THE END OF THE LINES FOR OX 169: NO BINARY BROAD-LINE REGION

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ABSTRACT

We show that unusual Balmer emission-line profiles of the quasar OX 169, frequently described as either self-absorbed or double peaked, are actually neither. The effect is an illusion resulting from two coincidences. First, the forbidden lines are quite strong and broad. Consequently, the [N II] $\lambda 6583$ line and the associated narrow-line component of H$\alpha$ present the appearance of twin H$\alpha$ peaks. Second, the redshift of 0.2110 brings H$\beta$ into coincidence with Na I D at zero redshift, and ISM absorption in Na I D divides the H$\beta$ emission line. In spectra obtained over the past decade, we see no substantial change in the character of the line profiles and no indication of intrinsic double-peaked structure. The H$\gamma$, Mg II, and Ly$\alpha$ emission lines are single peaked, and all of the emission-line redshifts are consistent once they are correctly attributed to their permitted and forbidden-line identifications. A systematic shift of up to 700 km s$^{-1}$ between broad and narrow lines is seen, but such differences are common and could be due to gravitational and transverse redshift in a low-inclination disk. Stockton & Farnham had called attention to an apparent tidal tail in the host galaxy of OX 169 and speculated that a recent merger had supplied the nucleus with a coalescing pair of black holes that was now revealing its existence in the form of two physically distinct broad-line regions. Although there is no longer any evidence for two broad emission-line regions in OX 169, binary black holes should form frequently in galaxy mergers, and it is still worthwhile to monitor the radial velocities of emission lines that could supply evidence of their existence in certain objects.

Subject headings: black hole physics — quasars: emission lines — quasars: individual (OX 169)

1. INTRODUCTION

The quasar OX 169 is a compact radio source (Gower & Hutchings 1984) as well as a source of curious optical emission lines, the nature of which has been the subject of interesting speculation for 20 years. Smith (1980) first noted the presence of apparent "self-absorption" in the Balmer lines of OX 169, which, if correct as a physical description, would be highly unusual for nonresonance lines. Gaskell (1981) preferred an alternative explanation based on displaced velocities in which the broad- and narrow-line regions differ by 1200 km s$^{-1}$. Ten years later, Stockton & Farnham (1991, hereafter SF) interpreted variability of the H$\beta$ line profile as evidence for two distinct broad peaks, thus assigning OX 169 to the family of double-peaked emitters (e.g., Chen & Halpern 1989; Eracleous & Halpern 1994), whose origin remains a subject of intense study. SF discussed both accretion-disk and binary broad-line region (BLR) models but settled on the binary explanation as more consistent with the nature of the variability (actually, only the difference between two spectra), and the one in their estimation to be the most likely to account for the range of double-peaked behavior seen up to that time in active galaxies in general. Of considerable interest was the connection made by SF between their emission-line evidence for a binary black hole, and an apparent tidal tail in the host galaxy which they showed had the spectrum of starlight. To the extent that black holes are thought to be common in galactic nuclei, and in view of the appearance of OX 169 as a recent merger, SF speculated that a bound pair of black holes had formed and was now revealing its existence in the form of two distinct BLRs. In this interpretation, it was assumed that a pair of supermassive black holes can maintain physically distinct BLRs that appear to the observer sufficiently separated in velocity.

In this paper, we reevaluate these interesting suggestions about OX 169 using an extensive set of optical spectra obtained over the past decade, as well as archival ultraviolet spectra from the Hubble Space Telescope (HST). Our conclusion is that there is little if any spectroscopic evidence for a binary BLR in OX 169. In addition to revising the observational description of the broad emission lines from double peaked to single peaked, we discuss how line-profile variability figured into previous interpretations, how our understanding of line-profile variability has developed over the past decade, and what lines of investigation remain to be pursued in this subject.

2. OBSERVATIONS

We obtained many spectra of OX 169 over the past 10 yr, with resolution in the range 4–12 $\AA$. Most of these covered the H$\beta$ and H$\alpha$ emission lines only, although H$\gamma$ and Mg II were each observed once. A log of the spectroscopic observations is given in Table 1. Reductions were performed using standard techniques. Of particular relevance to this study is the accuracy of the wavelength calibration, which is typically better than 1/20th of the resolution as determined by the dispersion in the fits to the arc lines. Wavelength calibrations were taken immediately after each object expo-
TABLE 1

| UT Date    | Telescope | Exposure Time (s) | Wavelength Range (Å) | Resolution (Å) |
|------------|-----------|------------------|----------------------|----------------|
| 1989 Nov 7| MDM 2.4 m | 1800             | 5300–8100            | 12             |
| 1990 May 30| KPNO 2.1 m | 2700             | 6300–8300            | 7              |
| 1992 Jan 7| HST FOS   | 2043             | 1160–1600            | 1              |
| 1992 Jan 7| HST FOS   | 1001             | 1600–2310            | 1.5            |
| 1992 Jan 7| HST FOS   | 1047             | 2220–3280            | 2              |
| 1993 Dec 13| KPNO 4m  | 1800             | 3000–9800            | 8              |
| 1994 July 4| KPNO 2.1 m | 4000             | 5500–8500            | 4              |
| 1995 June 4| KPNO 2.1 m | 4000             | 5500–8500            | 4              |
| 1996 June 15| KPNO 2.1 m | 3915             | 5500–8500            | 4              |
| 1996 Oct 11| Lick 3 m | 4800             | 6000–8300            | 5              |
| 1997 June 9| KPNO 2.1 m | 3600             | 5500–8500            | 4              |
| 1997 Sep 29| KPNO 2.1 m | 3600             | 5500–8500            | 4              |
| 1998 June 27| MDM 2.4 m | 3600             | 6300–8300            | 5              |
| 1998 June 29| MDM 2.4 m | 2500             | 4400–6400            | 7              |

Sure. Slit widths were in the range 1.7–2.0, and depending upon seeing and guiding, placement of the object within the slit can be the dominant source of systematic error in wavelength. The dispersion among measurements of the stronger lines in different spectra of OX 169 is approximately 1 Å, which we interpret as a systematic uncertainty of \( \pm 50 \) km s\(^{-1}\) in velocity. Our observational technique was not designed to achieve photometric precision in flux. Instead, we rely on assumed constancy of the \([\text{O} \text{III}] \lambda 5007\) line wherever possible to standardize the flux.

We also make use of archival (HST) spectra of OX 169 obtained in 1992 with the Faint Object Spectrograph (FOS) gratings G130H, G190H, and G270H. These were initially reported by Diplas et al. (1993). Details of the FOS spectra are also given in Table 1.

2.1. Narrow Emission Lines

We begin by assessing the “systemic” redshift of OX 169 as defined by its low-ionization forbidden lines and narrow components of its Balmer lines. Figure 1 shows a montage of spectra around the H\( \alpha \) line. Dashed lines indicate the wavelengths of H\( \alpha \), [N II] \( \lambda 6548, 6583 \), and [S II] \( \lambda 6716, 6730 \) for a best fitting redshift of 0.21103 \( \pm 0.00013 \). Of particular importance is the weak but clearly present [S II] doublet at the same redshift as H\( \alpha \) and [N II]. The [S II] lines are so broad as to be almost completely blended, but it is clear that all of the emission-line peaks can be attributed to the narrow components, either H\( \alpha \) or forbidden lines, at a single redshift. We also measured the [O III] \( \lambda 3727 \) redshift in the 1998 June spectrum, which gave \( z = 0.21096 \), consistent with the other low-ionization lines. We therefore adopt \( z = 0.21103 \pm 0.00013 \) as the systemic (low-ionization) redshift.

Next, we turn to the region around H\( \beta \). In Figure 2, we draw dashed lines at the low-ionization redshift of 0.21103 to see how well this agrees with [O III] and H\( \beta \). The agreement with [O III] is very good. Although [O III] prefers a slightly lower redshift of 0.21063 \( \pm 0.00016 \), the corresponding difference of only \( \approx 100 \) km s\(^{-1}\) between high- and low-ionization forbidden lines is common. This comparison assures us that we have correctly identified the peaks on the H\( \alpha \) line with their narrow-line region components. It is difficult to evaluate the agreement with narrow H\( \beta \), predicted to fall at 5887 Å, because, as we shall see, it nearly coincides with Na I D absorption in our Galaxy’s interstellar medium (ISM). In any case, it is clear that the large velocity widths of the strong narrow emission lines, FWHM = 700 km s\(^{-1}\) and FWZI = 2500 km s\(^{-1}\) as exemplified by [O III], have confused previous interpretations of the broad Balmer-line profiles in OX 169.

![Fig. 1. Spectra around the H\( \alpha \) line of OX 169 that have been renormalized and shifted vertically for clarity. The dashed lines correspond to the wavelengths expected for [N II] \( \lambda 6548, 6583 \), [S II] \( \lambda 6716, 6730 \), and [S II] \( \lambda 3727 \), all at \( z = 0.21103 \).](image-url)
contaminating these spectra. The accuracy of our sky subtraction is evidently very good, given the detailed reproducibility among the many spectra in this region and the lack of any systematic problems with other night-sky emission lines that are stronger than Na I D, such as [O I] λ5577 and [O I] λ6300. SF were also careful to rule out the possibility of errors in sky subtraction in their spectra, but they did not consider the possibility of interstellar Na I D absorption which, of course, persists after accurate subtraction of the night-sky emission.

Additional interstellar absorption lines whose equivalent widths are known to correlate with that of Na I D are present in the spectrum of OX 169. These are shown in Figures 3 and 4. The 1996 Lick spectrum covers the region of Ca II H & K (λλ3968.5, 3933.7), which have equivalent widths of 0.14 and 0.30 Å, respectively. As shown by the correlations presented in Hobbs (1974), the Ca II and Na I D absorption-line strengths are consistent with the moderate H I column at these coordinates (l, b of 72°116, −26°084) of 8.2 × 10^20 cm⁻² (Stark et al. 1992), and with the extinction E(B − V) = 0.111 estimated from IRAS 100 µm maps (Schlegel, Finkbeiner, & Davis 1998). In the HST spectrum, the Mg II λλ2795.5, 2802.7 doublet is strong, with equivalent widths of 1.57 and 1.03 Å, respectively, and Fe II, Mn II, and Mg I absorption lines are present as well. All of these features support the hypothesis that a modest interstellar Na I D absorption is to blame for the peculiar appearance of the Hβ emission line in OX 169.

2.3. Broad Emission Lines

The shapes of the broad emission lines in OX 169 are certainly quite varied. Figure 5 shows examples of all of the broad emission lines that can be extracted from our optical spectra, as well as from the HST spectra. The chosen zero velocity point corresponds to the narrow-line redshift of 0.21103. It is interesting that narrow Lyα absorption is present at exactly this redshift, which is presumably the systemic redshift of the host galaxy. The peak of Lyα emis-
sion, however, is at $z = 0.21334$, which is redshifted by $\approx 570 \text{ km s}^{-1}$ from the narrow lines. The other broad emission lines are also redshifted, by up to $\approx 700 \text{ km s}^{-1}$ as determined by Gaussian fits. Table 2 lists all of the broad emission-line widths and shifts from the spectra illustrated in Figure 5. In addition to this first-order characterization, there are complicating features in some of the line profiles, such as an extended red wing on Hβ that may be due in part to Fe II $\lambda 4923, 5018$. Supporting this interpretation are the appearance of broad Fe II multiplets around 4570 and 5250 Å and the fact that such an extended wing is not present in Hz. Hγ may contain a weak contribution from [O III] $\lambda 4363$, which could have contributed to the double-peaked appearance of this line in previous studies. Broad wings are present on Ly$\alpha$, but its red wing may also contain a contribution from N V $\lambda 1240$.

The C IV and C III] line profiles are noisy and difficult to characterize. Partly inspired by the previous reports of double-peaked Balmer lines in OX 169, Marziani et al. (1996) wrote that the C IV line is probably double peaked, although the evidence was not strong in their view. We also note that the apparent associated C IV absorption feature at $-500 \text{ km s}^{-1}$ is not highly significant, and it may be an instrumental artifact because it is narrower than the resolution. The C III] $\lambda 1909$ line is difficult to interpret because it is likely that a contribution from Si III] $\lambda 1892$ is present, as well as lines of the Fe III multiplet UV34. Aoki & Yoshida (1998) and Wills et al. (1999) show that Si III] $\lambda 1892$ typically contributes 20%–30% of the flux in this blend, and there is some evidence for such a contribution in Figure 5. In summary, there are small shifts between the broad-line and narrow-line velocities, as well as differences among the broad-line profiles themselves. These effects are well known among quasars. However, there is no evidence for a two-component broad-line region, or self-absorption in any of the nonresonance lines. After 10 yr of monitoring OX 169, we consider that a double-peaked description of its broad emission lines is pretty much ruled out.

TABLE 2

| Line Identification | Rest Wavelength (Å) | Measured Wavelength (Å) | Shift* (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|---------------------|---------------------|-------------------------|----------------------|-------------------|
| Hx                  | 6562.79             | 7956.12                 | 320                  | 3770              |
| Hβ                  | 4861.33             | 5895.88                 | 440                  | 4550              |
| Hγ                  | 4340.46             | 5269.20                 | 730                  | 4490              |
| Mg II               | 2799.07             | 3397.10                 | 650                  | 2650              |
| C III]              | 1908.73             | 2312.18                 | 80                   | 5380              |
| C IV                | 1549.48             | 1879.67                 | 30                   | 6930              |
| Ly$\alpha$          | 1215.67             | 1475.02                 | 570                  | 5030              |

* Velocity with respect to the systemic redshift of $z = 0.21103$. Velocities are all positive and therefore redshifted.
Tests of the Binary BLR Hypothesis

Actually, the variability studied by SF was limited to just two spectra of Hβ, taken in 1983 and 1989. The assumption behind the analysis of SF is that, when a line shape changes, the profile can be uniquely decomposed by differencing into two components, a variable part and a constant part. The resulting pair of line profiles were in turn attributed to two spatially separated sources. In our opinion, it is doubtful that a reliable interpretation of variability can be extracted from just two spectra. In this particular case, it is also important to evaluate the assumptions behind the method. As SF state, for their procedure to have meaning, the light-travel time across the broad-line region must be short compared to the timescale of variability of the photoionizing continuum. A pair of additional requirements that were not stated are (1) that each variable photoionizing source does not affect the other’s emission-line region and (2) that variability of a photoionizing source is the only mechanism of line profile variability. But all of these requirements together amount to assuming most of the properties of the desired solution, namely, that a pair of photoionizing sources are associated with spatially distinct BLRs that have stationary velocity fields and are immune from the effects of each other’s radiation. It does not seem possible that a single-difference spectrum could be used to justify all of the required assumptions without employing a circular argument.

A number of intensive monitoring programs have been conducted over the past decade that bear upon these issues. First, a sensitive search for the smoking gun of the binary BLR model in three bona fide double-peaked emitters yielded interesting but null results (Eracleous et al. 1997). The absence of long-term, systematic velocity variations characteristic of a double-lined spectroscopic binary effectively ruled out the binary BLR model for all reasonable black hole masses in Arp 102B, 3C 390.3, and 3C 332. The factor that makes this test feasible in a reasonable period of time is a large velocity separation of the emission-line peaks. The observed absence of radial-velocity variations can be translated into a lower limit on the mass of the assumed binary,

\[ M > 4.7 \times 10^8 (1 + q)^3 \left( \frac{P}{100 \text{ yr}} \right) \left( \frac{v_1 \sin i}{5000 \text{ km s}^{-1}} \right)^3 M_\odot, \]

where \( M = M_1 + M_2, q = M_1/M_2, P \) is an observed lower limit on the orbital period, and \( v_1 \sin i \) is the observed radial velocity of \( M_1 \). Since the mass depends on the cube of \( M_1 \), the velocity, those line profiles with peaks that are displaced by 5000 km s\(^{-1}\) or more can provide a very sensitive test of the hypothesis in a couple of decades. Eracleous et al. (1997) eliminated all binary masses less than \( 10^{-10} M_\odot \) in Arp 102B, 3C 390.3, and 3C 332. A previous analysis of Gaskell (1996), which found striking evidence for a radial-velocity drift and thus binary orbital motion in 3C 390.3, was contradicted by the longer timespan of the observations made by Eracleous et al. (1997), in which the trend did not continue as expected for a spectroscopic binary.

This demonstrated absence of binary BLRs in those three objects implies that there must be a mechanism by which a single black hole can produce a double-peaked emission line, but it does not rule out a scenario in which an unseen black hole perturbs the emission-line velocity of another. However, as can be seen by inverting equation (1) for the orbital period \( P \), it might be difficult to discover such a single-lined spectroscopic binary in an object like OX 169 for which the radial-velocity displacement of the broad emission lines is \( \lesssim 700 \text{ km s}^{-1} \).

Line-Profile Variability: Dynamics, not Reverberation!

A second major development in the study of emission-line variability is the realization that line-profile variability
is not the result of light-echo effects, i.e., reverberation. All of the Seyfert monitoring campaigns have shown that, although the total intensity of an emission line is modulated in response to the intensity of the ionizing continuum with a lag of days to months, the shape of the line changes hardly, if at all, on these timescales (Ulrich 1991; Wanders & Peterson 1996; Kassebaum et al. 1996). In particular, both sides of the double-peaked emission line in 3C 390.3 respond simultaneously to continuum variations (Dietrich et al. 1998; O'Brien et al. 1998). On the other hand, we have learned that major changes in line shapes on long timescales of years to decades is ubiquitous, especially in double-peaked emitters (Veilleux & Zheng 1991; Newman et al. 1997; Storchi-Bergmann et al. 1995; Gilbert et al. 1998), but that these slow profile variations are not responses to changes in the ionizing continuum. Rather, they must be due to physical changes in the velocity field of the emitting gas, i.e., dynamical motions. Some of the most dramatic examples are found in the emergence of new double-peaked broad emission lines in well-known objects that had no such component in the past, such as Pictor A (Halpern & Eracleous 1994; Sulentic et al. 1995), M81 (Bower et al. 1996), and NGC 1097 (Storchi-Bergmann, Baldwin, & Wilson 1993).

Much of the recent effort in modeling line-profile variability has focused on dynamical motions such as hot spots and spiral waves in accretion disks (Zheng, Veilleux, & Grandi 1991; Chakrabarti & Wiita 1994; Newman et al. 1997; M. A. Gilbert et al., in preparation 2000), tidal disruption of stars, and precessing eccentric accretion disks (Eracleous et al. 1995; Storchi-Bergmann et al. 1997). This is not to say that a universally applicable model of line-profile variability is in the offing. On the contrary, it is a warning that one should not expect to extract a dynamical model of a quasar broad-line region from two snapshots of an emission-line profile, or even from a dozen. In all of these studies, the double-peaked line profile is treated as a dynamic whole to be modeled with an evolving velocity field, as there is evidently no simple decomposition of the profile into a pair of independent, stationary entities.

Since much recent modeling involves an accretion-disk origin for the emission lines, we wish to address here a stock criticism of the accretion-disk hypothesis, which seems to persist, unjustifiably in our opinion, and should be put to rest. Several authors have noted that if line-profile variability is caused by the response of an axisymmetric accretion disk to a variable central photoionizing source, then the blue and red sides of an emission-line profile should vary in opposite ways (e.g., Gaskell 1996) as disklike because of the wide separation of their peaks, but this may be the exceptional case that obtains when the ratio of outer to inner radius is small, i.e., only ~3. As the outer radius of the line-emitting region increases, the two peaks merge together at small velocity, which may be the more general rule. Radiative transfer effects in the lines also tend to make single-peaked profiles. The small inclination inferred for OX 169 would be consistent with its single-peaked line profiles, and also with its core-dominated radio source.

4. Conclusions and Future Work

We have shown that the Balmer lines in OX 169 are neither self-absorbed nor double peaked. All previous
analyses of its spectra were led astray by some combination of the following effects: (1) The forbidden lines of OX 169 are unusually strong and broad, consequently, [N II] $\lambda 6583$ masquerades as an additional component of H\zeta; (2) H\beta coincidences with Galactic Na I D absorption, which has an equivalent width similar to the spurious “trough” between H\zeta and [N II] $\lambda 6583$; and (3) the broad emission lines are redshifted by as much as 700 km s$^{-1}$ from the forbidden lines. In spectra obtained over the past decade, we see no substantial change in the character of the line profiles, and no indication of intrinsic double-peak structure once the above effects are recognized. In support of this interpretation, we show that (1) the Na I D doublet is resolved in absorption, (2) ISM absorption in Ca II H and K and Mg II are detected at a strength consistent with that of Na I D, (3) the Mg II, Ly$\alpha$, and H\beta emission lines are single peaked, and (4) all of the emission-line redshifts are consistent once they are correctly attributed to their permitted and forbidden-line identifications.

A systematic shift of up to 700 km s$^{-1}$ between broad and narrow lines is seen, but such differences are common and could be due to gravitational and transverse redshift in a dislikable broad-line region viewed at small inclination. The single-peaked nature of the emission lines is not an obstacle to a disk model and may in fact be the general rule, while double-peaked lines are the exception. Long-term variability of the emission-line profiles in OX 169 appears to be modest and unexceptional, and it is probably due to dynamical motions. Ultimately, our understanding of why quasars vary will have to involve dynamics.

Stockton & Farnham (1991) interpreted the line profiles of OX 169 in terms of a binary BLR, which was especially intriguing since they also found an apparent tidal tail in the host galaxy, and speculated that a recent merger had supplied the nucleus with a pair of black holes that was now coalescing. Strictly speaking, our revised description of the line profiles is not to be taken as evidence against the presence of a binary black hole but only for the absence of two separate emission-line regions. In view of the mounting evidence for the ubiquity of black holes in galactic nuclei, the formation of binary black holes in galaxy mergers should be relatively common. Such binaries could spend anywhere from $10^8$ to $10^{10}$ yr at separations of 0.01–0.1 pc (Begelman et al. 1980), during which their orbital motion might be detected. According to equation (1), it would be worthwhile to monitor emission lines that have peaks displaced by more than 1500 km s$^{-1}$ for evidence of binary motion, especially if such displacements are not easily compatible with gravitational redshift alone, e.g., if they are blueshifted. We have several such candidates under surveillance. Even if only one emission-line region exists in such a system, the orbital acceleration by the unseen black hole could perturb the emission-line velocities in the manner of a single-lined spectroscopic binary. Such black hole binaries of $M \approx 10^8 M_\odot$ would undergo detectable orbital motion in just a couple of decades. If these candidates were also compact VLBI radio sources, it would feasible to obtain direct confirmation via proper motion of order microarcseconds per year (Eracleous et al. 1997). Indirect evidence for binary orbital motion may be present in the wiggles of a milliarcsecond radio jet (Kaasra & Roos 1992; Roos, Kaastra, & Hummel 1993).

Unfortunately, OX 169 is no longer a prime candidate for such a monitoring program. Over the past decade its emission lines have revealed little evidence for unusual velocities, and no other peculiarities that inspire thoughts of binarity. Regretfully we opine, this is the end of the lines for OX 169.

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