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LINE EMISSION FROM ANOTHER RELATIVISTIC ACCRETION DISK: 3C 332

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ABSTRACT

Observational and theoretical investigations are reviving interest in the hypothesis that the broad emission lines in some active galactic nuclei (AGNs) might arise in a relativistic accretion disk. But until now only one object, Arp 102B, has displayed the distinctive double-peaked, asymmetric line shape which is fitted well by the disk model. This *Letter* reports the discovery of a line profile in a second radio galaxy, 3C 332 ($z = 0.1511$), which is so similar to that of Arp 102B as to suggest the existence of a small but distinct class of objects in which the broad emission lines arise largely in the disk. In the context of the model, the line-emitting region in 3C 332 lies between $r_1 \sim 175$ and $r_2 \sim 525 r_g$. In comparison, the line profile of Arp 102B is fitted with $r_1 \sim 350$ and $r_2 \sim 1000$. All aspects of the model developed for Arp 102B are consistent with the properties of 3C 332.

Subject headings: galaxies: individual (3C 332) — galaxies: nuclei — line profiles — radio sources: galaxies

I. INTRODUCTION

Of the handful of AGNs that have double-peaked emission lines which might be attributed to Keplerian rotation, only Arp 102B provides a convincing fit to the detailed relativistic model (Chen, Halpern, and Filippenko 1989; Chen and Halpern 1989, hereafter CH). But even in this best case, the interpretation has been questioned on the basis of profile variability (Miller and Peterson 1990). Another suggested candidate, 3C 390.3 (Oke 1987; Perez *et al.* 1988), is more variable and deviates significantly from the simplest models. Objects in which double-peaked profiles have been seen in *difference* spectra, like Akn 120 (Peterson *et al.* 1985; Alloin, Boisson, and Pelat 1988) and NGC 5548 (Stirpe, de Bruyn, and van Groningen 1988), make perhaps even weaker claims to be included among the candidates.

Although it is believed, mainly for theoretical reasons, that most AGNs have accretion disks, there is no reason to prefer this for the location of the broad emission-line region in the majority of objects. A more or less "standard" cloud model may turn out to be a satisfactory description of the typical line profile, even though the velocity field of the clouds is not yet understood. But the line profile of Arp 102B is very different from the typical one and could indicate a different velocity field. Theoretical requirements for line emission from accretion disks have been discussed by CH and by Dumont and Collin-Souffrin (1990). But mainly, it would help to have more observed examples of double-peaked line profiles in order to evaluate whether the accretion disk is a viable origin for any of them.

II. OBSERVATIONS AND REDUCTIONS

One year ago, a program of spectroscopy was begun on the 2.1 m telescope of the Kitt Peak National Observatory (KPNO) to search for more examples of the Arp 102B phenomenon in the Hα and Hβ lines of known AGNs. To date, approximately 15 candidates have been observed using the Gold Camera CCD spectrometer. The objects were selected based on previous reports of unusually broad lines, or bumps in the line profiles which are displaced from the rest wavelength. The majority of the candidates are radio galaxies. Figure 1 shows the Hα line profile of 3C 332, the only one in this sample which resembles that of Arp 102B in striking detail and clearly fits the double-peaked accretion disk model. This spectrum is the sum of three exposures totaling 130 minutes, taken on 1990 May 28 and 29. The resolution is 6.5 Å. The slit width was 1".8, and the spectrum was extracted from a 3".9 length along the slit. The seeing was approximately 2" during these exposures. Standard stars of Oke and Gunn (1983) observed and reduced in the same manner were used for flux calibration and removal of all the atmospheric absorption bands in this spectral region. Emission-line fluxes measured from Figure 1 and uncorrected for reddening are listed in Table 1.

The continuum in the region of the Hα line contains a substantial starlight component, as evidenced not only by the strong Na D absorption line, but also by the TiO band which is present as a broad, shallow dip around 7100–7200 Å. A spectrum of the S0 galaxy NGC 7457, also shown in Figure 1, matches the absorption features and continuum shape of 3C 332 in detail, and a direct subtraction of the two spectra produces a nearly perfect removal of the continuum. Figure 2 shows the line profile of 3C 332 after subtraction of the continuum. For comparison, the Hα profile of Arp 102B from CH is also displayed. The disk model which best fits 3C 332 must be very close to that for Arp 102B, since the line profiles are so similar. The essential characteristics of a relativistic Keplerian disk are present in both profiles, namely, the blue peak is higher than the red peak due to relativistic beaming, and there is an asymmetry about the rest wavelength consistent with transverse and gravitational redshift. The main difference between the profiles is that the peaks in 3C 332 are about 50% farther apart than in Arp 102B, as are the wings of the line. The model described below can distinguish between a larger inclination angle and a smaller disk as the cause of the larger line width in 3C 332.

III. THE MODEL FITTING

Equation (11) of CH was used to fit the broad-line profile of 3C 332. The model refers to a disk with dimensionless inner

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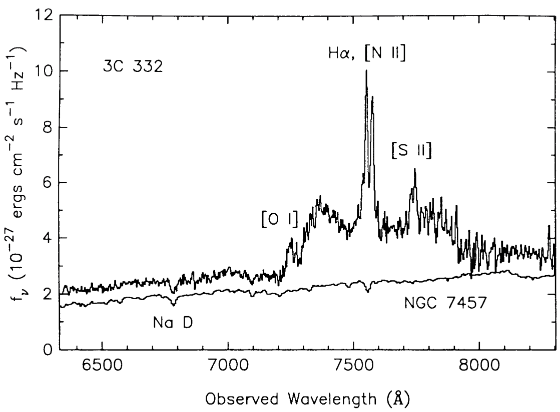

FIG. 1.—Summed spectrum of 3C 332 ($z = 0.1511$) obtained on 1990 May 28 and 29. Narrow emission lines are labeled, as is the stellar Na D absorption line. The broad, double-horned Hα profile is apparent. A suitably redshifted and scaled spectrum of the S0 galaxy NGC 7457, which is used to subtract the continuum, is also shown.

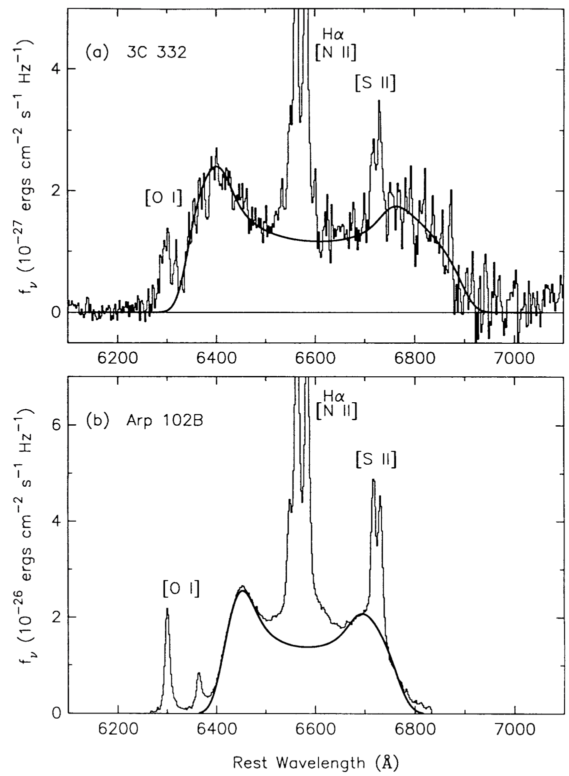

FIG. 2.—(*a*) Continuum-subtracted Hα line profile of 3C 332, shifted to the rest frame of the galaxy. The solid line is the best fit to the accretion disk model described in the text. The parameters of the fit are $\xi_1 = 175$, $\xi_2 = 525$, and $i = 35°$. (*b*) Hα line pofile of Arp 102B, and model fit from CH. The parameters of the fit are $\xi_1 = 350$, $\xi_2 = 1000$, and $i = 32°$.

and outer radii ξ_1 and ξ_2, respectively, in units of GM/c^2. M is the mass of the black hole. The line emissivity varies as ξ^{-q}, and i is the inclination angle of the disk axis with respect to the observer. Local broadening is represented as a Gaussian with standard deviation σ, which can be expressed in units of km s^{-1}. Thus, the five model parameters are ξ_1, ξ_2, q, i, and σ. However, it was found that the same values of q and σ which had been used to fit Arp 102B were adequate for 3C 332. Therefore, q and σ were held fixed at 3 and 850 km s^{-1}, respectively, while ξ_1, ξ_2, and i were varied. Evaluation of the fits by eye showed that a smaller disk in 3C 332 is the favored explanation for the wider line. The inner and outer radii ξ_1 and ξ_2 are 175 and 525, respectively, with an uncertainty of about a factor of 2 associated with the range of possible inclination angles, $i = 35° \pm 5°$. The corresponding parameters for Arp 102B are $\xi_1 = 350$, $\xi_2 = 1000$, and $i = 32°$, with similar uncertainties. The uncertainties are estimated as in Figure 2 of Chen, Halpern, and Filippenko (1989), in which the fits of a range of models to the peaks and wings of the line are evaluated by eye as to their acceptability.

In the model of CH, the inner radius of the thin line-emitting disk is identified with the inner boundary of the region dominated by gas pressure,

$$\xi_{rg} = 750\alpha^{2/21}\dot{m}^{16/21}M_8^{2/21}\ , \tag{1}$$

where α is the viscosity coefficient and $\dot{m}$ is the accretion rate in units of the Eddington value. The region interior to this radius is unstable and puffs up to form a hot ion torus which photoionizes the outer disk. This scenario would be consistent with a $10^8\ M_\odot$ black hole in 3C 332 accreting at $\sim$0.15 the Eddington rate. The emissivity index q is equal to 3 as a result of the oblique illumination of the outer disk by the ion torus.

TABLE 1

EMISSION-LINE FLUXES OF 3C 332

Line	Flux (10^{-15} ergs cm^{-2} s^{-1})
[O I] λ6300	1.6
[N II] λ6548	1.2
Hα (broad)	53.4
Hα (narrow)	4.1
[N II] λ6583	3.5
[S II] λ6716	0.7
[S II] λ6730	1.1

IV. DISCUSSION

3C 332 was selected from the classic study of broad-line radio galaxies by Grandi and Osterbrock (1978), in which it was noted that the full width at zero intensity of the Hα line is 31,000 km s^{-1} although the spectrum was not shown. Only a narrow line was reported at Hβ, although Grandi and Phillips (1979) and Antonucci (1984*b*) subsequently detected a broad Hβ component. A spectrum shown by Osterbrock (1979) looks similar to the present one at Hα and in addition shows weak broad Hβ. Unfortunately, contemporaneous data covering the Hβ region were not obtained for comparison with the Hα profile presented here.

Optical spectropolarimetry and radio observations of 3C 332 taken around 1981 were described by Antonucci (1984*a*), who noted that the *continuum* polarization is perpendicular to the axis connecting the inner parts of the radio lobes. The spectrum was not shown, but Antonucci concluded that the optical continuum contained very little starlight, with a fractional contribution of $\sim$0.03 at Hβ. This is somewhat surprising since the starlight fraction in the present data and that of Osterbrock (1979) is quite large. The rest-frame equivalent width of the stellar Na D absorption line in Figure 1 is 3.5 Å, which in comparison with normal elliptical or S0 galaxies (Tonry and Davis 1981) indicates that the starlight fraction is now *at least* 0.55, even in a narrow slit. Perhaps part of the discrepancy is due to the different region of the spectrum used, although it is difficult to evaluate Antonucci's claim because his spectrum was not shown. Barring a factor of 20 variation in the nonstellar continuum, it seems that the true starlight contribution must be large. Additional evidence in favor of the larger starlight contribution comes from the detection of the stellar Ca H and K lines in the discovery spectrum, also unpublished (Burbidge and Strittmatter 1972).

Independent evidence for accretion comes from the *Einstein Observatory* detection of a pointlike X-ray source with a flux of 1.0×10^{-12} ergs cm^{-2} s^{-1} in the 0.5–3.5 keV band (Morganti *et al.* 1988), corresponding to a luminosity of 1.0×10^{44} ergs s^{-1} for $H_0 = 50$ km s^{-1} Mpc^{-1}. (Note that Morganti *et al.* mistakenly associated 3C 332 with the galaxy NGC 6109 and so used the wrong redshift in the calculation of the X-ray luminosity.) The photoionizing continuum extrapolated from the X-ray detection is adequate to power the broad Hα line, which has a luminosity of 6.1×10^{42} ergs s^{-1}. In comparison, the X-ray and Hα luminosities of Arp 102B are 8.6×10^{42} ergs s^{-1} and 1.4×10^{42} ergs s^{-1}, respectively. In the ion torus model of CH, the line-emitting region of the disk intercepts just under 10% of the ionizing flux, which is sufficient to power the emission lines in both of these cases. The fact that both of these line-emitting accretion disks are in radio galaxies is in accord with speculations by CH that the structure of an ion torus, first proposed in connection with radio galaxies (Rees *et al.* 1982), might be particularly suited to the formation of optical lines in the outer, thin disk.

An independent test of the disk model using spectropolarimetry of the *emission line* is possible for 3C 332, as the assumption that electron scattering is responsible for the local broadening predicts that the line should be polarized perpendicular to the radio axis (Chen and Halpern 1990). Continued monitoring of the line profile for small changes caused by variability of the central illuminating source could in principle enable a precision measurement of the mass of the black hole via the reverberation mapping technique (Stella 1990). As in the case of Arp 102B, monitoring for just a few years will test the alternative binary black hole model, which predicts that the peaks will move in wavelength like a double-lined spectroscopic binary with a period P, given by Halpern and Filippenko (1988) as

$$P \leq 3.4 M_9 (v \sin i)_4^{-3} \text{ yr} , \quad (2)$$

where M_9 is the sum of the masses in units of 10^9 $M_\odot$ and $(v \sin i)_4$ is the observed radial velocity in units of 10^4 km s^{-1}. A binary with masses less than 10^{10} $M_\odot$ could be ruled out in less than 10 yr. Possibly, this test can already be performed by comparison with the published and unpublished spectra discussed above.

V. EDITORIAL

The object 3C 332 is in some ways a better prototype accretion disk candidate than Arp 102B, as the broad peaks are farther apart, and the [S II] lines are a negligible contaminant of the red peak. However, it is about 10 times fainter than Arp 102B, and more detailed modeling of the line profile of 3C 332 will have to await higher signal-to-noise ratio spectra obtainable on telescopes larger than the KPNO 2.1 m. The discovery of a line profile which is so unusual, yet so similar to that of Arp 102B, inspires hope that more candidates await detection. The near-infrared spectral region is somewhat difficult because of the numerous bright ionospheric emission lines and the deep atmospheric absorption bands. However, this is where new members of the class are likely to be discovered, because the moderate redshift samples a larger volume of space, and the broad Hα line seems to be much more prominent than Hβ in the successful candidates. To be optimistic, this means that accretion disk line profiles may continue to be found among known radio galaxies at moderate redshift, by concentrating on objects with very broad lines and large Balmer decrements.

But even before any further observations are made, the results reported here raise the following difficult questions:

1. To what extent does the discovery of a second profile which conforms to the accretion disk model lend additional support to this model for either Arp 102B or 3C 332?

2. How are these objects to be reconciled with the vast majority of AGNs whose lines do not fit the accretion disk model?

3. Is the model falsifiable, and does it have unique aspects which offer any possibility of being proven true with reasonable confidence?

In answer to the first question, it would seem that two objects which can be fitted by the model are better than one. And although the model is completely determined by five parameters, two of them, the emissivity index q and the broadening parameter σ, have been held fixed between the two objects. This consistency should be considered additional support, especially since these are the two parameters which one would think are least likely to vary among different disks.

With respect to the second question, it is not claimed here that the emission lines in any AGNs other than Arp 102B and 3C 332 are coming from a disk. It is possible that in the future, some empirical connection may be demonstrated between the characteristics of these unusual lines, and those of the majority of AGNs. Such a connection may or may not argue that the lines do or do not originate in a disk. But this connection has not yet been made (Sulentic 1989; Sulentic *et al.* 1990). Meanwhile, arguments of the form "we suspect that most AGNs have accretion disks; therefore, any model which attributes line emission to only a small minority of them must be wrong" are circular at best. There is no reason to rule out of hand the possibility that those few lines which are manifestly different from the rest can be coming from a disk rather than from clouds.

Related to the third question is an objection which is often raised about the number of parameters in the model: With five free parameters, cannot any profile be fitted? The answer is no, and the reason is that a good quality broad-line profile has perhaps 100 degrees of freedom, corresponding to the number of resolution elements. Five parameters (or perhaps only three if q and σ continue to remain constant) are a small number in comparison. The inability to fit any and all profiles is an advantage, since otherwise the model would not be falsifiable. There are common properties of any of the disklike profiles, including the relative heights of the peaks and the redward asymmetry of the wings, which can be used to falsify the model or to argue for its correctness in particular cases. To put it another way, one cannot rightfully object *both* that the model fits too few objects *and* that there are too many free parameters. If only a few disks emit lines, then a good model *should* fit only those objects. And if a model is to describe a disk, then it *needs* at minimum four parameters.

None of these questions have been answered definitively here. But at present, no better model than the relativistic disk has been presented for the spectra in Figure 2.

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