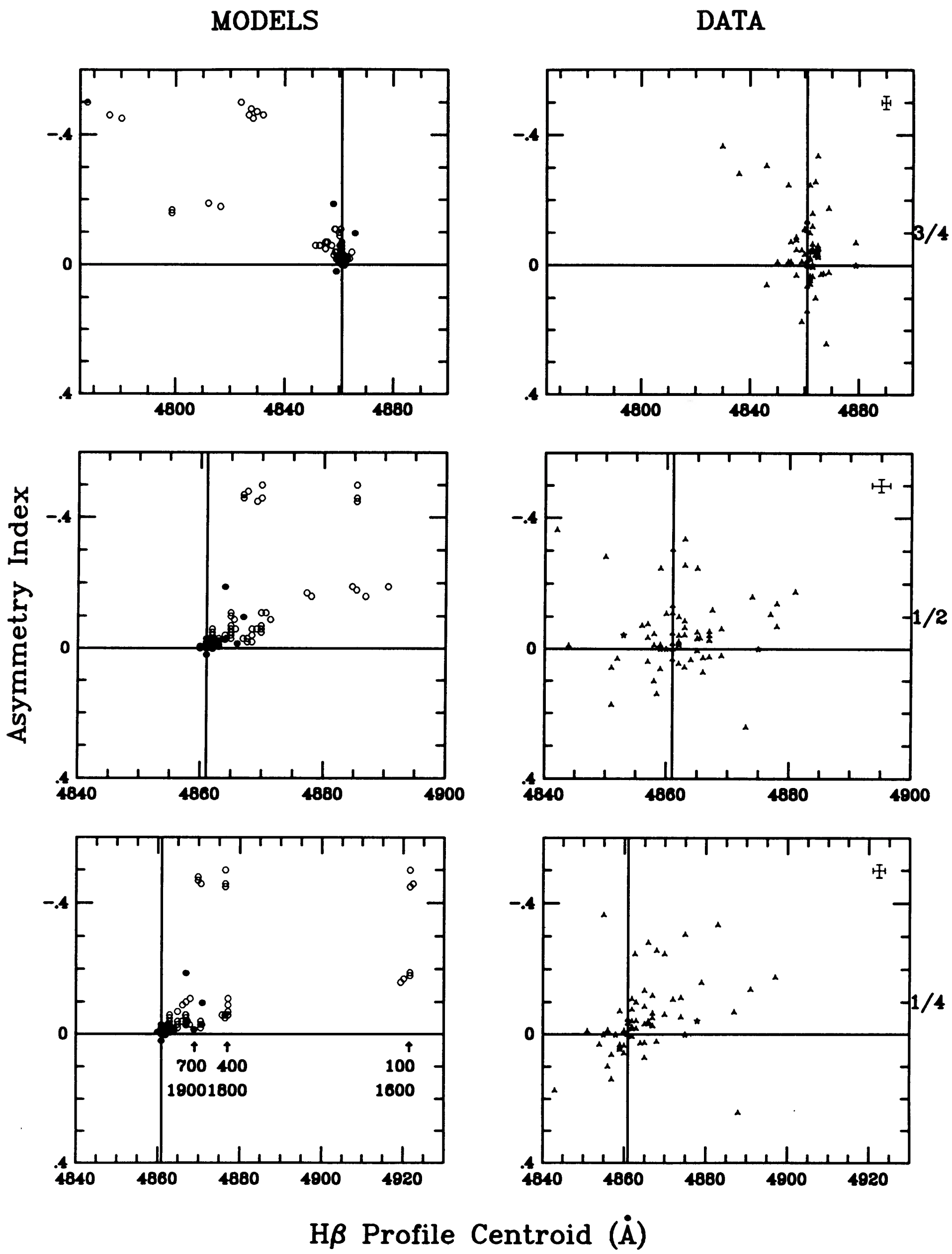

FIG. 1.—A comparison of model predictions (*left column*) and observations (*right column*—1 σ error bars in upper right corners) for the Hβ profile. The abscissae are profile centroid in angstroms, and the ordinates are profile asymmetry index. The first, second, and third rows present the comparison at 3/4, 1/2, and 1/4 profile height, respectively. Models were derived from Chen and Halpern (1989) (*open circles*) and Collin-Souffrin and Dumont (1989) (*filled circles*). A random and representative set of disk inclinations and radii were used. The data sample was taken from Sulentic (1989). Vertical axis corresponds to the rest wavelength for Hβ.

plotted for inclination angles of 15°, 25°, 45°, and 65°. We considered inner and outer disk radii in the ranges from 100 to 700 and 400 to 1900r_g for the Chen and Halpern (1989) model. Corresponding ranges for the Collin-Souffrin and Dumont (1989) model are 1000–4000 and 10^3–$5 \times 10^5 r_g$. We end up therefore with two sets of theoretical data to be compared with observations. The assumption here is that we have sampled a sufficiently large range of disk radii and inclination values in order to effectively define the domain of disk models.

Each of the three profile measures has certain advantages and disadvantages for the comparison with the models. The 3/4 level is most sensitive to the effect of Doppler boosting in the models. It is the only level where the models predict significantly blueshifted profiles. The lowest (1/4) level in the profile is most sensitive to the gravitational redshift which decreases rapidly as the inner radius of the emitting region is increased in the models. The lower left-hand plot in Figure 1 illustrates this by labeling the points corresponding to different values for the inner radius of the emitting region. Observationally, the 1/4 level is the most difficult to measure accurately.

The data measures for 3/4 height shows little correspondence with the models. We see no preference in the data for blue shifted profiles. Numerous data points fall outside of the model domain entirely. The disagreement between models and data becomes even more striking at the 1/2 level. The data show little preference for redshifts or blueshifts while the models strongly favor redshifts. The best agreement is seen at the lowest 1/4 level where models and data favor redshifted profiles. Still there are a large number of profiles that show properties that fall outside of the domain of the models. The models strongly favor red asymmetries while the data show a distribution more symmetric around zero except for eight extremely red asymmetric points. Even these extremely asymmetric profiles show equal numbers of red and blue centroid shifts.

The sample of Sulentic (1989) showed a tendency for the mean profile centroid to become increasingly redshifted as one goes from line peak to the base, a result, at first glance, consistent with the idea that the relatively blue peak of the profile is Doppler-boosted. This was mostly the effect of a few outliers pulling the mean of the distribution to the red or blue. Removal of the outliers from the calculation of the means reveals a possible profile redshift of about 100 km s^{-1} at all profile heights (Sulentic 1989). The distribution of centroids near the base of the profiles (1/4 maximum), however, reveals only a small number of cases where the redshift is similar to that for Arp 102B. Fifty-seven percent of the Sulentic (1989) sample shows a measurable shift; redshifts are only slightly more common than blueshifts. Blueshifts close to 2000 km s^{-1} are observed. The mean for the full width at quarter maximum distribution of 61 profiles is 4865.1 Å which corresponds to $\approx$200 km s^{-1} redshift. The lack of bimodality in the centroid distribution (ignoring the eight extremely asymmetric profiles) suggests that a single "stochastic" process is responsible for shifts. Disk emission models would be forced to invoke at least two mechanisms conspiring to produce the single smooth distribution of shifts that is observed. If the "extreme" sample were the second disk-emitting population, we would expect profiles of class AR, B (in the system used by Sulentic 1989) to be most common, which is not observed.

Ruling out a disk origin for the LIL emission in most AGNs reinstates the problem of the kinematic difference between the HIL and LIL BLR regions. Accepting a disk origin for all, or most, of the nonblueshifted [at $C(1/2)$ and $C(1/4)$] profiles raises the question of how the blueshifted ones arise. The existence of the blueshifts and blue asymmetries among so many LIL profiles must be considered a challenge to any model attributing the emission to an accretion disk.

The above results answer a question raised in Sulentic (1989). All basic profile types, symmetric (S), red or blue asymmetric (AR or AB), *and double-horned*, show red and blue displacements. Profiles of type SB, AB, and AB, R or B, as defined there (representing, respectively, symmetric profile with blue shift, blue asymmetric unshifted profile and blue asymmetric profile with redshift or blueshift) are virtually forbidden by the disk models. Other possibilities have been proposed to account for the complex, broad, double-horned or asymmetric profiles including (1) binary black holes (Gaskell 1983) and (2) conical or jet like configurations (W. Zheng and L. Binette, in preparation) for the BLR. The problem still remains in explaining a data distribution that, at this point, almost equally favors redshifted and blueshifted single-peaked profiles. One possibility is that the shift phenomenon arises by some other (external) mechanism. Such an effect would be necessary to resurrect a disk model for 3C 390.3 (assuming the shift is the only impediment). One could then argue that the line shifts were due to some external cause while the profile shape was determined by the disk kinematics. An explanation for the blue profile asymmetries would also have to be found.

Wolf (1987) and Wolf, Foley, and Gori (1989) have shown that correlations in the fluctuations of a source distribution can produce line shifts. This induced partial coherence could arise either directly from correlations between the elementary radiators (BLR clouds?) or through a scattering process (in the NLR?). This mechanism is attractive because it could provide redshifts and blueshifts independent of the AGN kinematics. It also produces shifts that are of the order or less than the line width which is generally observed (Sulentic 1989). A disadvantage of the mechanism is that the shifts would be frequency dependent. Another is, obviously, the lack of a mechanism for generating the required fluctuations in source or surrounding medium. Recent work (James, Savedoff, and Wolf 1990) suggests that appropriate scattering functions can be found in anisotropic radiation fields that result in frequency-independent shifts. This result brings to mind the increasing evidence for both collimated particle and radiation fields in AGN. The existence of significant numbers of *both* red and blue profile shifts is surely one of the biggest challenges to models of the BLR.

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