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EXTENDED BROAD-LINE EMISSION IN THE OBSCURED SEYFERT 1 NUCLEUS OF NGC 4388[1]

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ABSTRACT

We present spectroscopic observations of extended, off-nuclear broad Hα emission (FWZI ≈ 4000 km s^{-1}) in NGC 4388, a galaxy often classified as a type 2 Seyfert. These features are interpreted as scattered radiation from a Seyfert 1 nucleus that is obscured along our line of sight, possibly by the normal interstellar medium in this galaxy. NGC 4388 strongly resembles NGC 1068, another object with a hidden broad-line region, and may be useful for understanding the relationship between Seyfert 1 and Seyfert 2 galaxies. A scattering origin for the off-nuclear broad emission may be tested by spectropolarimetric observations.

Subject headings: galaxies: individual (NGC 4388) — galaxies: nuclei — galaxies: Seyfert

I. INTRODUCTION

NGC 4388 is a highly inclined disk galaxy ($i \approx 72°$, major axis P.A. ≈ 92°) with probable membership in the Virgo Cluster (Phillips and Malin 1982, hereafter PM). Observations in several wavelength domains indicate the presence of an active nucleus in this object. In optical light NGC 4388 displays an apparently unresolved nucleus with strong emission lines characteristic of Seyfert 2 galaxies (PM; Phillips, Charles, and Baldwin 1983). At this location Filippenko and Sargent (1985, hereafter FS) found a weak component of broad Hα with full width near zero intensity (FWZI) approximately 6000 km s^{-1} (incorrectly listed as 7600 km s^{-1} by FS), typical of Seyfert 1 galaxies. NGC 4388 shows substantial extended disk emission (Ford, Rubin, and Roberts 1971), which has been imaged by Colina *et al.* (1987) in [O III] λ5007 and by Pogge (1988*b*, hereafter Pogge) in Hα + [N II] λλ6548, 6583 and in [O III] λ5007. Corbin, Baldwin, and Wilson (1988, hereafter CBW) present similar narrow-band as well as broad-band images, and use long-slit spectra to map the galaxy's intensity and velocity fields in Hβ and [O III] λ5007. The images and spectra also reveal the presence of photoionized gas extending above and below the galaxy disk in several kinematically distinct components.

Unusual activity in NGC 4388 is also indicated by its X-ray, infrared, and radio properties. It was detected with the *Einstein Observatory* as a soft X-ray source (0.5–3.0 keV) with $L_X = 1.69 \times 10^{40}$ ergs s^{-1} (Forman *et al.* 1979). Observations with the *Infrared Astronomical Satellite* (*IRAS*) show that NGC 4388 has relatively warm infrared colors [$\alpha(60\ \mu m, 25\ \mu m) \approx \alpha(100\ \mu m, 60\ \mu m) \approx -1.2$, $S_\nu \propto \nu^\alpha$; Valenti and Filippenko 1988] that place it intermediate to typical locations of Seyfert 1 and Seyfert 2 galaxies in the infrared two-color plane (Miley, Neugebauer, and Soifer 1985). At radio wavelengths it shows an unusual crosslike structure composed of disk emission and emission extending out of the disk along the minor axis (Hummel, van Gorkom, and Kotanyi 1983; Stone, Wilson, and Ward 1988, hereafter SWW). Spectral indices for both components are indicative of a nonthermal origin ($\alpha \approx -0.4$ to -0.6; SWW).

While the apparent optical nucleus (hereafter the "apparent nucleus") of NGC 4388 would seem a plausible origin for many of these phenomena, other observations suggest that it is spatially displaced from much of this galaxy's central activity. PM noted relatively early that the apparent nucleus is offset south of the galaxy's center of symmetry. SWW subsequently resolved the central emission at 6 cm into a double-peaked source located north-northeast of the apparent nucleus; similar observations at 2 cm show a single core coincident with SWW's stronger, northern peak, at ~3″ north and ~1″ east of the apparent nucleus (Carral, Turner, and Ho 1988). Finally, SWW observed NGC 4388 at 10 μm and found that the mid-infrared emission peaks several arcseconds north of the apparent nucleus.

Here we present new observations revealing additional unusual activity in NGC 4388; preliminary results were reported by Shields and Filippenko (1988). Specifically, we find broad Hα emission characteristic of a Seyfert 1 nucleus, but extended over a region of up to 10″ in size. A resolved broad-line region (BLR) in a Seyfert 1 galaxy is without precedent, and we interpret the extended zone of observed emission as scattered radiation from a normal, but obscured, Seyfert 1 BLR that may be located at the radio core position.

II. OBSERVATIONS

During the course of a detailed spectroscopic study of NGC 4388, we used the Shane 3 m telescope at Lick Observatory to obtain long-slit CCD spectrograms at multiple positions, with 2″ slits roughly parallel (P.A. = 90°) and perpendicular to the galaxy's major axis. Typical integration times were 25–30 minutes. In addition, two long-slit spectrograms were obtained with the Hale 5 m reflector at Palomar Observatory. The atmospheric seeing disk was generally 1.″5–2″ (FWHM). The wavelength region surrounding Hα (~6200–6850 Å) was included, with resolution 2.5–3.0 Å. We used standard techniques to reduce and calibrate the spectrograms; further details will be described in a later paper.

Preliminary inspection of the spectra revealed broad wings (FWZI ≈ 4000 km s^{-1}) on the Hα + [N II] λλ6548, 6583 blend at a position approximately 3″ north and 4″ east of the appar-

[1] Based primarily on observations obtained at Lick Observatory, which is operated by the University of California.

[2] Guest Observer, Palomar Observatory, which is owned and operated by the California Institute of Technology.

ent nucleus. Since weak, broad Hα had previously been detected in the optical nucleus (FS), we undertook a search for similar broad components elsewhere in this object. To improve the signal-to-noise ratio, we binned and averaged individual spectrogram columns in the spatial dimension with overlapping spectra in grid cells, usually of size 2″ × 2″. The total grid thus constructed covered a rectangular region extending approximately from 9″ east to 5″ west and from 9″ south to 6″ north of the apparent nucleus.

Detection of broad Hα was determined visually. The underlying continuum was quite flat in most grid cells, and broad Hα was identified unambiguously in three contiguous cells centered 2″ east, 3″.2 northeast, and 4″.7 east-northeast of the apparent nucleus. Weaker broad components were detected throughout a roughly conelike region (P.A. ≈ 0°–70°) extending from the apparent nucleus to a distance of ~6″. An average of columns best displaying the broad feature in a region of 6.4 arcsec^2 centered ~3″ north, ~4″ east of the apparent nucleus is illustrated in Figure 1*a*. For comparison, the spectrum averaged over 5.9 arcsec^2 centered 2″.5 north, 8″ east of the apparent nucleus and showing no clear evidence for broad Hα is depicted in Figure 1*b*. A second broad component (FWZI ≈ 4000 km s^{-1}) having greater contrast with the narrow lines and no obvious extension beyond the seeing disk

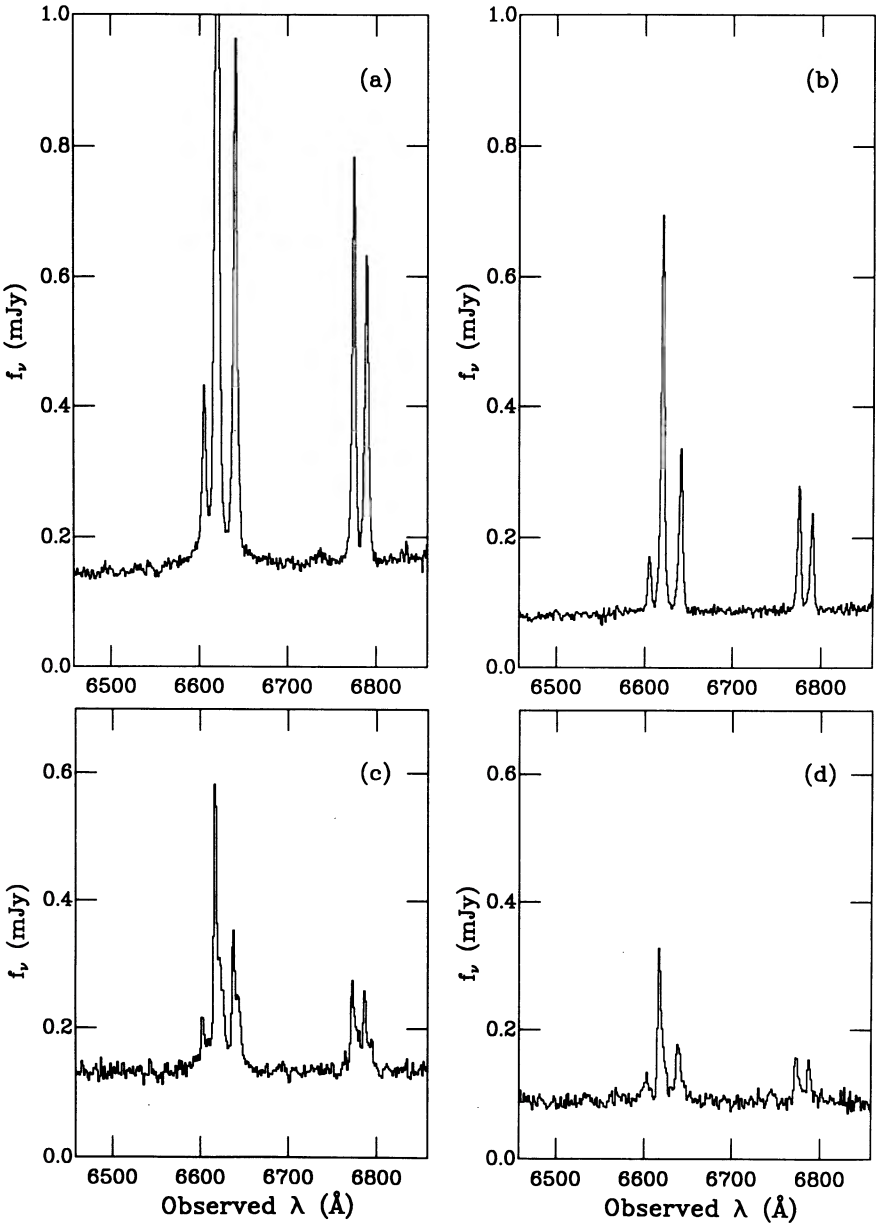

FIG. 1.—Spectra of NGC 4388 showing the strong emission lines [N II] λ6548, Hα λ6563, [N II] λ6583, [S II] λ6716, and [S II] λ6731. The flux scale corresponds to an effective aperture of approximately 1.5 arcsec^2 and is accurate to within a factor of 2. (*a*) Spectrum averaged over 6.4 arcsec^2 centered 3″ north, 4″ east of the apparent nucleus, showing broad wings on the [N II] + Hα blend. (*b*) Comparison spectrum averaged over 5.9 arcsec^2 centered 2″.5 north, 8″ east of the apparent nucleus, showing no evidence of a broad feature. (*c*) Spectrum averaged over 4 arcsec^2 centered 6″ south of the apparent nucleus, again showing apparent broad Hα; the narrow lines show split profiles noted earlier in this vicinity by CBW. (*d*) Comparison spectrum averaged over 4 arcsec^2 centered 8″ south of the apparent nucleus, showing no obvious broad emission.

was located 6″ south of the apparent nucleus; the spectrum centered at this position and averaged over 4 arcsec^2 is illustrated in Figure 1*c*. An additional comparison spectrum centered 8″ south of the apparent nucleus and averaged over 4 arcsec^2 is shown in Figure 1*d*. Further suggestions of a broad component were seen at positions 2.″5 north, 2″ west, and 2″ south, 4″ east of the apparent nucleus. Our measured width of broad Hα (FWZI $\approx$ 4000 km s^{-1}) in the apparent nucleus is less than that found by FS, probably because our signal-to-noise ratio is lower.

III. DISCUSSION

The broad Hα emission lines observed at various locations in NGC 4388 are best understood as signatures of a heavily obscured Seyfert 1 nucleus. The gas velocities represented by their large widths are far in excess of values expected from a superposition of normal kinematic components of the galaxy disk. Moreover, emission lines other than the Hα + [N II] blend (e.g., [S II] λλ6716, 6731 and [O I] λ6300) do not show such velocities. Since the BLRs of all known Seyfert 1 galaxies are completely unresolved, the broad emission in NGC 4388 is remarkable for its visibility throughout a region that is considerably larger than the seeing disk in the north as well as in a second, independent region 10″ away, neither of which can be identified with the apparent nucleus. The spatial properties of the observed emission are readily understood, however, if a Seyfert 1 nucleus in NGC 4388 is obscured along our line of sight but radiates freely in other directions where scattering particles allow us to see emission from the BLR; off-nuclear scattering regions of this sort were in fact hypothesized for NGC 4388 by Pogge.

The observed distribution of broad Hα thus depends on the solid angle into which this radiation is directed from the central engine and on the distribution of scattering material, in this case probably dust. While the bounds we have used to describe the northern spatial pattern of observed broad emission are subjectively determined, and hence crude in describing both shape and extent, a conelike distribution is at least suggestive in this regard. As noted by Pogge, high-ionization gas located northeast of NGC 4388's center takes the approximate form of a cone with apex in the vicinity of the apparent nucleus; the sides of this cone fall within the limits of the conelike domain we observe for the broad-line emission. A similar coincidence is seen between the northern broad-line zone and a "tongue" of 6 cm radio emission observed by SWW to extend north-northeast of the radio core. Unlike the northern feature, the southern broad-line zone is not extended, yet is noteworthy for its location near the central axis of the well-defined southern high-ionization cone imaged by Pogge and CBW, and the southern 6 cm extension originally noted by Hummel, van Gorkom, and Kotanyi (1983). A schematic representation of these components and their spatial relation to each other is depicted in Figure 2.

The coincidence of radio structure, high-ionization emission, and apparently scattered broad-line emission suggests that the central region of NGC 4388 has a Seyfert 1 nucleus (hereafter

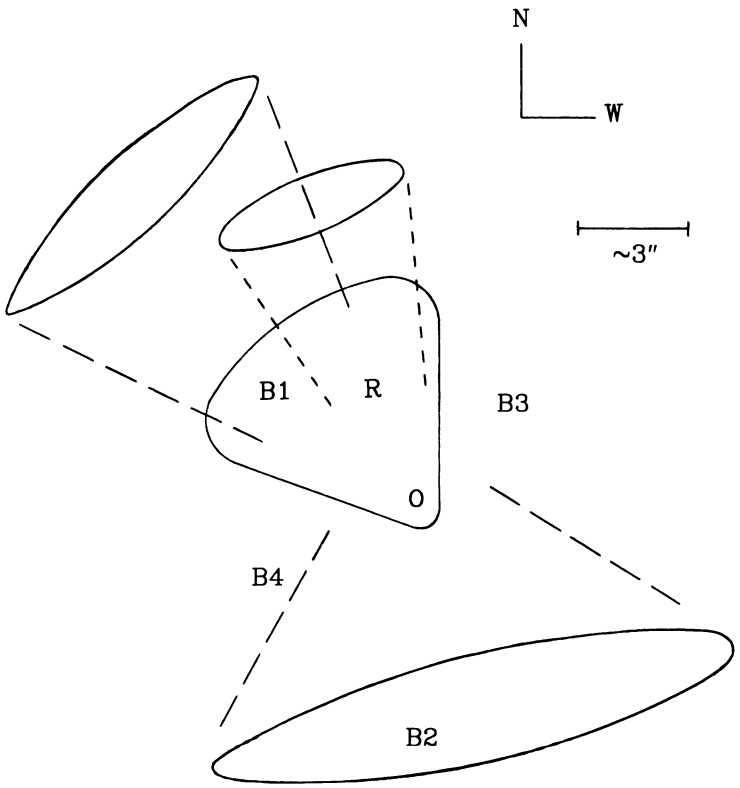

FIG. 2.—Schematic representation of the central region of NGC 4388, indicating positions of the apparent optical nucleus (*O*), the radio core seen at 6 and 2 cm (*R*), the approximate orientation of the northern 6 cm radio feature detected by SWW (*short-dashed lines*), and approximate opening angles of the extended high-ionization cones reported by Pogge (*long-dashed lines*). The northeastern region in which broad Hα was observed is enclosed by a solid line; the location of strongest broad emission in this region is labeled *B1*. The compact southern region showing broad emission is indicated as *B2*. Additional locations of probable broad emission are labeled *B3* and *B4*.

the "true nucleus") with a biconical outflow of radiation, relativistic particles, and possibly the material seen as extended ionized gas. Different scenarios for collimating such outflows are reviewed by Pogge. If the radio core does indeed mark the central engine, its position is plausible as the apex of the conical phenomena seen on both sides of the disk. The apparent optical nucleus south of the radio core may thus be where the southern radiation cone breaks out of an obscuring medium. The broad Hα emission observed at this point is again presumably scattered into our line of sight.

Ionizing radiation from the true nucleus may be less collimated to the northeast of the disk than we have implied, however. As noted earlier, we see a probable broad Hα line in one location northwest of the apparent nucleus. Furthermore, CBW and Pogge found additional high-ionization gas above the disk to the northwest of the apparent nucleus and lying outside the high-ionization cone depicted in Figure 2. Evidently some additional windows to the true nucleus exist. Ionizing radiation from the true nucleus could in fact be escaping north of the disk in a large solid angle representing little collimation if the gas above the disk is itself clumped into the roughly conical structure seen in the northeast quadrant.

Given the high inclination of NGC 4388, it is not surprising that the true nucleus may be heavily obscured by the normal interstellar medium of the disk. Such obscuration could also explain why the soft X-ray luminosity of NGC 4388 is somewhat low compared with that of other Seyfert 1 galaxies. In this regard NGC 4388 differs from NGC 1068, which is otherwise similar with its bright Seyfert 2 nucleus, relativistic ejecta (e.g., Wilson and Ulvestad 1987), cones of high-ionization gas (Pogge 1988*a*), and obscured Seyfert 1 nucleus (Antonucci and Miller 1985) complete with at least one off-nuclear cloud mirroring the BLR (Miller and Goodrich 1986). Antonucci and Miller (1985) posited a thick torus surrounding the BLR in NGC 1068 to explain its obscuration in this relatively low-inclination system. A similar structure may shadow the BLR in NGC 4388 and also play a role in collimating the galaxy's high-ionization and radio structures. In view of its high inclination, however, NGC 4388 does not provide a definitive test for the proposition that many or all Seyfert 2 galaxies are type 1 Seyferts obscured by structures in the nucleus.

While the broad-line emission away from NGC 4388's true nucleus can be plausibly explained by scattering processes, a compelling test for this hypothesis can be achieved through spectropolarimetry of these zones. Based on our observations, we predict strong polarization of the broad Hα emission in these regions; a contrary result would be remarkable, considering the lack of alternative explanations for line formation with the observed widths. Spectropolarimetry of the southern broad-line zone may provide the easiest test on account of its high contrast and well-defined position.

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