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DISCOVERY OF AN EXTREMELY LOW LUMINOSITY SEYFERT 1 NUCLEUS IN THE DWARF GALAXY NGC 4395

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ABSTRACT

We have discovered a Seyfert 1 nucleus in the center of the nearby ($d \approx 2.6$ Mpc), late-type (Sd III–IV), dwarf galaxy NGC 4395. Such nuclei have never been seen in galaxies of this kind. The optical spectrum reveals very strong, narrow emission lines covering a wide range of ionization from [O I] to [Fe X]. Weak wings having FWZI $\approx$ 4000–8000 km s^{-1} are visible in the permitted-line profiles, including He II λ4686. H II regions in the rest of the galaxy have normal spectra. The luminosity of the broad Hα emission is $\sim 1.2 \times 10^{38}$ ergs s^{-1}, a factor of 10 fainter than in the nucleus of M81; thus, NGC 4395 contains the least luminous known Seyfert 1 nucleus. The equivalent width of broad Hα (270 Å) is similar to that in normal, luminous Seyfert 1 galaxies. The optical continuum is featureless, and has $M_B \approx -9.8$ mag—less luminous than the brightest known supergiant stars. It is possible that the nuclear properties of NGC 4395 can be explained in terms of stellar phenomena, rather than by accretion onto a black hole.

Subject headings: galaxies: individual (NGC 4395) — galaxies: nuclei — galaxies: Seyfert — line profiles — spectrophotometry

I. INTRODUCTION

One of the last objects to be observed in the course of our survey for weak Seyfert activity in the centers of ~ 500 galaxies brighter than $B_T = 12.5$ mag (Filippenko and Sargent 1985, 1986) was the nearby, spatially well-resolved, dwarf galaxy NGC 4395. A superb photograph of this object is shown in panels 10 and 56 of the recent Atlas of Galaxies compiled by Sandage and Bedke (1988). The galaxy is classified as Sd III–IV, with $B_T \approx 10.7$ mag and a heliocentric redshift of 317 km s^{-1} (Sandage and Tammann 1987); adopting a distance of 2.6 Mpc (distance modulus 27.1 mag; Rowan-Robinson 1985), we find $M_B \approx -16.4$ mag, uncorrected for extinction.

In the photograph there is a faint starlike knot very close to the center of symmetry of NGC 4395 which could be identified as a nucleus, although in at least one other case we found that the putative "nucleus" of a dwarf irregular galaxy was actually a foreground Galactic M-dwarf star. Generally, however, we have found that knots and other features near the centers of late-type galaxies are giant H II regions. Accordingly, we were surprised to discover that the spectrum of this object is very unusual: strong, narrow emission lines from ions spanning a wide range of ionization are superposed on a featureless continuum, and there are weak broad wings on all permitted lines. We interpret the spectrum as indicating that the center of NGC 4395 harbors a type 1 Seyfert nucleus, the faintest active galactic nucleus (AGN) with broad lines yet discovered. A preliminary discussion of this unique object is given by Filippenko (1989*b*).

McCall, Rybski, and Shields (1985, hereafter MRS) included NGC 4395 in their study of giant H II regions in nearby groups of galaxies. Among the observed H II regions was the central starlike knot discussed above, which they designated NGC 4395($-001-005$) according to its position in the galaxy.[3] MRS noted that this H II region falls off the sequences defined by normal H II regions in plots of various emission-line intensity ratios; see their Figure 14. In particular, they wrote that "Besides having anomalously strong [N II] and [S II], this object shows strong [O I] and blue [S II] lines. The density appears to be high. All of these features are signatures of strong shock activity. The object appears to be the 'nucleus' of NGC 4395, the presence of which is very unusual for a galaxy so late. It is also possible that the object is a supernova remnant, although [S II] is quite weak relative to Hα." MRS observed this particular H II region to have an abnormally red continuum that is rather weak relative to the emission lines. Because of its unique properties, which MRS recognized easily, they included NGC 4395($-001-005$) among four H II regions designated as "Rosetta Stones" in terms of their overall importance for the study of giant H II regions in other galaxies.

II. OBSERVATIONS

Spectra of the center of NGC 4395 were obtained in 1988 April 7 UT with the CCD Double Spectrograph (Oke and Gunn 1982) at the Cassegrain focus of the Hale 5 m reflector at Palomar Observatory; see Filippenko and Sargent (1988, hereafter FS88) for details. In the initial exposure, a long slit of width 2″ was set at an angle of 100°, the approximate parallactic angle at the midpoint of the 1 hr exposure. The air mass varied from 1.19 to 1.07, and the seeing was $\sim 1''$. There may have been thin cirrus in the sky, but the calibration of absolute

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

[3] The numbers in parentheses give the offsets (arcseconds) in right ascension (east positive) and declination (north positive), respectively, from MRS's adopted position of the center of the galaxy: $\alpha_{1950} = 12^h23^m19\overset{s}{.}9$, $\delta_{1950} = 33°49'29''$.

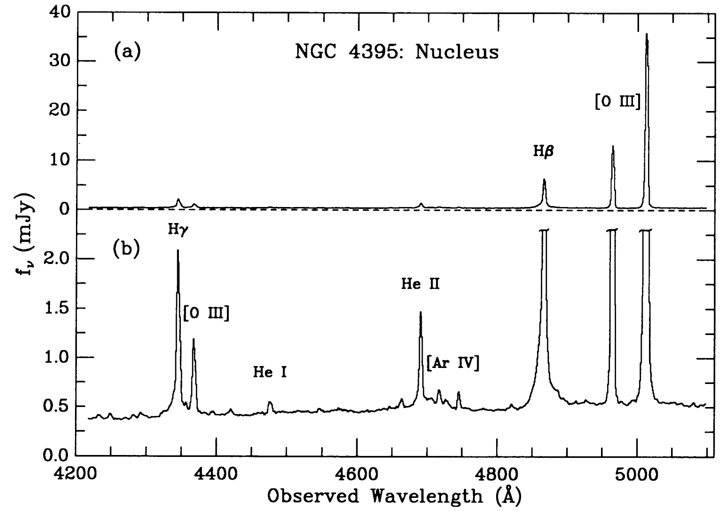

FIG. 1.—Blue CCD spectra of the nucleus of NGC 4395, obtained through an effective aperture of 2″ × 4″. The resolution (FWHM) is ~4 Å. (*a*) Short (400 s) exposure, showing the relative strengths of the strong emission lines. (*b*) Long (1 hr) exposure, showing the continuum and the weak emission lines. There are broad wings on Hβ, Hγ, and He II λ4686.

fluxes is believed to be accurate to ≲20%. Several strong emission lines were found to be saturated in both the blue and the red spectra, so we took a 400 s exposure immediately afterwards, at an average air mass of 1.06. An additional 400 s exposure was obtained with a 1″ slit at a position angle of 130°, in order to obtain better measurements of the intrinsic widths of emission lines. Extraction and calibration of the spectra were performed in the normal manner (FS88).

Figures 1 and 2 show, respectively, our blue and red spectra of the nucleus, obtained with a 2″ slit. In each case spectrum (*a*) represents the short (400 s) exposure so that strong lines have the correct relative intensities, whereas spectrum (*b*) represents the long (1 hr) exposure, in which the continuum and weak features are best discerned. Narrow emission lines of very high ionization (up to [Fe X] λ6374) are visible, together with strong low-ionization lines (e.g., [O I] λλ6300, 6364); the emission-line spectrum is very rich. Additional spectra have subsequently been obtained with the 3 m Shane reflector at Lick Observatory, revealing [Ne V] λ3426, [Ne III] λ3869, and other important lines. The H II regions near the nucleus appear to be normal.

The overall narrow-line spectrum of NGC 4395 resembles that of a Seyfert 2 nucleus, but several emission-line intensity ratios are peculiar, if plotted on diagrams such as those discussed by Baldwin, Phillips, and Terlevich (1981). Specifically, [O I] λ6300 and [S II] λλ6716, 6731 are unusually strong with respect to [N II] λλ6548, 6583. This may be due to the fact that the nitrogen-to-oxygen ratio in NGC 4395 is low with respect to the Sun (MRS), and possibly lower than in most of the Seyfert galaxies comprising the reference sample. Another striking difference is the extreme narrowness of the emission lines; they are nearly unresolved in the moderate-resolution (2–3 Å) red spectrum, indicating that their full widths at half-maximum (FWHM) are at most 60 km s^{-1}, compared with 300–400 km s^{-1} for typical narrow lines in Seyfert nuclei (Whittle 1985). Previously, the narrowest known forbidden

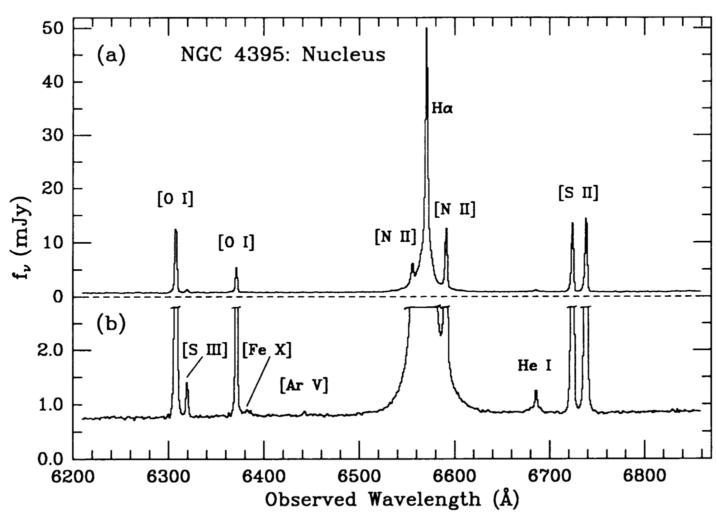

FIG. 2.—Red CCD spectra of the nucleus of NGC 4395, obtained through an effective aperture of 2″ × 4″. The resolution is 2–3 Å. (*a*) Short (400 s) exposure, showing the relative strengths of the strong emission lines. (*b*) Long (1 hr) exposure, showing the continuum and the weak emission lines. Note the broad wings on Hα and He I λ6678, as well as the faint [Fe X] λ6374 emission.

lines in a Seyfert nucleus were those in NGC 7314, with FWHM $\approx$ 110 km s^{-1} (Filippenko 1984). Nevertheless, as we will demonstrate in a future paper using our full data set, comparisons of the line intensity ratios with models and observations of other objects reveal that photoionization by a reasonably hard nonstellar continuum is almost certainly responsible for the observed spectrum. We note, in particular, the definite presence of [Fe X] λ6374 emission, a "coronal" line which cannot be produced by shock-heated gas unless it is extremely hot ($T \approx 10^6$ K).

Although the strongest emission lines are narrow, it is clear that Hα has very broad wings as well. Close inspection of Figures 1 and 2 also reveals broad, but weaker, components of Hβ, Hγ, He I λ6678, and He II λ4686. These wings are not present in the forbidden-line profiles and would probably not have been detected at all if the signal-to-noise ratio of the spectra were considerably lower. The full width near zero intensity (FWZI) of Hβ is $\sim$4000 km s^{-1}, that of Hα is $\sim$7000 km s^{-1}, and that of the He II λ4686 emission might be as high as 8000 km s^{-1}; adjacent narrow lines, and the possible presence of Fe II emission, make this last measurement uncertain by a few thousand km s^{-1}. Thus, NGC 4395 has a Seyfert 1 nucleus, specifically a Seyfert 1.8 or 1.9 (Osterbrock 1981) judging from the relative strengths of the narrow and broad components. The featureless, blue continuum is also consistent with the Seyfert 1 classification, but is atypical of type 1.8 and 1.9 Seyfert nuclei. No unambiguous stellar absorption lines, such as Mg *b* and the G band, can be detected in Figures 1 and 2; we estimate that at most 10% of the continuum flux is produced by late-type stars.

III. THE "DWARF" SEYFERT 1 NUCLEUS

It is very surprising to find a late-type galaxy whose nucleus has a Seyfert 1 spectrum; to our knowledge, this is the *only* reported case of an Sd III–IV galaxy with such characteristics. To quantitatively compare the spectrum with those of normal type 1 Seyferts, we need to measure the luminosity of the broad Hα emission line. This is done in a manner similar to that described by FS88.

The spectrum was initially rebinned logarithmically so that each bin corresponds to 22.00 km s^{-1}. Since [S II] λ6731 seems to match the profiles of the [N II] $\lambda\lambda$6548, 6583 and narrow Hα lines in other galaxies (e.g., M81; FS88), we used it to remove the narrow-line contribution to the [N II] + Hα blend in the unsaturated (400 s) exposure of NGC 4395. The [S II] line profile was shifted and scaled appropriately, with the goal of producing the smoothest possible profile for the broad Hα emission. This is illustrated in Figure 3. Our results are satisfactory, with very small residuals at the positions of the [N II] lines. The removal of the narrow Hα is less certain, since smoothness of the broad-line profile could be achieved with either a relatively flat top (large narrow-line contribution) or a relatively sharp top (small narrow-line contribution). The resulting uncertainty in broad-line *flux*, however, is $\lesssim$2%.

A measured flux of 1.53×10^{-13} ergs s^{-1} cm^{-2} is found for the broad component of Hα emission. This is a factor of 6.2 lower than in M81 (FS88) and represents the smallest accurately measured flux of broad Hα in any Seyfert 1 galaxy. At a distance of 2.6 Mpc, it corresponds to an Hα luminosity of 1.2×10^{38} ergs s^{-1}, a factor of 10 fainter than in the "dwarf" (low-luminosity) Seyfert 1 nucleus of M81 (FS88). The corresponding Hβ emission has a luminosity of 1.5×10^{37} ergs s^{-1}—a truly *dwarf* Seyfert 1 nucleus resides in the dwarf galaxy NGC 4395! Such faint, broad Balmer emission would have been extremely difficult to detect in the starlight-dominated nucleus and bulge of M81 (an Sb galaxy), but it was quite easy to see in the nearly face-on, well-resolved, Sd galaxy NGC 4395. Given the paucity of nearby, morphologically similar galaxies, this may well remain the least luminous known extragalactic Seyfert 1 nucleus for a long time.

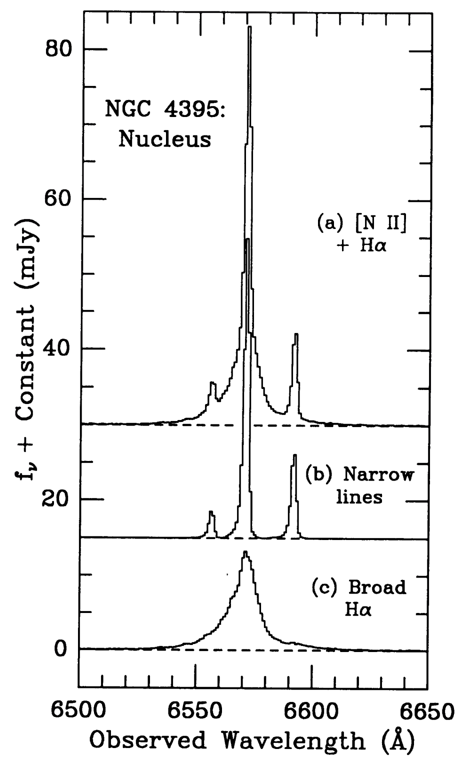

FIG. 3.—(*a*) The [N II] + Hα blend of Fig. 2 (400 s exposure) is illustrated on an expanded scale, offset by 30 mJy. Each bin corresponds to 1 Å. (*b*) Suitably scaled versions of the [S II] λ6731 line, offset by 15 mJy. (*c*) Subtraction of the narrow components leaves only the broad Hα, which can now be measured reliably.

An important question is whether the equivalent widths (EWs) of the broad Balmer lines in NGC 4395 are similar to those in canonical, luminous Seyfert 1 nuclei. The observed EW of Hα is 270 Å, very close to the average value of 260 $\pm$ 140 Å for 35 X-ray–selected QSOs and type 1 Seyferts published by Stephens (1989). (Note, however, that the Hα EWs in this large sample may be slightly contaminated by narrow Hα emission.) Broad Hβ, by comparison, has EW = 31 Å in NGC 4395, near the low end of the distribution in the Stephens (1989) sample ($\langle$EW$\rangle$ = 67 $\pm$ 31 Å). Using data from Osterbrock (1981), on the other hand, we find that in Seyfert 1.8 and 1.9 nuclei the average EW of broad Hβ *relative to the featureless continuum* is $\sim$21 Å. The approximate agreement in equivalent width strongly suggests that the broad Balmer emission is produced by photoionization followed by recombination, and that the visual continuum is an extrapolation of the ionizing continuum. Another close similarity between the starlike nucleus of NGC 4395 and those of classical Seyfert 1.8 and 1.9 galaxies includes the large intensity ratio (8.0) of broad Hα to Hβ emission (Osterbrock 1981).

It is instructive to compare NGC 4395 with G1200−2038 (Kunth, Sargent, and Bothun 1987; cz = 6420 km s^{-1}), a dwarf galaxy with Seyfert 2 characteristics. The latter object is well approximated by an exponential disk of scale length 1.0 kpc, diameter 6.7 kpc (out to the $m_V = 25.0$ mag arcsec^{-2} level), and $M_V \approx -16.9$ mag; $H_0 = 67$ km s^{-1} Mpc^{-1}, as advocated by Rowan-Robinson 1985). Its nucleus, whose spectrum exhibits narrow (FWHM ≈ 320 km s^{-1}) emission lines spanning a wide range of ionization, has $M_V \approx -17.0$ mag. In NGC 4395, the ratio of "nonstellar" (nuclear) to stellar luminosity is only about 0.002, whereas in G1200−2038 it is 1.1, more representative of QSOs. Finally, the nonstellar nucleus of G1200−2038 is ~ 500 times more luminous than that of NGC 4395, yet it does not show clear evidence for broad permitted emission lines. Hence, the two objects are really quite different.

IV. THE MASSIVE STAR HYPOTHESIS

From Figure 1, the flux density of the featureless continuum at 4400 Å is found to be 0.42 mJy, so that $m_B \approx 17.3$ and $M_B \approx -9.8$ mag. The nucleus of NGC 4395 is therefore less luminous than the brightest known Galactic supergiant stars (see Rowan-Robinson 1985 for a summary). Moreover, it appears stellar on the TV acquisition screens of large optical telescopes and on panel 10 of Sandage and Bedke (1988). Thus, it is possible that the spectrum of the nucleus can be explained by a hot star, or a compact cluster of stars, embedded in gas having a range of densities (e.g., 10^2–10^9 cm^{-3}). This is especially relevant in light of the interesting "Warmers" hypothesis advanced by Terlevich and Melnick (1985). The basic idea is that the spectrum of a cluster of extremely massive stars that have blown away their outer envelopes can resemble a power law of index 1.5 (i.e., $f_\nu \propto \nu^{-1.5}$), as in Seyfert galaxies. In this case, the emission-line spectrum will also look like that of a Seyfert galaxy.

The observed luminosity of broad Hβ, 1.5×10^{37} ergs s^{-1}, corresponds to a probable bolometric luminosity of $\sim 1.5 \times 10^{40}$ ergs s^{-1}, if we use the approximate assumption that the bolometric luminosity of a typical Seyfert 1 nucleus is 1000 times that of its broad Hβ emission (Weedman 1976). The Eddington limit for accretion of fully ionized material having solar composition is $\sim 1.5 \times 10^{38}\ M/M_\odot$ ergs s^{-1}, so a *single star* of roughly 100 $M_\odot$ could, in principle, produce the observed flux. A more likely possibility is that a tight cluster of a few somewhat less massive stars within the central 13 pc (1″) is responsible. They would have to be extremely hot, since [Ne V] and [Fe X] emission are visible in the spectrum of NGC 4395. Moreover, the observed widths of the broad permitted lines indicate velocities of up to 4000 km s^{-1}—a severe, though not necessarily impossible, constraint. An additional problem with the massive-star hypothesis is that one might expect Wolf-Rayet features to be present in the optical spectrum (e.g., Kunth and Sargent 1981), but none are seen. Specifically, we should detect a relatively broad blend of N III λλ4634, 4641, 4642 and C III λλ4647, 4651, 4652, yet the broad line centered on ~ 4700 Å is clearly He II λ4686 and the very narrow line at ~ 4663 Å is probably [Fe III] λ4657.

As mentioned by MRS, the narrow-line spectrum of the nucleus of NGC 4395 resembles the spectra of supernova remnants in certain respects, and such remnants would be expected in the massive-star hypothesis. Moreover, spectra of several recent supernovae have been shown to bear, at least at optical wavelengths, a striking resemblance to those of Seyfert 1 nuclei (Filippenko 1989*a*). The massive-star hypothesis should definitely be pursued in the future, with the help of data at UV, X-ray, and other wavelengths.

V. CONCLUSIONS

Despite the above discussion, so far there is no *direct* evidence that the physical mechanisms responsible for the observed properties of the starlike nucleus of NGC 4395 differ from those in classical type 1 Seyfert nuclei. With $M_B \approx -10$ mag, this object is a factor of $\sim 10^8$ less luminous than the brightest known QSOs, and a factor of 10^6 fainter than typical ones; it can therefore be called a "microquasar" (Elvis 1984). Such an object implies, for the time being, that there might be no fundamental lower limit to the intrinsic luminosity of the QSO phenomenon. With the Hubble Space Telescope, it may be possible to discover nearby AGNs with even smaller luminosities, comparable to those of typical stars.

NGC 4395 constitutes a striking exception to the rule that AGNs are found only in galaxies with well-developed bulges. (It may, however, have a bar, as do many normal Seyfert galaxies.) This demonstrates that the formation of black holes, and/or the retention of surrounding gas, need not be inhibited in the rather shallow potential wells of late-type and dwarf galaxies. It provides us with by far the best opportunity to explore the QSO phenomenon at incredibly low intrinsic luminosities. Observations of this unique object over a wide range of wavelengths should prove to be extremely illuminating, and a detailed study at optical wavelengths is currently in preparation.

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