NGC 3065: A CERTIFIED LINER WITH BROAD, VARIABLE BALMER LINES

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ABSTRACT

Motivated by the X-ray properties of the galaxy NGC 3065, we have obtained new optical spectra that reveal that it has a low-ionization nuclear emission-line region (LINER) as well as broad Balmer emission lines, establishing it as an active galactic nucleus. We also examined an older spectrum from the CfA Redshift Survey that lacks broad Balmer lines, indicating that these lines appeared sometime after 1980. Thus NGC 3065 joins the set of LINERs with broad, variable Balmer lines, which includes such well-known galaxies as NGC 1097 and M81. Inspired by the sometimes double-peaked profiles of the variable Balmer lines in other LINERs, we speculate that the broad Balmer lines of NGC 3065 also come from an accretion disk. We illustrate the plausibility of this hypothesis by fitting a disk model to the observed H\alpha profile. We also estimate the mass of the central black hole to be \((9 \pm 4) \times 10^7 M_\odot\) from the properties of the host galaxy, which leads to the conclusion that the accretion rate is only \(~2 \times 10^{-4}\) times the Eddington value, a property that appears to be common among LINERs. At such a low relative accretion rate, the inner accretion disk can turn into a vertically extended ion torus, which can illuminate the outer thin disk and power the broad-line emission. The reason for the sudden appearance of broad Balmer lines is an open question, although we suggest two possible explanations: (1) tidal disruption of a star or (2) a sudden transition in the structure of the accretion disk.

Subject headings: galaxies: active — galaxies: individual (NGC 3065) — line: profiles

1. INTRODUCTION

Low-ionization nuclear emission-line regions (LINERs; Heckman 1980) are a heterogeneous population of objects for which low-luminosity active galactic nuclei (LAGN) and compact starbursts are two of the many possible power sources (see, e.g., Filippenko 1996, for a review). From the point of view of the physics of accretion onto compact objects, those LINERs that are true LLAGNs are particularly interesting. Having low accretion rates onto the supermassive black holes that are at the center of these LINERs, the accretion flows are qualitatively different from those that occur in more luminous Seyfert galaxies and quasars. It is therefore extremely interesting that in the past few years several LINERs have been identified as bona fide AGNs based on the presence of broad and sometimes variable Balmer lines in their optical spectra (e.g., Ho, Filippenko, & Sargent 1997b). Here we report our discovery of a previously unrecognized LINER and a true AGN with variable and broad Balmer lines in the S0 galaxy NGC 3065 (also known as VII Zw 303). Thus NGC 3065 joins the growing set of LINERs with variable, broad Balmer lines, which includes such famous objects as NGC 1097 (Storchi-Bergmann, Baldwin, & Wilson 1993) and M81 (Bower et al. 1996).

NGC 3065 (\(z = 0.00667\), at a distance of 47.3 Mpc, from Tully 1987; but \(H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}\) has been known to have emission lines since the mid-1950s (Humason, Mayall, & Sandage 1956; Burbidge & Burbidge 1965). It was detected as a radio source at 1.4 GHz in the NRAO VLA Sky Survey (Condon et al. 1998) with a monochromatic luminosity of \(1.2 \times 10^{23} \text{ W Hz}^{-1}\) and as an X-ray source with the \textit{Einstein IPC}, with a 0.2–4 keV luminosity of \(2.1 \times 10^{41} \text{ ergs s}^{-1}\) (Fabbiano, Kim, & Trinchieri 1992). More recent X-ray observations with \textit{ASCA} gave a 2–10 keV luminosity of \(5 \times 10^{41} \text{ ergs s}^{-1}\), with a spectrum that can be described either as a power law with a photon index of 1.8 or as a 6 keV thermal plasma (Iyomoto et al. 1998). There was no evidence for X-ray emission from a cooler thermal plasma, as is found in many other LINERs (e.g., Ptak et al. 1999; Terashima et al. 2000). The hard X-ray spectrum led Iyomoto et al. (1998) to suggest that NGC 3065 harbors an LLAGN and motivated us to obtain new optical spectra in order to evaluate its credentials further.

2. OBSERVATIONS AND SPECTRA: NEW AND OLD

We obtained spectra of NGC 3065 with the MDM Observatory’s 2.4 m telescope and Boller & Chivens CCD Spectrograph on 2000 May 31 and with the Kitt Peak National Observatory’s (KPNO) 2.1 m telescope and GoldCam spectrograph on 2000 June 5. In the former set of observations we used a 1.5 slit and a 150 groove mm\(^{-1}\) grating with a total exposure time of 2000 s to cover the wavelength range 3200–6860 Å at a spectral resolution of 12.4 Å. In the latter we used a 1.9 slit and a 600 groove mm\(^{-1}\) grating with a total exposure time of 1800 s to cover the wavelength range 5570–8540 Å at a spectral resolution of 4.2 Å. In both cases, spectra were extracted from a 1” window along the slit. Because of the narrow apertures used, which were comparable to the size of the seeing disk, the absolute flux scale is somewhat uncertain. Wavelength calibration was carried out with the help of arc spectra obtained immediately after the object exposure, and flux calibration was carried out with the help of standard stars observed on the same night and reduced in the same manner as the object. The final reduced and combined spectra are shown in Figure 1. To investigate possible variability of the broad H\alpha line, we also examined the spectrum of NGC 3065 taken during the CfA Redshift Survey on 1980

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the flux at the wavelengths of Hβ stellar continuum need not contribute more than 10% of the emission. We found that the spectrum of NGC 4339 was assumed to have a power-law spectrum of the form $I = I_0 (\lambda/\lambda_0)^{-\alpha}$. We subtracted it. To describe the starlight, we experimented with spectra of elliptical S0 galaxies (NGC 3379, NGC 4339, NGC 4366, and NGC 5322), while the nonstellar continuum was assumed to have a power-law spectrum of the form $f_\nu \propto \nu^\beta$. We found that the spectrum of NGC 4339 provides an excellent match to the continuum of NGC 3065, with no need for a nonstellar component. The nonstellar continuum need not contribute more than 10% of the flux at the wavelengths of Hα or Hβ and no more than 15% of the flux at the wavelength of [O II] $\lambda3727$. The residual spectrum is shown in Figure 1 with the emission lines identified. It shows the broad Hα line very clearly as well as an unambiguously broad Hβ line. A hint of a broad Hγ line is discernible as well. It is worth emphasizing that a careful subtraction of the starlight is needed to isolate the emission lines in the vicinity of Hβ since the starlight spectrum has a rather rich absorption-line structure in this region. It can easily hide or distort the appearance of the Hβ line as well as the nearby [O III] $\lambda4959$ line. Our approach to subtracting the starlight from the Mount Hopkins spectrum was somewhat different since the flux scale of this spectrum is not calibrated. We used as a template the spectrum of S0 galaxy M42 (NGC 4472), observed during the CFA redshift with the same setup as the NGC 3065 observation and within 7 weeks of it. We subtracted the template spectrum from that of NGC 3065 after normalizing the continuum around Hα to unity in both spectra. This procedure resulted in the removal of all stellar absorption features from the NGC 3065 spectrum.

A lower limit to the equivalent width of the Hα line relative to the nonstellar continuum is $EW > 170$ Å. This limit is comparable to the equivalent widths of other LINERs with broad Hα lines (e.g., NGC 4579, NGC 4450, NGC 4203, M81), which are in the range 140–530 Å. For comparison, the equivalent widths of the Hα lines of well-known Seyfert galaxies (e.g., NGC 4151, NGC 5548, Mrk 6, Mrk 841; measured from the spectra of Eracleous & Halpern 1993) are somewhat larger, falling in the range 500–600 Å.

In Table 1, we list the relative emission-line intensities measured from the spectra after subtracting the continuum. They have been corrected for galactic reddening using $E(B - V) = 0.067$ (Schlegel, Finkbeiner, & Davis 1998). We also list the widths of the broad Balmer lines as well as the widths of the narrow lines included in the KPNO spectrum (unfortunately, the narrow lines in the MDM spectrum are not resolved). If we naively fit the broad Balmer lines with single Gaussian models, we find that their centroids are blueshifted by about 450 km s$^{-1}$ from the reference frame defined by the narrow lines. However, we also note that at least the Hα line shows a red asymmetry: the red wing extends about 2000 km s$^{-1}$ farther from the narrow component of the line than the blue wing does. To illustrate the properties of the broad-line profiles, we plot Hα and Hβ spectra on a common velocity scale in Figure 2. This illustration brings out the features of the Balmer-line profiles: a blueshifted shoulder and a red wing that is more extended than the blue wing. It also shows that the broad Hα line was absent in the 1980 spectrum, indicating that it must have appeared sometime in the past 20 years. To illustrate the difference between the 1980 and 2000 Hα spectra more clearly, we superpose the two in the third panel of Figure 2. The 1980 spectrum has been scaled to match the [N II] $\lambda6584$ strength of the 2000 spectrum. The difference between the two is easily discernible, especially on the blue side of the broad Hα line, where the intensity in the 2000 spectrum is 4 times higher than what would be consistent with the noise in the 1980 spectrum.

To assess whether the normalization procedure we adopted above is fair, we examined our two-dimensional...
broad line profile (see 1980 Hspectrum has been scaled to match the [N II] 6584 a LINER. The oxygen line ratios, [O III] 5007/[N II] 6584, [O I] 6300/Hα = 0.8, and [S II] λ6717, 6731/Hα = 1.3, place NGC 3065 in the regions of the diagnostic ratio diagrams occupied by LINERs, albeit close to the boundary with Seyferts (see, e.g., Ho, Filippenko, & Sargent 1997a). The widths of the narrow forbidden lines appear to follow a trend with critical density: lines of higher critical density are broader than lines of lower critical density. Such a trend is often observed in LINERs and it has been interpreted as an indication that the narrow-line-emitting gas is stratified in density (Filippenko 1985). The presence of broad Balmer lines in the spectrum of NGC 3065 establishes it as an AGN beyond doubt and confirms the suggestion of Iyomoto et al. (1998) based on the X-ray properties.

Finding broad Balmer lines in the spectra of LINERs is not unusual. For example, M81 has been known for quite some time to have broad Balmer lines (Peimbert & Torres-Peimbert 1981; Filippenko & Sargent 1988). More recently, broad Balmer lines have been found in several LINERs with the Hubble Space Telescope (HST), which can obtain spectra through very small apertures that exclude the contaminating starlight very effectively. Examples include NGC 4203 (Shields et al. 2000), NGC 4450 (Ho et al. 2000), and NGC 4579 (Barth et al. 2000). The sudden appearance or dramatic variability of broad Balmer lines in LINERs is not unheard of either; it has been observed in at least two other cases so far: NGC 1097 (Storchi-Bergmann et al. 1993) and M81 (Bower et al. 1996). It is also possible that the broad Hα lines of NGC 4203, NGC 4450, and NGC 4579 varied dramatically between the early observations from the mid-1980s (Ho et al. 1997b) and the later HST observations from the late 1990s, although one cannot be confident in view of the available data.

The broad Balmer lines of LINERs often have double-peaked profiles, which are characteristic of rotation and suggest an origin in an accretion disk around a supermassive black hole (see above references). This underscores an intimate connection between LINERs and another class of double-peaked emission-line AGNs, the broad-line radio galaxies (BLRGs; Eracleous & Halpern 1994), which is bolstered by other similarities between the two classes of object. In particular, the relative strengths of the narrow emission lines of BLRGs with double-peaked emission lines approach those of LINERs (the prototype, Arp 102B, is a certified LINER; Stauffer, Schild, & Keel 1983). Moreover, in Pictor A, whose relative narrow-line strengths are close to LINER-like (Filippenko 1985), the double-peaked Balmer lines appeared abruptly in the mid- to late 1980s (Halpern & Eracleous 1994; Sulentic et al. 1995).

Although the broad Balmer lines of NGC 3065 are not double peaked, the fact that their red wing extends farther than their blue wing is reminiscent of gravitational redshift of photons originating in the inner part of an accretion disk. We thus speculate that the broad Balmer lines of NGC 3065 originate in the outer parts of an accretion disk around a supermassive black hole. We emphasize that this is by no means a unique explanation for the origin of the broad Balmer lines; it is merely inspired by the profiles of the Balmer lines of other similar objects. To assess the plausibility of this hypothesis we have tried to fit their profiles with the disk model developed by Chen, Halpern, & Filippenko (1989) and Chen & Halpern (1989). The result of this exercise is superimposed on the observed Hα profile shown in the top panel of Figure 2. According to the adopted model,
the axis of the disk is inclined at an angle of 50° to the line of sight, and the line-emitting region is between radii of 900 and 100,000 GM c⁻², where M is the mass of the black hole. The emissivity is a broken power law with radius: $e \propto r^{-q}$, where $q = 1.7$ for $r < 10,000$ GM c⁻², and $q = 3$ elsewhere. In this context it is noteworthy that the profiles of emission lines coming from an accretion disk need not be double peaked; if the ratio of the inner-to-outer radius of the line-emitting part of the disk is large or if the disk is close to face on, the two peaks get close enough together that they merge, and the profile appears flat-topped or single-peaked (Eracleous 1999; Corbin 1997). Other combinations of model parameters may be able to produce equally good fits. We have not explored the parameter space because we are only focusing on the plausibility of the interpretation here. Also, more sophisticated disk models that include an eccentricity (Eracleous et al. 1995) or a spiral wave (Gilbert et al. 1999) may be able to reproduce the observed Hz profile even better, but such detailed modeling is well outside the scope of this paper.

To further explore the similarities of NGC 3065 to LINERs and BLRGs with double-peaked Balmer lines, we have estimated the mass of its central black hole and the corresponding Eddington luminosity. To estimate the black hole mass we used the recently established correlation between it and the stellar velocity dispersion in the host galaxy (Ferrarese & Merritt 2000; Gebhardt et al. 2000). The stellar velocity dispersion of 173 ± 16 km s⁻¹, as reported by Tonry & Davis (1981), yielded $M_\bullet = (9 \pm 4) \times 10^7 M_\odot$, where the error bar reflects not only the uncertainty in the velocity dispersion but also uncertainties in the parameters describing the correlation between the velocity dispersion and the black hole mass (see Ferrarese & Merritt 2000; Gebhardt et al. 2000). As a check, we also estimated the black hole mass based on the correlation between it and the blue luminosity of the bulge of the host galaxy (see the latest version in Kormendy 2000) and using the bulge-disk decomposition of Kormendy (1977), obtaining $M_\bullet = 2 \times 10^7 M_\odot$. This value is almost a factor of 2 greater than that obtained with the previous method, which is very likely a result of the large scatter about the mean trend between the black hole mass and the bulge luminosity. Because of this large dispersion, we prefer the black hole mass value inferred from the stellar velocity dispersion. The implied Eddington luminosity is $L_{\text{edd}} = 1.5 \times 10^{44}$ ergs s⁻¹. If we take the bolometric accretion luminosity of NGC 3065 to be 10 times larger than the observed 2–10 keV X-ray luminosity (see, e.g., Ho 1999), we find an Eddington ratio of $L_{\text{bol}}/L_{\text{edd}} \approx 2 \times 10^{-4}$, which indicates a very low relative accretion rate, a common feature of LINERs (see Ho 1999). At such a low accretion rate, the inner accretion disk is likely to be advection dominated (an ADAF or ion torus; Narayan & Yi 1994, 1995; Rees et al. 1982) and form a vertically extended structure that can illuminate the outer thin disk effectively. Thus, it could power the observed broad-line emission (cf. Chen & Halpern 1989). This geometrical requirement may very well be the reason why dislikable emission lines are preferentially found in AGNs with very low accretion rates relative to the Eddington rate. In fact, if we are to associate the broad Balmer lines of NGC 3065 with emission from an accretion disk, then external illumination of the disk is needed in order to power the line emission. This is because the Hz luminosity is $3 \times 10^{40}$ ergs s⁻¹, while the viscous power output of the line-emitting portion of the disk (calculated following Eracleous & Halpern 1994) is only $4 \times 10^{39}$ ergs s⁻¹. Yet another appealing feature of ADAFs in LINERs is the fact that when combined with a low ionization parameter, their hard spectral energy distribution, which lacks a “UV bump,” can explain the relative strengths of the narrow emission lines (Halpern & Steiner 1983; Ferland & Netzer 1983).

The reason for the recent emergence of the broad Balmer lines in NGC 3065 as well as in similarly behaving objects remains an open question. One possibility is that the emission lines come from a transient accretion disk which formed from the debris released by the tidal disruption of a star by the black hole (cf. NGC 1097; Eracleous et al. 1995; Storchi-Bergmann et al. 1995). Another possibility is a change in the structure of the inner accretion disk associated with a change in the accretion rate, i.e., a transformation from a thin disk to an ADAF (Storchi-Bergmann et al. 1997). Perhaps the long-term variations of the Balmer line profiles will provide clues to their origin. The variations may show evidence for dynamical phenomena (e.g., spiral waves in the disk; Gilbert et al. 1999), which may cause fluctuations in the accretion rate. Alternatively, the variations may show evidence for a disk geometry that can be related to its formation process (e.g., an eccentric disk formed from tidal debris; Eracleous et al. 1995). We will continue to monitor the broad Balmer lines of NGC 3065 in an effort to uncover their cause.

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REFERENCES

Barth, A. J., Ho, L. C., Filippenko, A. V., Rix, H.-W., & Sargent, W. L. W. 2000, ApJ, in press (astro-ph/0006273)
Bower, G. A., Wilson, A. S., Heckman, T. M., & Richstone, D. O. 1996, AJ, 111, 1901
Burbridge, E. M., & Burbridge, G. R. 1965, ApJ, 142, 634
Chen, K., & Halpern, J. P. 1989, ApJ, 344, 115
Chen, K., Halpern, J. P., & Filippenko, A. V. 1989, ApJ, 339, 742
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., & Taylor, G. B. 1998, ApJ, 115, 1693
Corbin, M. R. 1997, ApJ, 485, 517
Eracleous, M. 1999, in ASP Conf. Ser. 175, Structure and Kinematics of Quasar Broad Line Regions, ed. C. M. Gaskell et al. (San Francisco: ASP), 163
Eracleous, M., & Halpern, J. P. 1993, ApJ, 409, 584
———, 1994, ApJS, 90, 1
Eracleous, M., Livio, M., Halpern, J. P., & Storchi-Bergmann, T. 1995, ApJ, 438, 610
Fabbiano, G., Kim, D.-W., & Trinchieri, G. 1992, ApJS, 80, 531
Ferland, G. J., & Netzer, H. 1983, ApJ, 264, 105
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Filippenko, A. V. 1985, ApJ, 289, 475
Ferland, G. B. 1998, ApJ, 115, 1693
Filippenko, A. V., & Sargent, W. L. W. 1988, ApJ, 324, 134
Gebhardt, K., et al. 2000, ApJ, 539, L9
Gilbert, A. M., Eracleous, M., Filippenko, A. V., & Halpern J. P. 2000, in ASP Conf. Ser. 175, Structure and Kinematics of Quasar Broad Line Regions, ed. C. M. Gaskell et al. (San Francisco: ASP), 189
Ho, L. C. 1999, ApJ, 524, L13
Halpern, J. P., & Eracleous, M. 1994, ApJ, 433, L17
Halpern, J. P., & Steiner, J. E. 1983, ApJ, 269, L37
Heckman, T. M. 1980, A&A, 87, 152
Ho, L. C. 1999, ApJ, 516, 672
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997a, ApJS, 112, 315
Ho, L. C., Filippenko, A. V., Sargent, W. L. W., & Peng, C. Y. 1997b, ApJS, 112, 391
Ho, L. C., Rix, H.-W., Shields, J. C., Rudnick, G., McIntosh, D. H., Filippenko, A. V., & Sargent, W. L. W., & Eracleous, M. 2000, ApJ, 541, 120
Humason, M. L., Mayall, N. U., & Sandage, A. R. 1956, AJ, 61, 97
Iyomoto, N., Makishima, K., Matsushita, K., Fukazawa, Y., Tashiro, M., & Ohashi, T. 1998, ApJ, 503, 168
Kormendy, J. 1977, ApJ, 217, 406
———. 2000, in ASP Conf. Ser., Galaxy Disks and Disk Galaxies, ed. J. G. Funes & E. M. Corsini (San Francisco: ASP), in press (astro-ph/0007401)
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
———. 1995, ApJ, 452, 710
Peimbert, M., & Torres-Peimbert, S. 1981, ApJ, 245, 845
Ptak, A., Serlemitsos, P., Yaqoob, T., & Mushotzky, R. F. 1999, ApJS, 120, 179
Rees, M. J., Begelman, M. C., Blandford, R. D., & Phinney, E. S. 1982, Nature, 295, 17
Schlegel, D., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shields, J. C., Rudnick, G., Rix, H.-W., Ho, L. C., McIntosh, D. H., Filippenko, A. V., & Sargent, W. L. W. 2000, ApJ, 534, L27
Storchi-Bergmann, T., Baldwin, J. A., & Wilson, A. S. 1993, ApJ, 410, L11
Storchi-Bergmann, T., Eracleous, M., Livio, M., Wilson, A. S., Filippenko, A. V., & Halpern, J. P. 1995, ApJ, 443, 617
Storchi-Bergmann, T., Eracleous, M., Ruiz, M. T., Livio, M., Wilson, A. S., & Filippenko, A. V. 1997, ApJ, 489, 87
Stauffer, J., Schild, R., & Keel, W. C. 1983, ApJ, 270, 465
Sulentic, J. W., Marziani, P., Zwitter, T., & Calvani, M. 1995, ApJ, 438, L1
Terashima, Y., Ho, L. C., Ptak, A. F., Mushotzky, R. F., Serlemitsos, P., Yaqoob, T., & Kunieda, H. 2000, ApJ, 533, 729
Tonry, J. L., & Davis, M. 1981, ApJ, 246, 666
Tully, R. B. 1987, Nearby Galaxies Catalog (Cambridge: Cambridge Univ. Press)