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THE DOUBLE BROAD-LINE EMITTING REGIONS IN NGC 5548 AS POSSIBLE EVIDENCE FOR A SUPERMASSIVE BINARY

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ABSTRACT

The Seyfert 1 galaxy NGC 5548 is shown to have two distinct broad-line emitting regions at different radial velocities. The more luminous region is redshifted relative to the galaxy's systemic velocity by ~ 275 km s^{-1} and undergoes flux changes that are correlated with the continuum variability with a lag of 15 ± 9.4 days. The weaker component is blueshifted relative to the systemic velocity by ~ 2475 km s^{-1}; it also varies with time, but the variability of this region is uncorrelated with the continuum variability. Although there is at this time no direct evidence that the components are gravitationally bound, it is suggested that these observations might be explained by a supermassive binary system, with each binary component having its own associated broad-line region. The period of this system is expected to be at least of order 110 yr, and the semimajor axis of the orbit must be at least $\sim 10^{17}/\sin i$ cm (i.e., $48/\sin i$ lt-days); these parameters lead to total masses for the system which are consistent with other estimates.

Subject headings: black holes — galaxies: individual — galaxies: Seyfert — spectrophotometry

I. INTRODUCTION

The emission-line profiles of the Seyfert 1 galaxy NGC 5548 are strongly asymmetric (Anderson 1971) and variable. It has been suggested by several investigators that the emission-line profiles of NGC 5548 are due to a superpositioning of a number of physically distinct components. Ulrich and Boisson (1983), in analogy with work on NGC 4151, argue that the different structure of various UV emission lines indicates the existence of at least three separate broad-line regions (BLRs) with different physical conditions in each. Recently, Peterson and Ferland (1986) have shown that during a continuum outburst in 1984, He II λ4686 underwent a dramatic increase, much greater than would be expected in even a radiation-bounded geometry, and that the line profile was much broader than the Balmer line profiles. They therefore conclude that the He II emission arises in gas which was not previously seen in emission and suggest that this increase may be the signature of an accretion event in the nucleus of NGC 5548. Peterson (1987) has shown that the Balmer lines are comprised of at least two separate components at different radial velocities and argues on the basis of the continuum flux, line flux, and line profile variations that the components arise in at least two physically distinct regions.

In this *Letter*, new spectroscopic observations of NGC 5548 are reported and compared with the earlier observations of Peterson (1987). The new observations reveal that the weak component blueward of line center has undergone a pronounced increase in strength since it was first identified. An attempt is made to deconvolve the two emission-line components, and it is shown that they both vary, but the flux in only the stronger component is correlated with the continuum variations.

II. OBSERVATIONS AND ANALYSIS

The new observations reported here were obtained with the Ohio State University image-dissector scanner (Byard *et al.* 1981) on the Perkins 1.8 m telescope of Ohio Wesleyan University and The Ohio State University at Lowell Observatory. A journal of observations is presented in Table 1. The data acquisition, reduction, calibration, and analysis are as described by Peterson (1987). Attempts were made to remove the stellar component from the continuum and the narrow-line contribution from the broad emission lines, as described by Peterson (1987 and references therein). The continuum fluxes given in column (5) of Table 1 and the Balmer-line fluxes given in columns (6)–(8) have been corrected for these effects. The continuum level is found to be comparable to that during mid-1984 and early 1985, but the Balmer-line fluxes have increased significantly since our earlier observations. More striking are the changes in the emission-line profiles; the weak component in the blue wing of the Balmer lines has increased greatly in strength. This increase in the blue wings of the Balmer lines which first became apparent in 1985 (Peterson 1987) has been independently noted by Chuvaev (1986).

As in 1984 and 1985, the Balmer line profiles changed little if at all during the course of a single observing season. Therefore in an effort to increase the signal-to-noise ratio in each profile, data from the three separate years were averaged. The resulting Hβ profiles are shown in Figure 1. Clearly the line has become decidedly more blueward asymmetric each year.

In our earlier paper (Peterson 1987), the differences between the 1985 and 1984 Hβ and Hγ profiles are shown, clearly demonstrating the existence of a second fairly broad, blueward displaced component. The profiles shown in Figure

TABLE 1

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UT Date (1986) (1)	JD (2,440,000 +) (2)	Aperture (3)	Wavelength Range (Å) (4)	$F_\lambda(5500)$[a] (5)	$F(\mathrm{H}\beta)$[b] (6)	$F(\mathrm{H}\gamma)$[b] (7)	$F(\mathrm{H}\alpha)$[b] (8)
Jan 11	6441	7″	4000–6300	6.75	10.55	4.71	...
Jan 24	6454	7	4000–6300	6.39	10.81	5.15	...
Feb 23	6484	7	4000–6300	6.62	9.22	4.04	...
Mar 4	6493	7	4600–7200	7.28	10.17	...	42.44

[a] In units of 10^{-15} ergs s^{-1} cm^{-2} Å^{-1} in the rest frame of NGC 5548.
[b] In units of 10^{-13} ergs s^{-1} cm^{-2} in the rest frame of NGC 5548.

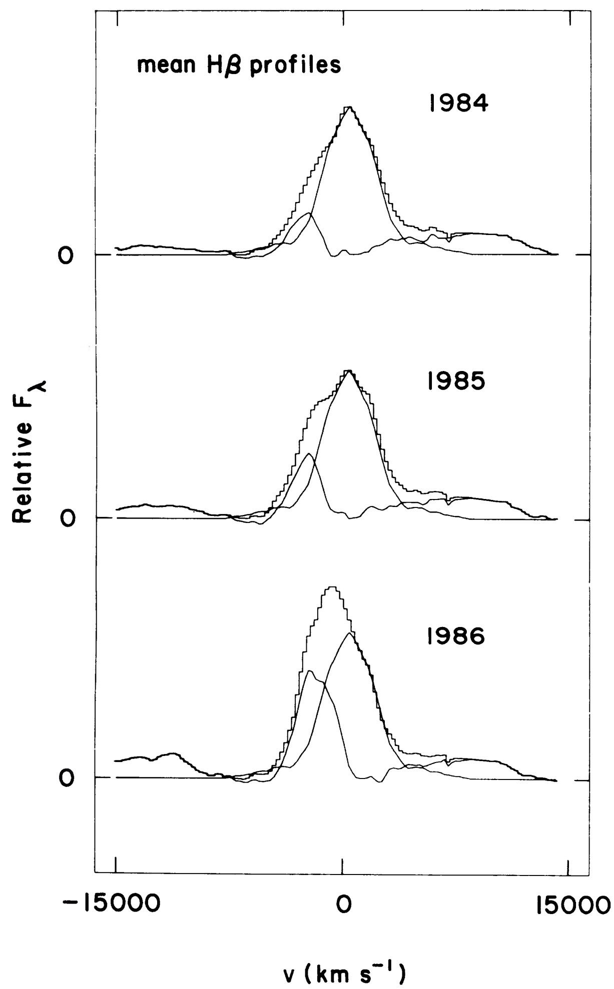

FIG. 1.—The mean Hβ profiles for the 1984, 1985, and 1986 observing seasons are shown as histogram plots. Also shown to illustrate the deconvolution process are scaled template profiles, constructed from Hβ and Hα profiles from 1984, as described in the text, and the difference between the observed and template profiles. The residuals clearly demonstrate the existence of a second broad-line component, blueshifted by about 2300 km s^{-1} relative to the narrow emission lines.

1 reveal that this component was probably present but very weak even in the 1984 data. It was therefore decided to try to deconvolve the two components by making a few straightforward assumptions:

1. It is assumed that the blue component was sufficiently weak in 1984 that the red wing of Hβ is uncontaminated by it.

2. The red wing of Hβ can be deconvolved from the shelf of emission longward of Hβ by using the Hα profile from 1984 February 7 as a template to model the far red wing of Hβ (see Crenshaw 1986). This turns out to be not a critical assumption, so long as some reasonable effort is made to remove the shelf emission from the Hβ profile.

3. It is assumed that the red component is symmetric about the peak wavelength of the 1984 profile. This symmetric template profile is shown along with the observed profile in the top frame of Figure 1; the effect of removing the shelf emission from the red wing is easily seen, and the presence of the blue component is obvious, particularly in the difference between the observations and the symmetric template profile.

4. It is then assumed that the template profile can be used to model the contribution of the red component in all other spectra. The red component is allowed to change in total flux, but it is assumed that the central wavelength and shape remain constant with time.

The blue component was then isolated in each spectrum by modeling the red component as described above. This operation was performed for each spectrum listed in Table 1, as well as for the spectra shown by Peterson (1987). The results of modeling the components in the mean spectra from each year are shown in Figure 1 for illustrative purposes.

The component fluxes which result from this two-component deconvolution of the Hβ profiles are shown in Figure 2. Also included in Figure 2 are the results of applying the same procedures to data obtained before 1984 (also reported by Peterson 1987), but the continuum determinations are less reliable because different size spectrograph entrance apertures were employed, which makes subtraction of the starlight from the galaxy less certain. The red component seems to follow the continuum variations fairly closely,

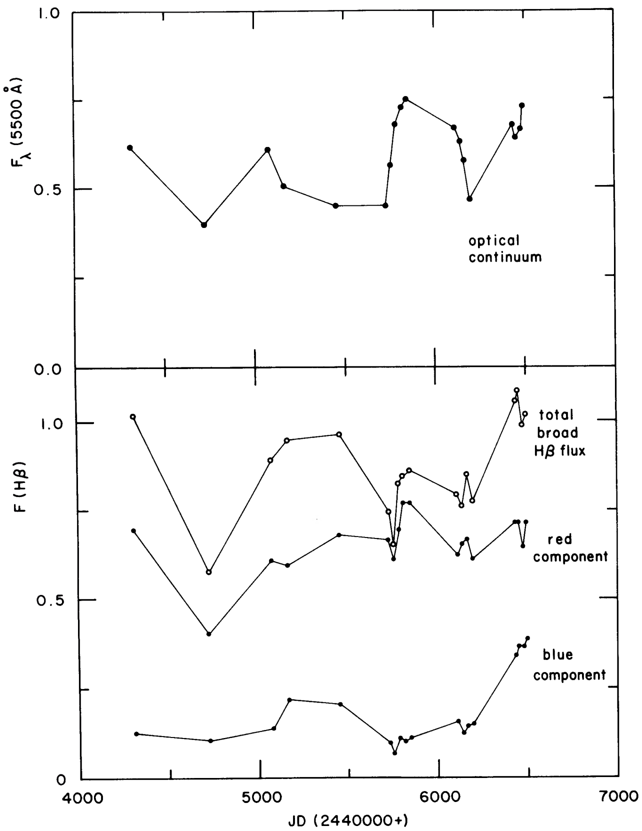

FIG. 2.—The upper panel shows the behavior of the optical continuum of NGC 5548 over the last 6 yr. The lower panel shows the total broad-line Hβ flux and the flux in the blue and red components, separated as described in the text. The small differences between the red component plus blue component fluxes and the total fluxes arise from different methods of isolating the shelf emission redward of Hβ. Variations in the red component fluxes are correlated with continuum variations, but variations in the blue component are not.

but it is clear that while the blue component changes in strength, changes in the flux of this component are not obviously correlated with continuum changes. This analysis can be formalized by employing the cross-correlation technique of Gaskell and Sparke (1986). Peterson and Gaskell (1986) used this technique to examine the correlation between the continuum and the *total* Hβ fluxes in this galaxy and find that emission-line changes are significantly correlated with continuum changes at a most probable lag of 31 ± 9 days, which, as Gaskell and Sparke (1986) show, can be identified as the radius of peak emissivity of the BLR. Cross-correlation of the red component fluxes and continuum fluxes shown in Figure 2 shows that the peak in the cross-correlation function occurs at 15 days, where the peak value of the correlation coefficient is $r = 0.74$. The correlation is thus significant at a confidence level greater than 99%. The uncertainty in the lag, following the error analysis of Gaskell and Peterson (1987), is ±9.4 days. A similar cross-correlation of the blue component fluxes and the continuum fluxes yields a peak correlation coefficient of $r = 0.36$, which occurs at a lag of 73 days; the blue component fluxes are thus not significantly correlated with the continuum fluxes over the test range of ±200 days. (The current observations are inadequate for testing longer lags between continuum and line variations.)

III. DISCUSSION

The width of each component ($\Delta v_{\rm FWHM} \approx 3900$ km s^{-1} for the red component, $\Delta v_{\rm FWHM} \approx 2540 \pm 450$ km s^{-1} for the blue component) and the fact that they vary in flux on different time scales leads us to believe that the two components of the emission lines represent two separate broad-line regions. The emission component which is displaced blueward from line center could arise in gas ejected from the central object (Peterson 1987). The difficulty with this interpretation is that the blue component is quite broad (which would indicate a poorly collimated ejection) but varies in flux on a fairly short time scale, which argues against an extended emitting region. As an alternative explanation, it is suggested that the nucleus of NGC 5548 may actually contain two energetic sources, specifically two supermassive collapsed objects. While there is no direct evidence which indicates that the central sources of these two BLRs are gravitationally bound to one another, it seems plausible that two supermassive objects in the spatially unresolved nucleus of an active galaxy might form a binary. This is not a new idea. Aarseth (1973) has shown that the most massive members of stellar systems will tend to migrate toward the center of the system and form binaries as the system relaxes. The evolution of supermassive binary systems and their possible role in quasars has been considered by Begelman, Blandford, and Rees (1980) and Collins (1980), among others. Gaskell (1983) has discussed how supermassive binaries, with each component having its own associated BLR, might explain the double peaks and asymmetries (both blueward and redward) observed in the spectra of many active galactic nuclei.

If it is assumed that the two distinct BLRs in NGC 5548 represent two components of a supermassive binary, it is possible to use these observations to discern some of the properties of the system in order to test the plausibility of the hypothesis. Of particular importance is the observation that the wavelength of the peak of the blue component is apparently nearly constant over a long period of time (though, unfortunately, migration of the peak wavelength across the profile is precisely the observation that can prove or disprove our hypothesis). After subtracting the red component from each of our observed Hβ profiles, it is found that the peak of the residual blue component is constant to within approximately one pixel (~ 250 km s^{-1}). Furthermore, examination of Hα profiles from 1970 published by Anderson (1971) shows that the blue component has not moved significantly in 16 yr. This allows us to place interesting limits on both the period and semimajor axis of the orbit. The lowest line-of-sight acceleration in a binary system will occur when the secondary is crossing a node; this allows us to set the smallest possible lower limit on the period of the system. If it is assumed that the binary period is long and that no radial velocity change greater than ~ 250 km s^{-1} has occurred within the last 16 yr, it is found that $P > 110$ yr. The large radial velocity of the blue component relative to the systemic velocity also shows that the gas which produces it has moved $\sim 1.2 \times 10^{17}$ cm (i.e., about 48 lt-days) along the line of sight in the last 16 yr, which gives a lower limit on $r \sin i$, where r is an approximation to the size of the orbit and i is the inclination of the system. The large radial velocity difference between the two BLR components suggests that the inclination is not very small. Application of Kepler's third law then gives an estimate of the mass of the binary system

$$M_{\text{total}} \approx 4.5 \times 10^7/\sin^3 i \, M_{\odot}. \tag{1}$$

This exceeds by nearly two orders of magnitude the mass required by the Eddington limit. Moreover, for the separation given here, the binding energy of the binary is sufficiently large that it should be stable against random perturbations by stars in the nucleus.

The relative masses of the binary components can be estimated as about 9:1 from the relative displacement of the red (+275 km s^{-1}) and blue (−2475 km s^{-1}) emission-line components relative to the systemic redshift (as given by Heckman, Balick, and Sullivan 1978) of NGC 5548. This is in fact a lower limit, since at least the BLR near the systemic redshift is sufficiently small that a gravitational redshift should contribute as well (Netzer 1977; Peterson 1987).

It is possible to estimate the mass of the primary if it is assumed that its BLR is gravitationally bound and virialized, which is a reasonable assumption given that no clear profile changes occurred during the 1984 observing season when the total line flux was increasing significantly. (It is noted in passing that the blue component was very weak in 1984 and thus did not have any significant effect on the overall line profile even as the red component varied.) The mass of the primary is estimated as

$$M \approx rv^2/G = 4 \times 10^7 \, M_{\odot}. \tag{2}$$

This implies that the gravitational redshift of the BLR should amount to about 50 km s^{-1}, which does not significantly alter the mass ratio given above.

IV. SUMMARY

In this *Letter*, it has been shown that the asymmetric Balmer lines in NGC 5548 are attributable to two separate components, both of which are broad and vary in flux. The flux from only the stronger redward component, which is close to the systemic redshift, is correlated with the continuum variations. These observations might be plausibly interpreted in terms of a supermassive binary system, with each binary component having its own BLR. It is shown that this assumption leads to mass estimates which are not at variance with other independent estimates.

This hypothesis can be tested over the long term by determining whether or not the relative velocities of the two emission-line components change. Over the shorter term, it might be possible to show that a second continuum source is associated with the less massive component if a continuum outburst produces a change in the blue emission-line component, and not in the red component; such an opportunity may have been missed late in 1985, when the blue emission-line component underwent a much larger increase than did the red component.

The idea that collapsed supermassive objects power active nuclei, while an attractive and popular explanation, is neither a proven hypothesis nor a universally embraced notion. An attempt is made here to interpret a newly established phenomenon, i.e., the existence of two physically distinct BLRs in an unresolved nucleus, in a manner that is consistent with the observations and not a radical departure from current thinking on active nuclei. The explanation offered here is observationally testable and indeed could lead eventually to unambiguous measurement of the masses of the central engines in active nuclei.

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