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HST OBSERVATIONS OF NGC 4395, THE LEAST LUMINOUS SEYFERT 1 NUCLEUS: EVIDENCE AGAINST THE STARBURST HYPOTHESIS FOR BROAD-LINED ACTIVE GALACTIC NUCLEI[1]

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ABSTRACT

We have used the *Hubble Space Telescope* to obtain ultraviolet spectra and optical images of the nucleus of NGC 4395, the least luminous and nearest known type 1 Seyfert. The spectrum closely resembles those of normal Seyfert nuclei; narrow emission lines span a wide range of ionization, and the permitted lines have broad wings. If parameterized by a power law ($f_\nu \propto \nu^\alpha$), the essentially featureless continuum has a wavelength-dependent spectral index of -1 to -2. The nucleus is spatially unresolved in the optical images obtained through broad-band filters; we set an upper limit of 0".05 (~0.7 pc) for the diameter of the continuum source. These data, together with optical and near-infrared spectra that reveal no stellar absorption lines whatsoever, constitute strong evidence against the starburst hypothesis for the origin of the activity. A cluster of stars having the requisite characteristics is highly unlikely, while a single or binary star would require unprecedented properties. The continuum cannot be dominated by a young supernova, given the object's exceedingly low luminosity and lack of optical variability. In addition, the broad components of the permitted emission lines are probably not produced by a supernova remnant embedded in a star cluster. Since the nucleus of NGC 4395 resembles those of other Seyfert 1 galaxies in most respects, we conclude that luminous type 1 Seyferts and QSOs are also powered by nonstellar phenomena, consistent with the standard black hole model.

Subject headings: galaxies: individual (NGC 4395) — galaxies: nuclei — galaxies: Seyfert — galaxies: starburst

1. INTRODUCTION

During the course of an extensive spectroscopic survey of nearby galaxies, Filippenko & Sargent (1989, hereafter FS89; see also Filippenko 1992a) discovered that the starlike nucleus of the Sd IV galaxy NGC 4395 is a type 1 Seyfert, the first ever detected in such a late-type, low-luminosity galaxy. Strong, narrow emission lines spanning a wide range of ionization stages are superposed on a featureless continuum, and the permitted lines exhibit weak broad wings. Based on the relative intensities of the narrow and broad components, FS89 classified the nucleus of NGC 4395 as a type 1.8 or 1.9 Seyfert. Only 2.6 Mpc away (Rowan-Robinson 1985, p. 171, based on measurements of H II regions by Kennicutt 1979), NGC 4395 is the nearest known Seyfert 1 galaxy. The luminosity of its broad Hα emission line is $\sim 1.2 \times 10^{38}$ ergs s^{-1}, about a factor of 10 lower than in M81, the previous champion of low-luminosity Seyfert 1 nuclei (Filippenko & Sargent 1988). With an absolute blue magnitude of -10 in the continuum, the nucleus of NGC 4395 is less luminous than the brightest known supergiant stars.

FS89 suggested that it might be feasible to explain the active galactic nucleus (AGN) of NGC 4395 in terms of stellar phenomena, rather than by accretion onto a black hole. Specifically, Terlevich & Melnick (1985) have shown that the spectrum of a cluster of massive stars can resemble a power law of index $\alpha \approx -1.5$ (where $f_\nu \propto \nu^\alpha$), as in classical AGNs. The ionizing continuum will therefore cause nearby gas to produce an emission-line spectrum similar to that of type 2 Seyfert nuclei and low-ionization nuclear emission-line regions (LINERs; Heckman 1980). Over the past few years, R. Terlevich and collaborators (Terlevich et al. 1992, and references therein) have extended their starburst model to include Seyfert 1 galaxies and radio-quiet QSOs. A range of stellar masses and evolutionary phases is required to explain the multiwavelength spectra of AGNs. Thus, although the estimated bolometric luminosity of NGC 4395 ($\sim 1.5 \times 10^{40}$ ergs s^{-1}; FS89) could be produced by a single extremely massive star, a tight cluster of relatively massive stars is more realistic. Our best ground-based measurements provide an upper limit of 1" (~13 pc) for the full width at half-maximum (FWHM) of this cluster.

In order to test the starburst hypothesis, and to explore the overall properties of NGC 4395, a coordinated effort to observe the object throughout the entire electromagnetic spectrum was initiated. Preliminary results include the absence of absorption lines in the spectral range 1200–10,000 Å, the absence of variability in the profile and flux of Hα in several spectra taken over a 2 year interval (Shields & Filippenko 1992), the detection of an unresolved radio point source with a nonthermal spectrum ($f_\nu \propto \nu^{-0.66}$ between 6 and 20 cm; Sramek 1992), and a *ROSAT* X-ray detection with a flux of 8.2×10^{-14} ergs s^{-1} cm^{-2} ($L = 6.6 \times 10^{37}$ ergs s^{-1} if d = 2.6

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Mpc) in the 0.1–2.4 keV band (S. L. Snowden & T. Belloni 1993, private communication). Full details will be given in a future paper. Here we report on optical images and ultraviolet (UV) spectra of NGC 4395 obtained with the *Hubble Space Telescope* (*HST*).

2. OBSERVATIONS

UV spectra of the nucleus of NGC 4395 were obtained with the *HST* Faint Object Spectrograph (FOS; Ford 1990) on 1992 July 15 and 19 UT. The 4"3 × 4"3 aperture (effectively 4"3 × 1"4, due to diode size) was employed to maximize the throughput, with only a moderate loss of spectral resolution for a point source. The gratings used were G130H (1150–1608 Å, 1.0 Å diode^{-1}, blue digicon) for 260 minutes, G190H (1573–2323 Å, 1.5 Å diode^{-1}, red digicon) for 97 minutes, and G270H (2227–3306 Å, 2.1 Å diode^{-1}, red digicon) for 32 minutes. The spectra were calibrated by the Space Telescope Science Institute (STScI) staff in the normal manner. Multiple exposures were summed, and the spectra were concatenated, with software written by one of us (A. V. F.). Discontinuous spikes or dips in a few defective pixels were removed by interpolation.

Direct images of NGC 4395 were taken with the *HST* Planetary Camera (PC; Griffiths 1990) on 1992 July 18 UT. The nucleus was located near the default pointing position on the PC6 CCD. Filters, nominal mean wavelengths/effective widths (Å), and exposure times were as follows: (F336W, 3358/402, 400 s), (F487N, 4869/31, 900 s), (F502N, 5019/30, 300 s), (F547M, 5462/433, 120 s), and (F785LP, 8958/1742, 60 s). The CCD was preflashed before each exposure to improve charge transfer efficiency. The data were automatically processed by the WFPC Routine Science Data Processing pipeline at STScI, but removal of cosmic rays and analysis of images was done at U. C. Berkeley.

3. RESULTS

3.1. *Spectroscopy*

Our complete UV spectrum of the nucleus of NGC 4395 is shown in Figure 1. Comparison with Figure 1 of Snijders, Netzer, & Boksenberg (1986) reveals that the relative intensities of the prominent narrow emission lines resemble those of the type 2 Seyfert galaxy NGC 1068, at least to first order. Moreover, the strongest permitted lines (e.g., C IV λ1549) exhibit weak, broad bases (full width near zero intensity $\approx$5000–10,000 km s^{-1}), as in the optical spectra published by FS89; hence, NGC 4395 is indeed a type 1.8 or 1.9 Seyfert.

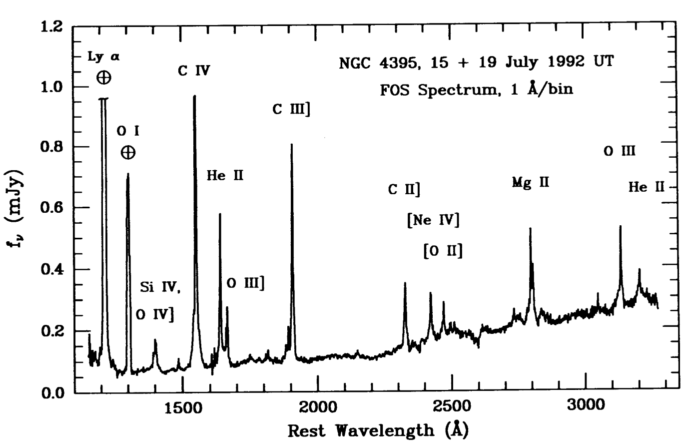

FIG. 1.—UV (*HST* FOS) spectrum of the nucleus of NGC 4395. The wavelength scale is in the rest system of NGC 4395, and the absolute flux density has been adjusted for consistency with that of FS89. Lyα and O I λ1304 are obliterated by geocoronal emission lines, which appear broad because of the large entrance aperture. Excess noise near 1610 Å and below 1180 Å is due to the low sensitivity of the G190H and G130H gratings, respectively.

Some weak absorption lines (the deepest of which are Si II λ1260 and Fe II $\lambda\lambda$2344, 2375, 2383, 2587, 2600) can be discerned in the otherwise featureless continuum. These are clearly produced by the interstellar medium of our Galaxy at the latitude of NGC 4395 ($b \approx 82°$), since (1) their equivalent widths (EW $\approx$ 0.8 Å, typically) are comparable to or smaller than those measured by Bahcall et al. (1992, and references therein) in the quasars 3C 273 ($b \approx 64°$), Mrk 205 ($b \approx 42°$), and H1821+643 ($b \approx 27°$), and (2) their measured redshifts are $\lesssim$100 km s^{-1}, inconsistent with that of NGC 4395 ($cz = 317$ km s^{-1}). UV absorption lines intrinsic to NGC 4395, if present at all, must have EW $\lesssim$ 0.5 Å. (The only clear exception is a line with EW $\approx$ 1 Å in the blue wing of C IV λ1549, at $\sim$1544 Å; perhaps NGC 4395 is an extremely low luminosity counterpart of a broad absorption line QSO.) This complements our results from ground-based spectroscopy: no absorption lines are visible in the spectral range 3200–10,000 Å. In particular, an upper limit of $\sim$0.9 Å is measured for each component of the near-IR Ca II triplet.

The continuum redward of 2200 Å can be approximated by a power law of index $\alpha \approx -2$, but the slope flattens to -1 below 2200 Å. Undulations in the continuum can largely be attributed to blends of broad Fe II emission lines; see Snijders et al. (1986) and Francis et al. (1991). These are generally present in Seyfert 1's and QSOs (e.g., Wills, Netzer, & Wills 1985). The most obvious blend appears centered on $\sim$2500 Å, but additional ones are visible near 1750 Å, 2100 Å, 2750 Å, and 2840 Å. The latter two blends symmetrically straddle the Mg II λ2798 doublet (whose narrow component is resolved), suggesting that at least part of the very broad wings seen in the Mg II profile of many QSOs (Steidel & Sargent 1991) may actually be Fe II.

The Bowen O III λ3133 fluorescence emission is strong relative to He II λ3204, as in other high-ionization Seyfert nuclei (Schachter, Filippenko, & Kahn 1990). Si III] λ1892, usually quite blended with C III] λ1909, is weak but clearly visible, and there is a very faint, unidentified line at 1882 Å. Although details will be presented in a future paper, we note here that almost all of the emission-line intensity *ratios* agree with those for power-law photoionization models having ionization parameters of 10^{-3} to 10^{-2} and $\alpha \approx -1.5$. On the other hand, the EW of the broad component of C IV λ1549 (76 Å) is a factor of $\sim$10 lower than predicted by a simple extrapolation of the Baldwin relation taken from Kinney, Rivolo, & Koratkar (1990).

3.2. *Direct Images*

Figure 2 shows contour plots of two *HST* images of NGC 4395, along with comparison point-spread functions (PSFs) provided by the STScI staff. The comparison stars and the nucleus of NGC 4395 were observed at nearly the same positions on the CCD, but at different times, so the possibility of minor differences in telescope focus cannot be eliminated. It is clear that the nucleus of NGC 4395 is unresolved in the F547M image, which excludes all significant emission lines, and somewhat resolved in the F502N image centered on the [O III]

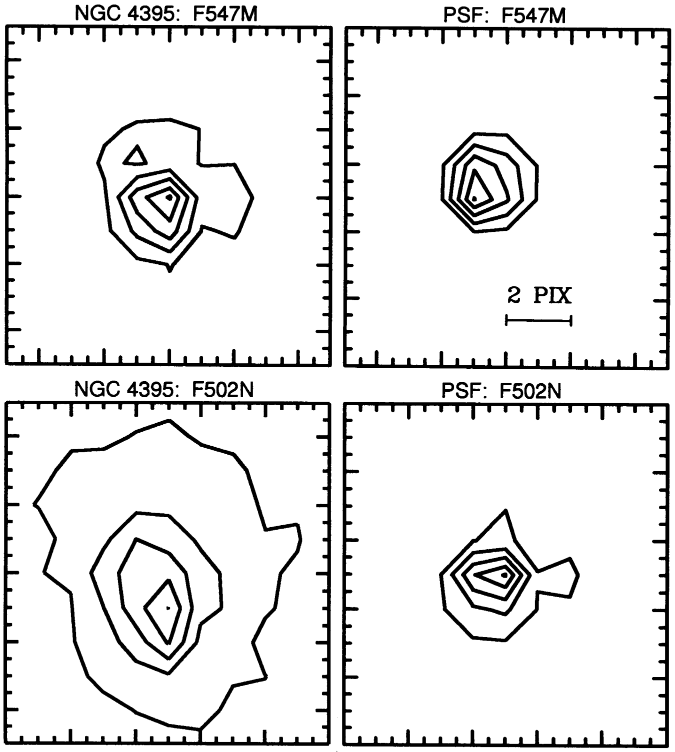

FIG. 2.—Contour plots of optical (*HST* PC) images of the nucleus of NGC 4395, compared with those of an unresolved star. North is to the right, east is up, and the scale is 0."043 pixel^{-1}. The images have not been deconvolved. Contours correspond to 80%, 60%, 40%, and 20% of peak intensity, but the lowest contour in NGC 4395 is noisy. NGC 4395 is unresolved in the line-free visual continuum (F547M filter; *top panels*), and resolved in [O III] λ5007 (F502N filter; *bottom panels*).

λ5007 line. Thus, there is some spatially extended emission-line gas in the nuclear region. Images taken through the other broad-band filters are also consistent with an unresolved point source.

The FWHM of the nucleus in the F547M image, obtained by fitting a Gaussian to the inner core of the profile, is 1.83 pixels (0."079), consistent with the FWHM of the comparison star (1.74 pixels = 0."075). If the intrinsic FWHM of the nucleus were 1.2 pixels (0."052), the measured profile would have FWHM $\approx$ 2.2 pixels, 20% larger than observed. This should have been readily noticeable. We therefore conclude that the nucleus of NGC 4395 has an intrinsic FWHM not greater than 0."05, which corresponds to $\sim$0.7 pc at the assumed distance of 2.6 Mpc for NGC 4395. This is the smallest upper limit for the size of a Seyfert 1 nucleus ever determined through optical imaging.

4. DISCUSSION

4.1. *The Starburst Hypothesis*

In a very provocative series of papers, Terlevich et al. (1992, and references therein) argue that the properties of the broad-line region of Seyfert 1 nuclei and QSOs can be produced by Type II (hydrogen-rich) supernovae evolving in a dense ($n \approx 10^7$ cm^{-3}), high-metallicity medium. These objects become strongly radiative while still expanding at velocities of several thousand km s^{-1}. The calculated emission-line spectrum is similar to those observed in the broad-line regions of low-luminosity AGNs. Empirical evidence for this hypothesis is provided by the observed spectra of some Type II supernovae, which do indeed superficially resemble those of Seyfert 1 nuclei (Filippenko 1989). Only one supernova per year is required for an object with $M_B \approx -21$ mag. The high-excitation spectrum of the narrow-line region is produced by clouds of gas irradiated by hot, evolved Wolf-Rayet stars in the cluster. These stars could account for the smooth UV/optical continuum, and the associated red supergiants would produce the near-IR Ca II absorption triplet often observed at least in Seyfert 2 nuclei (Terlevich, Díaz, & Terlevich 1990). Terlevich (1990) calculates the overall spectrum of an AGN in the starburst model, emphasizing that *several different components* (massive stars, supernovae, supernova remnants) are required for consistency with observations.

Heckman (1991) and Filippenko (1992b) discuss the strengths and weaknesses of the starburst hypothesis for AGNs. Their general conclusion is that the scenario has severe problems for AGNs that have radio jets, shown rapid X-ray variability, or emit a substantial fraction of their power at hard X-ray and gamma-ray energies. On the other hand, it might explain some Seyfert 2 nuclei and a subset of LINERs (Filippenko & Terlevich 1992; Shields 1992), and perhaps those QSOs and Seyfert 1 nuclei lacking the above properties. NGC 4395 provides an excellent test of the starburst hypothesis for broad-lined AGNs; it is the nearest known Seyfert 1 galaxy, and its nucleus is essentially uncontaminated by bulge stars, unlike the case in M81.

4.2. *Application to NGC 4395*

We feel that the *HST* data described here, together with our optical and near-IR spectra, provide strong evidence against the starburst hypothesis for NGC 4395, and hence for other broad-lined AGNs as well.

First, we argue that the nucleus of NGC 4395 is probably not a cluster of normal stars. The main problem is not its size, but its spectrum; although the *HST* upper limit to its diameter ($\sim$0.7 pc) is much more restrictive than the previous ground-based value ($\sim$13 pc), there exist equally small or even smaller clusters of comparable luminosity, such as the nucleus of M33 (Kormendy & McClure 1993) and the giant H II regions 30 Dor and NGC 3603 (Moffat, Seggewiss, & Shara 1985). Unlike NGC 4395, however, M33 exhibits strong absorption lines indicative of an intermediate-age ($\sim 10^9$ yr) population (A–F in the optical range, depending on wavelength). A more appropriate comparison can perhaps be made with the much younger objects 30 Dor and NGC 3603, whose optical stellar absorption lines are weak or coincide with prominent emission lines—but the integrated emission-line spectrum of 30 Dor is quite different from that of type 1 or type 2 Seyfert nuclei (especially at UV wavelengths; W. D. Vacca 1993, private communication), even though it is *known* to contain many Wolf-Rayet stars. It is also improbable that the absorption line in the blue wing of the C IV profile is produced by the winds of massive stars; if we compare Figure 1 with the *IUE* spectra of nearby starburst galaxies, such as NGC 5253 and NGC 1705 (Kinney et al. 1993), we see that there should be a few stellar UV absorption lines uncontaminated by emission (notably Si II λ1260 and C II λ1336), yet none are visible in NGC 4395. These lines would be absent only if the UV luminosity were dominated by O-type or Wolf-Rayet stars, but then the spectral index (α) of the continuum should be roughly 1, instead of

-1 as observed. Finally, if a significant fraction of the stars in the cluster have an age of $\gtrsim 8$ Myr, as might be expected if the broad wings of the permitted emission lines are from a supernova remnant (see below), red supergiants should produce prominent Ca II triplet lines (EW [Ca II λ8542] $\approx$ 4–6 Å; Bica, Alloin, & Schmidt 1990; García-Vargas et al. 1992), inconsistent with our measured upper limit of 0.9 Å.

Next we consider the possibility of a single supermassive star (or perhaps a binary system) as the origin for the activity in NGC 4395. This would have to be a truly extraordinary star with unprecedented properties. The UV spectra of Wolf-Rayet stars, for example, are very blue and show lines of moderately ionized metals with prominent P Cygni profiles, unlike the case in NGC 4395. Furthermore, it must exhibit all of the phenomena normally associated with a *cluster* of stars having a range of stellar masses and evolutionary phases (including supernovae) consistent with the model of Terlevich et al. (1992). Even if a single young supernova could account for the entire multifrequency spectrum of an AGN (contrary to Terlevich 1990), this cannot be the explanation for the nucleus of NGC 4395 because its observed UV/optical luminosity is very low and there has been no obvious Hα variability over the past several years (Shields & Filippenko 1992). In addition, inspection of published photographs of NGC 4395, and of the Palomar Observatory Sky Survey (1956 May 8 UT), reveals that the starlike nucleus has been visible at approximately its current brightness ($B \approx 17$ mag) for at least 36 years.

It is intriguing that the $\lambda = 20$ cm luminosity and the nonthermal radio spectral index of NGC 4395 are comparable to those of Cas A (Sramek 1992). This suggests that the nucleus of NGC 4395 may be a fairly young ($t \lesssim 400$ yr) supernova remnant. If so, only the broad emission lines, radio continuum, and X-rays would be produced by the remnant; most of the near-IR, optical, and UV luminosity would have to come from the surrounding cluster of normal stars. This might be consistent with the model of Terlevich et al. (1992), but only if we *ignore* our previous arguments against the presence of a star cluster. A relatively long evolutionary time scale (tens to hundreds of years) would not violate the measured limits on Hα variability and is expected if the supernova's progenitor had a circumstellar envelope of medium density ($\sim 10^5$ cm^{-3}) rather than high density ($\sim 10^7$ cm^{-3}), as could be the case in the low-metallicity environments typical of late-type dwarfs like NGC 4395. On the other hand, we would then have no explanation for the observed absence of extranuclear, low-metallicity H II regions having the spectra of genuine type 1 Seyferts (i.e., broad permitted emission lines, narrow forbidden lines spanning a wide range of ionization, and a featureless continuum). Terlevich and collaborators have always maintained that the spectroscopic properties of broad-lined AGNs are a consequence of vigorous star formation in the *high-metallicity* nuclei of galaxies; in a sense, their general hypothesis is weakened if used to account for NGC 4395.

We conclude that the apparent activity in the Seyfert 1 nucleus of NGC 4395 probably cannot be explained in the context of the starburst hypothesis of Terlevich et al. (1992). The strongest piece of evidence is the absence of stellar absorption lines, especially in the UV and near-IR spectra. Other relevant characteristics are the UV spectral index ($\alpha \approx -1$), small physical size, low luminosity, and lack of obvious variability. Since classical Seyfert 1 nuclei and QSOs have spectral properties that closely resemble those of NGC 4395 in many respects, the most reasonable deduction is that they, too, are powered by nonstellar processes. This is consistent with, but does not confirm, the standard model involving an accreting black hole. Moreover, it remains to be seen whether accretion onto a black hole can explain some of the observed anomalies of NGC 4395, such as its subtle or nonexistence variability at optical wavelengths.

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