THE ASTROPHYSICAL JOURNAL, 624:L13–L16, 2005 May 1

EVIDENCE OF A STARBURST WITHIN 9 PARSECS OF THE ACTIVE NUCLEUS OF NGC 1097[1]

T. STORCHI-BERGMANN,[2] R. S. NEMMEN,[2] P. F. SPINELLI,[2] M. ERACLEOUS,[3] A. S. WILSON,[4] A. V. FILIPPENKO,[5] AND M. LIVIO[6]
Received 2005 February 1; accepted 2005 March 23; published 2005 April 4

ABSTRACT

We report evidence of a recent burst of star formation located within 9 pc of the active nucleus of NGC 1097. The observational signatures of the starburst include UV absorption lines and continuum emission from young stars observed in a small-aperture *Hubble Space Telescope* spectrum. The burst is $\leq$ a few $\times\ 10^6$ yr old, has a mass of $\sim 10^6\ M_\odot$, an observed luminosity of $1.5 \times 10^7\ L_\odot$, and is obscured by $A_V \approx 3$ mag. The importance of this finding is twofold: (1) the proximity of the starburst to the active nucleus and thus its possible association with it, and (2) its obscuration by and apparent association with a dusty absorbing medium, while the broad emission lines appear unobscured, suggesting that the starburst could be embedded in a circumnuclear torus as predicted in the unified model of active galactic nuclei.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (NGC 1097) — galaxies: starburst

1. INTRODUCTION

The standard model of an active galactic nucleus (AGN) consists of a supermassive black hole being fed via an accretion disk. The model also postulates the presence of a dusty molecular torus surrounding this inner region and blocking it from view in AGNs where the line of sight intercepts the torus (Antonucci 1993).

For several years, the only plausible signature of the accretion disk was the "big blue bump," observed in the ultraviolet (UV) spectra of active galaxies, which was supposed to be the thermal emission from the disk (Shields 1978; Malkan & Sargent 1982; Koratkar & Blaes 1999). A more telling feature, such as the kinematic signature of rotating gas, in the form of double-peaked line emission as observed in cataclysmic variables, was only discovered in optical spectra in the 1980s (Halpern & Filippenko 1988; Chen et al. 1989; Halpern 1990), and systematic searches were later published by Eracleous & Halpern (1994, 2003) and by Strateva et al. (2003). Broad, double-peaked emission lines from the nucleus of NGC 1097 were reported by Storchi-Bergmann et al. (1993), and similar lines were found in other nearby galaxies with the *Hubble Space Telescope* (*HST*; Bower et al. 1996; Shields et al. 2000; Ho et al. 2000; Barth et al. 2001).

NGC 1097 is particularly interesting because the double-peaked line originates in a low-luminosity AGN and is a transient phenomenon, as it was not seen in previous observations. These characteristics indicate that we would have a good chance of observing temporal variations in a reasonable (not too long) time interval. Indeed, monitoring of the double-peaked emission over the years 1992–2001 (Storchi-Bergmann et al. 1997, 2003) has put further constraints on the accretion disk model and provided evidence against other possible origins for the double-peaked emission in this particular object, such as double jets and a binary black hole (Storchi-Bergmann et al. 1995; Livio & Pringle 1996; Eracleous et al. 1997).

In this Letter, we report the presence of absorption features in small-aperture *HST* UV spectra of NGC 1097, and we argue that they are characteristic of young O and B stars and of a low-ionization interstellar medium, all within a radius of at most 9 pc from the nucleus. Such dimensions are typical of those of star clusters and also of those expected for obscuring tori in the standard model of AGNs. Besides the absorption features, the UV continuum also reveals the spectral energy distribution of a young starburst extinguished by a dusty medium.

2. OBSERVATIONS

UV and optical spectra of NGC 1097 were obtained with the Space Telescope Imaging Spectrograph (STIS) aboard *HST* on 2001 February 7 and 11 UT, using a $0\farcs2 \times 52''$ slit and the G140L, G230L, G430L, and G750L gratings. These gratings have resolving powers $500 \leq R \leq 1000$, which allow the separation of absorption features in the galaxy from those in the Milky Way. The exposure times were 8302 s for each of the two UV gratings, 1008 s for grating G430L and 936 s for grating G750L. In order to obtain the best possible angular resolution achievable with the observations, we extracted a nuclear spectrum within a window of $0\farcs2$, corresponding to a 9 pc radius region centered on the nucleus. We then combined the various spectral segments to construct one UV/optical spectrum spanning the spectral range 1100–9000 Å.

The combined spectrum was corrected for the foreground reddening $A_V = 0.088$ mag from Schlegel et al. (1998). The spectrum, in the rest frame of the galaxy, is shown in Figure 1, where we have edited out the geocoronal Lyα and O I λ1302.08 emission lines. The main features readily observed in this spectrum are a "hump" in the UV continuum peaking near 2500 Å and several double-peaked emission lines, identified in the figure: Mg II λ2800, Hβ, He I λ5876, and Hα. Broad components are also observed in Lyα, C IV λ1550, and C III] λ1909, although the double-peaked nature is not clear because of the lower signal-to-noise ratio.

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[1] Based on observations with the NASA/ESA *Hubble Space Telescope* at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

[2] Instituto de Física, Universidade Federal do Rio Grande do Sul, Av. Bento Goncalves 9500, Campus do Vale, CP 15051, 91501-970 Porto Alegre RS, Brazil; thaisa@if.ufrgs.br.

[3] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802; mce@astro.psu.edu.

[4] Department of Astronomy, University of Maryland, College Park, MD 20742-2421; wilson@astro.umd.edu.

[5] Department of Astronomy, University of California at Berkeley, 601 Campbell Hall, Berkeley, CA 94720-3411; alex@astro.berkeley.edu.

[6] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; mlivio@stsci.edu.

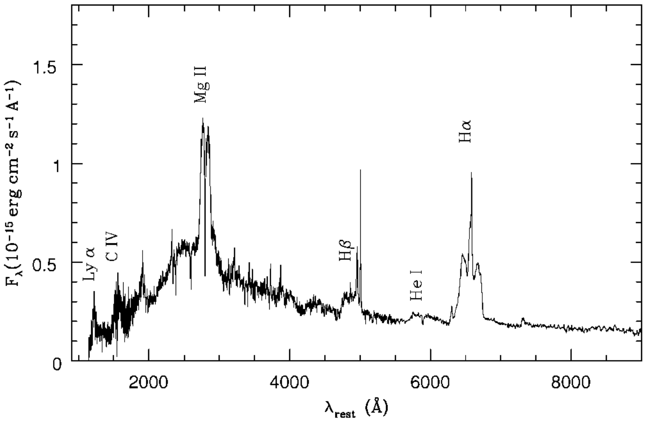

FIG. 1.—UV + optical spectrum of NGC 1097 from a region within 0″.1 (9 pc at the galaxy) of the nucleus, in the rest frame of the galaxy. The double-peaked and other broad lines are identified.

3. A CLOSE LOOK AT THE UV SPECTRUM: ABSORPTION FEATURES

The UV spectra of nuclei with broad double-peaked emission lines (hereafter dubbed "doublepeakers") show a number of common absorption features in the spectral range 2000–3000 Å, mostly metastable Fe II absorption lines (Eracleous 2002; Eracleous et al. 2004). The absorption spectrum of NGC 1097 in the above spectral range is similar to that of the prototypical doublepeaker, Arp 102B (Halpern et al. 1996), which Eracleous et al. (2003) have proposed to originate in thin sheets or filaments embedded in an outflowing wind that overlays the accretion disk (and thus is close to it, within roughly 5000 gravitational radii). Eracleous et al. (2004) propose that many doublepeakers may have these filaments, and NGC 1097 probably also fits within this scenario.

Here we will focus on the range 1100–1600 Å of the nuclear spectrum of NGC 1097. In this spectral range, NGC 1097 shows a number of absorption lines, some of which are superposed on the broad Lyα and C IV emission lines, as illustrated in the top panel of Figure 2. The absorption features are identified at the bottom of the figure. We include in this figure, for comparison, the STIS spectrum of the Seyfert galaxy Ark 564 (representative of Seyfert galaxy spectra) and of the starburst nuclei of NGC 7552 and NGC 5253, all in the rest frame of the galaxies. Upon inspection of the UV spectra of many other Seyfert and starburst galaxies, we conclude that the absorption features in the UV spectrum of NGC 1097 are not common in AGNs but are frequently observed in the spectra of starburst galaxies.

We also include in Figure 2 a synthetic spectrum of a starburst obtained using the code Starburst 99 (Leitherer et al. 1999), with the following parameters: instantaneous burst of mass $10^6\ M_\odot$, age 10^6 yr, Salpeter initial mass function (IMF), lower and upper limits for the IMF of 1 and 100 $M_\odot$, respectively, and solar metallicity. The spectra of Figure 2 have been normalized at 1350 Å to allow a better comparison among them, and they have been shifted vertically for clarity.

In order to further emphasize the similarity of the nuclear UV spectrum of NGC 1097 with those of starbursts, we show in the lower panels of Figure 2 the NGC 1097 spectra on top of those of NGC 7552 and NGC 5253. We decided to keep in the spectra the geocoronal Lyα and O I λ1302 emission lines, in order to avoid introducing artificial discrepancies.

The following stellar absorption features, characteristic of the spectra of early-type stars (O, B), are observed in the spectra of NGC 1097, NGC 7552, and NGC 5253 (Kinney et al. 1993; Vázquez et al. 2004): C III λ1175.7, N V λλ1238.8, 1242.8, Si IV λλ1393.8, 1402.8, and C IV λλ1548.2, 1550.8. The last three are resonance lines and can also originate in the interstellar medium. Other interstellar lines present in the spectra are Si II λλ1190.4, 1193.3, N I λ1199.9, Si II λλ1259.5, 1260.4, O I λ1302.1, Si II λ1304.4 (the last two partially filled by the geocoronal O I emission line), C II λλ1334.5, 1335.7, and Si II λ1526.7. There are also in the nuclear spectrum of NGC 1097 a few absorption lines from our Galaxy, but they can be separated from the absorption lines of NGC 1097 because of the redshift of the latter.

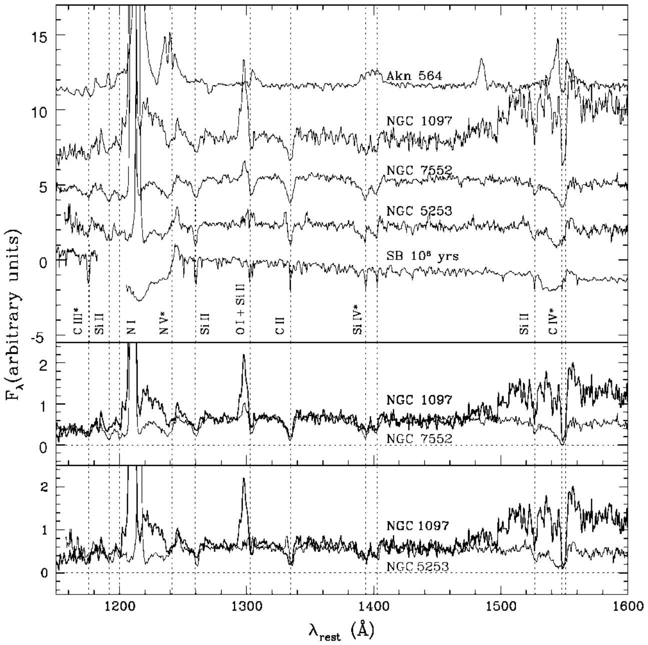

FIG. 2.—*Top:* UV spectrum of NGC 1097 compared to those of the Seyfert 1 galaxy Ark 564 and the starburst nuclei of NGC 7552 and NGC 5253. All spectra are in the rest frame of the galaxies. Also included is a synthetic spectrum of a $10^6\ M_\odot$, 10^6 yr old starburst obtained using the code Starburst 99 (Leitherer et al. 1999). The absorption lines are identified at the bottom. An asterisk means that the line is present in the atmosphere of young stars. *Middle:* NGC 1097 spectrum superposed on the scaled NGC 7552 spectrum. *Bottom:* NGC 1097 spectrum superposed on the scaled NGC 5253 spectrum.

Among the stellar absorption features, only C III λ1175 is not a resonance line and must originate in the atmosphere of young stars. This line is sharp and deep in the starburst synthetic spectrum but is broader and shallower in the spectra of the actual starbursts NGC 5253 and NGC 7552. In the NGC 1097 spectrum, it has a similar profile to those observed in the starburst galaxies, as can be seen in Figure 2. The presence of young stars is also supported by the P Cygni profile of the line N V λ1240, which can be clearly observed in NGC 1097 and NGC 5253 and in the synthetic starburst spectra, although only a hint of it appears in the NGC 7552 spectrum. Notice, in particular, the similarity between the emission portion of this line in NGC 1097 and NGC 5253 (Fig. 2).

A P Cygni profile is also observed in the C IV λ1550 line of the NGC 5253 and synthetic starburst spectra but not in NGC 7552. In NGC 1097, there is only a hint of a P Cygni profile in the C IV line, superposed on the broad emission line profile. The large depth of the absorption, which reaches practically zero flux, indicates that this line probably does not originate exclusively in the stellar atmospheres of young stars. A large depth is also observed in the Mg II λ2800 absorption. These two deep absorption lines suggest that some of the absorbing gas is along our line of sight to the AGN. The absorber could be the starburst superwind whose filaments cross our line of sight to the nucleus (e.g., Heckman et al. 2000) or filaments embedded in an accretion disk wind (as is the case favored for the other doublepeakers; Eracleous et al. 2004), or both.

4. THE UV/OPTICAL CONTINUUM AND THE ROLE OF REDDENING

Is the spectral energy distribution (SED) compatible with the presence of a young starburst in the nucleus of NGC 1097? In order to answer this question, we have used the code Starburst 99 (Leitherer et al. 1999) to construct model SEDs of continuous and single bursts of star formation of different ages. Inspection of the nuclear continuum of NGC 1097 in Figure 1 shows that the flux increases from the optical to the UV, as expected for a young starburst, but then, at ~2500 Å, decreases to shorter wavelengths. The only way to have this flux decrease in the UV is through reddening.

We have tried different combinations of starburst models and reddening laws. For the starbursts, we have also experimented with different slopes for the IMF, and our conclusions are as follows. Continuous bursts provide too much flux in the optical, as do single bursts older than a few times 10^6 yr. When combined with any of the known reddening laws, they fail to produce the observed shape of the UV SED. The most suitable starburst model is the one of a single burst of age 10^6 yr. The SEDs of younger bursts or bursts with different IMFs are only slightly different from that of a single burst of age 10^6 yr, and they do not provide significant improvement to the fit of the observed spectrum. We have also concluded that models including the contribution of the gas produce a strong Balmer jump in emission that is not observed in the data. The best fit to the NGC 1097 continuum that we could obtain from the available synthetic spectra includes only the stellar contribution to the continuum.

In order to produce the observed flux decrease in the UV, we have tried the Calzetti reddening law (Calzetti et al. 1994), the Milky Way (MW) reddening law (Cardelli et al. 1989), the Large Magellanic Cloud (LMC) reddening law (Koornneef & Code 1981; Pei 1992), and the Small Magellanic Cloud (SMC) reddening law (Bouchet et al. 1985; Pei 1992). The Calzetti reddening law did not have enough UV extinction to reproduce the data, both the MW and LMC laws introduced the characteristic 2200 Å absorption feature that is not present in the data, while the SMC reddening law produced better agreement with the data for $A_V = 3$ mag and $R = 3.1$. Although it is surprising that the best reddening law is that of the SMC (as NGC 1097 is a much more luminous and a more metal-rich galaxy than the SMC), we point out that extinction by an "SMC-like" reddening law has also been found to best explain the SEDs of red quasars in the Sloan Digital Sky Survey (Richards et al. 2003).

Not only is the SED in approximate agreement with the observations but so is the flux of the reddened 10^6 yr starburst, indicating that the mass of the starburst is roughly the one adopted in the model, $10^6\ M_\odot$. This is illustrated in Figure 3, where we show the NGC 1097 spectrum compared to the reddened starburst SED. An inset in the figure shows the SED of the unreddened starburst in comparison with the galaxy spectrum in order to illustrate the effect of reddening. Figure 3 also shows the contribution of the continuum emitted by the AGN, borrowed from R. S. Nemmen et al. (2005, in preparation), but with preliminary results already published (Nemmen 2004). In R. S. Nemmen et al. (2005, in preparation), the nuclear SED—from X-ray to radio wavelengths—is found to be well reproduced by a model consisting of the emission from a radiatively inefficient accretion flow (RIAF) plus that of a thin accretion disk. Although this model produces a good overall description of the SED, it does not reproduce the excess in the UV, as illustrated in Figure 3. We point out that in R. S. Nemmen et al. (2005, in preparation), the thin-disk emission is self-consistently derived from the incidence of the RIAF radiation on the disk. The thin-disk continuum emission peaks in the optical/infrared and cannot reproduce the excess UV emission.

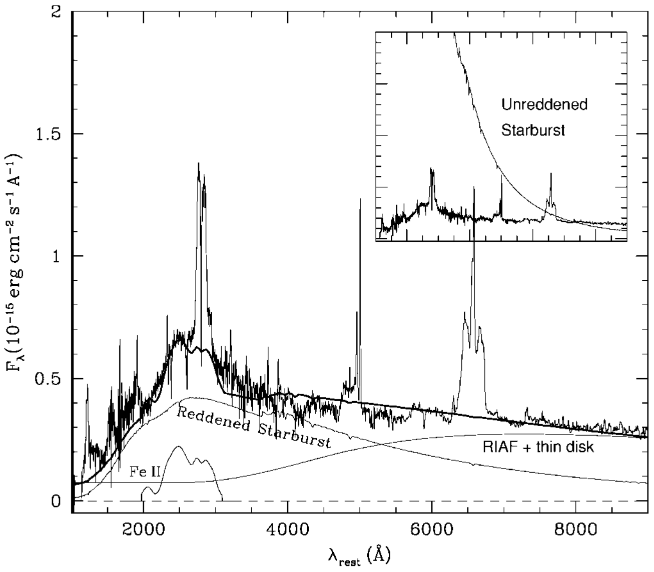

FIG. 3.—Thin lines show the nuclear spectrum of NGC 1097, together with the synthetic spectrum of the 10^6 yr old starburst reddened by $A_V = 3$ mag, the RIAF + thin-disk model, and the Fe II model. The thick line is the model continuum obtained by combining these three components. The inset shows the unreddened spectrum of the starburst compared to the NGC 1097 spectrum.

4.1. *Contribution of UV* Fe II *Emission*

Although the introduction of a reddened starburst continuum can approximately reproduce the UV and its decrease to shorter wavelengths, there is still a small remaining "bump" around 2500 Å that is not reproduced by the RIAF + thin-disk + reddened starburst (Fig. 3). In this wavelength region, there is a blend of Fe II emission lines that is frequently present in the UV spectra of Seyfert 1 galaxies and quasars (Wills et al. 1985; Vestergaard & Wilkes 2001).

In order to investigate the possibility that the above bump is due to the blend of Fe lines, we have used an archival spectrum of I Zw 1 (kindly provided to us by K. Leighly) as a template for the Fe emission. Although this template covers only the 2000–3000 Å spectral region, it includes the most intense Fe II emission lines. [The contribution of Fe II lines in the optical is much smaller—with peak intensities ~10% of that in the UV (Baldwin et al. 2004; Sigut & Pradham 2003). Detailed modeling of the optical Fe II emission is beyond the scope of this work.]

Under the assumption that the Fe II emission is coming from the accretion disk, we have convolved the template with the double-peaked profile of the emission lines. Combining this component with the others, we could successfully reproduce the remaining bump around 2500 Å. This is also illustrated in Figure 3, where we further include the Fe II template and a model (*thick line*) for the NGC 1097 continuum comprising all the components: the reddened starburst, the RIAF + thin-disk model, and the Fe II template, properly scaled to fit the data. The reddened starburst model was scaled by 0.85, corresponding to a UV + optical flux of 1.7×10^{-12} ergs cm^{-2} s^{-1} and a luminosity of 1.5×10^7 $L_\odot$ (both uncorrected for reddening) for an adopted distance to NGC 1097 of 17 Mpc.

Finally, we point out that it is not our goal to produce a detailed fit to the spectrum, as there are many uncertainties. For example, the reddening law may be somewhat different from that of the SMC, and the starburst properties may also differ from those of the Starburst 99 model.

5. CONCLUDING REMARKS

We have shown evidence of an obscured starburst located within 9 pc of the active nucleus of the galaxy NGC 1097. The importance of this finding is twofold: (1) the proximity of a young starburst to the nucleus and thus its possible association with it, and (2) the fact that the starburst is obscured but the AGN is not.

The maximum distance between the starburst and the nucleus of NGC 1097 (9 pc) is comparable to the sizes of star clusters with masses $\sim 10^6$ $M_\odot$ (Calzetti et al. 1997); hence, the cluster is quite close to the nuclear black hole (Perry & Williams 1993). The disruption of a cluster star passing closer to the black hole than its tidal radius could be the origin of the transient accretion disk, as we have proposed in Storchi-Bergmann et al. (1993). Flares in the UV (Renzini et al. 1995) and X-rays (Halpern et al. 2004) suggest that we are beginning to witness such events. Alternatively, mass loss from evolving stars in the cluster could be the origin of the accretion disk. In any case, we may be seeing a rare example of the "starburst-AGN connection"—the starburst is responsible for feeding the AGN!

Another interesting characteristic of this starburst is that it is immersed in an obscuring medium. Its maximum size is also on the order of that predicted for the torus of the "unified model" of AGNs (Antonucci 1993). Although we cannot prove that the geometry is that of a circumnuclear torus, there is no evidence that the nuclear source is obscured, as we can observe the RIAF + thin-disk continua and the double-peaked emission lines with no signs of obscuration; indeed, the Mg II line in the UV is the strongest double-peaked line of the spectrum. Thus, the starburst *may be* within a dusty toroidal structure that leaves the nuclear source unobscured. If this is the case, we are observing, for the first time, a starburst inside a torus, as has been proposed in the literature as a solution for the stability problem of the torus: the toroidal structure is supported by the pressure produced by the evolving starburst inside (Wada & Norman 2002; Cid Fernandes & Terlevich 1995).

Finally, we point out that the starburst reddening, $A_V = 3$ mag, is not very high. An additional reddening of 2–3 mag would render the starburst undetectable. Since higher reddening values have been found in the nuclear regions of many AGNs, our results show that starbursts may be present, but most will not be detected, at least in the UV.

We acknowledge valuable discussions with E. Bica, C. Bonatto, G. Kriss, C. Leitherer, and P. Hall. We thank K. Leighly for providing the Fe II spectrum and the referee for valuable suggestions. This work was supported by NASA grant GO-08684 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555, and the Brazilian institutions CNPq, CAPES, and FAPERGS. A. V. Filippenko is grateful for a Miller Research Professorship at UC Berkeley, and M. Eracleous and A. S. Wilson acknowledge support from NASA LTSA grants NAG5-10817 and NAG5-13065, respectively.

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