TRANSIENT AND HIGHLY POLARIZED DOUBLE-PEAKED Hα EMISSION IN THE SEYFERT 2 NUCLEUS OF NGC 2110

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ABSTRACT

We have discovered an extremely broad, double-peaked Hα emission line in the polarized flux spectrum of NGC 2110, establishing that this well-studied Seyfert 2 galaxy contains a disk-like hidden broad-line region (BLR). Several properties of NGC 2110 suggest that it is an obscured twin of Arp 102B, the prototypical double-peaked emission-line active galactic nucleus (AGN). A comparison between our data and previous spectra of NGC 2110 indicates that the double-peaked Hα feature is transient. The presence of a disk-like BLR in NGC 2110 has important implications for AGNs: it expands the range of properties exhibited by Seyfert 2 galaxies, and the fact that the BLR is obscured by a torus-like structure provides the first evidence that double-peaked emitters and classical Seyfert nuclei may have the same basic parsec-scale geometry.

Subject headings: galaxies: individual (NGC 2110) — galaxies: Seyfert — polarization

1. INTRODUCTION

NGC 2110, an S0/E galaxy at a distance of ~ 30 Mpc, is host to one of the most extensively studied active galactic nuclei (AGNs) in the local universe. The nuclear activity in this object was originally recognized because of its intense X-ray emission (Bradt et al. 1978), and it has been a popular target for X-ray investigations ever since ( Mushotzky 1982; Turner & Pounds 1989; Weaver et al. 1995; Hayashi et al. 1996; Malaguti et al. 1999). NGC 2110 is classified as a type 2 Seyfert galaxy based on its nuclear optical spectrum, which is dominated by narrow emission lines (McClintock et al. 1979). Observations of the circumnuclear environment of NGC 2110 have revealed peculiar kinematics and complex structure at all wavelengths (Ulvestad & Wilson 1983; Wilson et al. 1985; Pogge 1989; Haniff et al. 1991; Mulchaey et al. 1994; Ferruit et al. 1999, 2004; Quillen et al. 1999; González Delgado et al. 2002; Evans et al. 2006). As a result, NGC 2110 has emerged as an important laboratory for studying the interaction between an active nucleus and its surroundings.

NGC 2110 has been frequently considered in the context of AGN unification (e.g., Antonucci 1993). The presence of a hidden type 1 nucleus is implied by X-ray observations, which indicate heavy absorption of the soft X-ray spectrum and a Seyfert 1–like intrinsic luminosity at hard X-ray energies (Mushotzky 1982; Turner & Pounds 1989; Malaguti et al. 1999). Similarly, if the extended narrow-line region is powered by photoionization from the nucleus, the morphology of this region and the strength of the Balmer recombination lines relative to the observed ionizing flux would suggest that the nuclear continuum source is obscured from our view (Wilson et al. 1985; Mulchaey et al. 1994). Yet despite a number of direct searches for broad emission lines in both the optical (Shuder 1980; Veilleux 1991) and near-infrared (Veilleux et al. 1997; Storchi-Bergmann et al. 1999; Knop et al. 2001; Lutz et al. 2002), conclusive evidence that NGC 2110 harbors a hidden broad-line region (BLR) has been elusive. In this Letter, we report the discovery of a spectacular broad Hα emission line in the polarized flux spectrum of this object.

2. OBSERVATIONS

We observed NGC 2110 on 2005 December 30 (UT) with the LRIS spectropolarimeter (Cohen et al. 1997) on the Keck I 10 m telescope. Both beams of the instrument were employed in conjunction with the D560 dichroic beam splitter. On the blue side, a 400 line mm−1 grism blazed at 3400 Å was used, providing coverage of the 3200–5700 Å range at ~12 Å resolution (FWHM). The red side data, obtained with a 600 line mm−1 grating blazed at 7500 Å, span 5520–7990 Å at ~4.5 Å resolution. A 900 s exposure was acquired at each of the four wave plate positions using a 1.0” slit, which was oriented at the midobservation parallactic angle of 16°. The observations were obtained under photometric conditions at an average air mass of 1.13. We extracted one-dimensional spectra from the reduced images within a 3.15” region centered on the galaxy’s nucleus. Spectropolarimetric processing and measurements were performed following the methods described by Miller et al. (1988) and Barth et al. (1999).

Because of the proximity of NGC 2110 to the Galactic plane [b = −16.5°, E(B − V) = 0.375 mag], we explored whether transmission through Galactic dust might affect the observed polarization. A search of the Heiles (2000) catalog of stellar polarizations reveals two stars within ~12’ of NGC 2110 with linear polarization data. The stars have nearly identical polarization levels and position angles; using the average values of these ρ = 0.33%, θ = 34.5°, we made synthetic q and u spectra assuming a Serkowski et al. (1975) curve for p(λ). These were then subtracted from the normalized Stokes parameters for NGC 2110 to correct the galaxy’s polarization and position-angle spectra. As discussed below, these corrections prove to be relatively minor.

3. BROAD, POLARIZED Hα EMISSION

Our spectropolarimetry results are displayed in Figure 1. The total-flux spectrum of NGC 2110 (top panel) is clearly dominated by narrow emission lines. The small but significant amount of continuum polarization observed (middle panel) is...
Fig. 1.—Spectropolarimetry of NGC 2110. Top: Total flux, in units of \(10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\). Middle: Degree of linear polarization, given as the rotated Stokes parameter. Bottom: Polarized flux, or “Stokes flux,” which is the product of the total flux and rotated Stokes parameter.

approximately constant with wavelength, suggesting that it is caused by electron scattering. In the 5200–6200 Å range the polarization and polarization angle are \(p = 0.8\%\) and \(\theta = 70^\circ\), respectively. After correction for interstellar effects, the value of \(p\) is virtually unchanged, while the polarization angle rotates a modest amount to \(\theta = 83^\circ\). The corrected value of \(\theta\) is nearly orthogonal to the arcsecond-scale radio and optical emission-line structures observed along P.A. \(\approx 0^\circ\) in NGC 2110 (González Delgado et al. 2002 and references therein). This is consistent with expectations based on the unified AGN model, whereby scattering of the nuclear continuum occurs along a direction parallel to the axis of the obscuring torus (Antonucci 1984).

A dramatic increase in polarization (peaking at \(p \approx 5\%\)) is observed on either side of the H\(\alpha\)[N II] narrow-line blend in Figure 1. As a result, the polarized flux spectrum of NGC 2110 (bottom panel) exhibits an extremely broad, double-peaked H\(\alpha\) line. The full width at zero intensity of the broad H\(\alpha\) line is roughly 2.7 \(\times\) 10\(^4\) km s\(^{-1}\). A similar feature is not observed at H\(\beta\), although the H\(\beta\) line is broader (∼1200 km s\(^{-1}\) FWHM) than the forbidden lines in the polarized flux spectrum. Previous studies have shown that the polarized H\(\alpha\) lines of hidden Seyfert 1s can be asymmetric and broad (e.g., Schmidt et al. 2002), but because of the structure observed in its H\(\alpha\) profile, NGC 2110 is perhaps the most extreme example discovered to date.

4. NGC 2110 AS A DOUBLE-PEAKED EMISSION-LINE AGN

The broad H\(\alpha\) line shown in Figure 1 closely resembles those exhibited by double-peaked emission-line AGNs, a small but important class of active nuclei (Eracleous & Halpern 1994, 2003; Strateva et al. 2003). In fact, NGC 2110’s broad H\(\alpha\) profile is nearly identical to that of the prototypical double-peaked AGN Arp 102B (cf. Fig. 2 of Halpern et al. 1996). An important secondary characteristic of double-peaked emitters is that they often display strong low-ionization forbidden lines, such as [N II] \(\lambda 6584\), [O I] \(\lambda 6300\), and [S II] \(\lambda 6717, 6731\). Similar to many radio-selected double-peakers, the emission-line flux ratios in NGC 2110 suggest a LINER classification (Heckman 1980; Veilleux & Osterbrock 1987): log ([N II]/H\(\alpha\)) \(\approx 0.17\), log ([O I]/H\(\alpha\)) \(\approx -0.23\), and log ([S II]/H\(\alpha\)) \(\approx 0.00\). The Seyfert-like [O III] \(\lambda 5007, H\beta\) flux ratio of ∼4 in NGC 2110 is common among optically selected double-peaked emitters (Strateva et al. 2003). Thus, on spectroscopic grounds, NGC 2110 appears to be a genuine double-peaked emission-line AGN. This marks the first time that this type of object has been discovered via spectropolarimetry in a Seyfert 2 galaxy.

Although at one time the origin of broad, double-peaked emission lines in AGNs was a matter of considerable debate (see Gaskell et al. 1999), the prevailing interpretation today is that such lines are produced in BLRs that have a disk geometry (Eracleous & Halpern 2003). We have thus fitted relativistic Keplerian disk models to the H\(\alpha\) profile in the polarized flux spectrum of NGC 2110. A circular disk model (Chen & Halpern 1989) provides a rather poor fit, so we have instead fitted the line profile with an elliptical disk model (following Eracleous et al. 1995) under the assumption that the emissivity of the disk scales with radius as \(r^{-1}\) (Collin-Souffrin & Dumont 1989; Eracleous & Halpern 2003; Strateva et al. 2006). As illustrated in Figure 2, this model provides a very good fit to the polarized H\(\alpha\) line profile. The best-fitting model is described by the
following parameters: the inner and outer pericenter distances of the line-emitting portion of the disk (in units of the gravitational radius, \( r = GM_{\text{BH}}/c^2 \), where \( M_{\text{BH}} \) is the black hole mass) are \( \xi_1 = 200^{+10}_{-20} \) and \( \xi_2 = 850^{+230}_{-230} \); the inclination of the disk axis is \( i = 30^{+5}_{-10} \) deg; the eccentricity of the disk is \( e = 0.3 \pm 0.1 \); the orientation of the major axis relative to the line of sight (see Fig. 2 of Eracleous et al. 1995) is \( \varphi_y = 100^\circ \pm 30^\circ \); and the broadening parameter (representing turbulent motions in the line-emitting “skin” of the disk) is \( \sigma = 600^{+300}_{-250} \) km s\(^{-1}\). These parameters are consistent with those obtained for Arp 102B by Chen & Halpern (1989), i.e., \( \xi_1 = 350 \), \( \xi_2 = 1000 \), \( i = 32^\circ \), and \( \sigma = 850 \) km s\(^{-1}\). (Note that because the broad H\( \alpha \) line in NGC 2110 is reflected, the angles \( i \) and \( \varphi_y \) describe the orientation of the disk to the scattering medium, not the observer.) The residuals of the fit, also shown in Figure 2, show a weak, broad, bell-shaped pedestal underlying the H\( \alpha \)+[N \( \text{ii} \)] complex. Such a kinematic component is also observed in the H\( \alpha \) and Ly\( \alpha \) profiles of Arp 102B (it is in fact the dominant component of the Ly\( \alpha \) line; Halpern et al. 1996). Based on a four-component Gaussian fit to the H\( \alpha \)+[N \( \text{ii} \)] lines in the residuals spectrum, we estimate the width of the bell-shaped broad component to be \( \sim3100 \) km s\(^{-1}\) (FWHM), similar to the widths of the Ly\( \alpha \) and H\( \alpha \) lines of Arp 102B (Halpern et al. 1996).

For a final comparison to other double-peaked AGNs, we have estimated the bolometric-to-Eddington luminosity ratio \( L_{\text{bol}}/L_{\text{Edd}} \) of NGC 2110. Using the Tremaine et al. (2002) \( M_{\text{BH}}-\sigma_{*} \) relation, the observed stellar velocity dispersion of \( \sigma_{*} = 220 \pm 25 \) km s\(^{-1}\) (Nelson & Whittle 1995) indicates a black hole mass of \( M_{\text{BH}} = 2 \times 10^8 M_{\odot} \) which implies \( L_{\text{Edd}} \approx 3 \times 10^{46} \) ergs s\(^{-1}\). The intrinsic 2–10 keV X-ray luminosity of \( L_{\text{X}} \approx 4 \times 10^{42} \) ergs s\(^{-1}\) (Malaguti et al. 1999), combined with a bolometric correction factor of \( L_{\text{bol}}/L_{\text{X}} = 30 \) (typical of radio-quiet quasars; Elvis et al. 1994), yields \( L_{\text{bol}} \approx 1.2 \times 10^{44} \) ergs s\(^{-1}\). We note that the extinction-corrected [O \( \text{iii} \)] 5007 luminosity of \( -6 \times 10^{40} \) ergs s\(^{-1}\) derived from our Keck data, combined with a bolometric correction of \( L_{\text{bol}}/L_{5007} = 3500 \) (Heckman et al. 2004), yields \( L_{\text{bol}} \approx 2.1 \times 10^{44} \) ergs s\(^{-1}\). Thus, for NGC 2110 we estimate that \( L_{\text{bol}}/L_{\text{Edd}} \approx 4 \times 10^{-3} \). Despite the rough numbers used here, this is in close agreement with the value of \( L_{\text{bol}}/L_{\text{Edd}} = (1-2) \times 10^{-3} \) obtained by Lewis & Eracleous (2006) for Arp 102B, which further strengthens the case that NGC 2110 is an obscured twin of Arp 102B.

5. TRANSIENT NATURE OF THE BROAD H\( \alpha \) LINE

Close inspection of the top panel of Figure 1 reveals that the blue peak of the broad H\( \alpha \) line is faintly visible in the total-flux spectrum of NGC 2110. This is perhaps not too surprising, given the high polarization of the feature and the unconfused nature of the spectrum in its vicinity. To investigate whether the double-peaked line was present in previous years, we have combed the literature for published nuclear spectra of NGC 2110. The most recent spectrum we were able to find was one obtained on 2000 December 30 (UT) with the STIS instrument on board the Hubble Space Telescope (Ferruit et al. 2004), which we have retrieved from the HST archive. A total exposure of 4445 s was obtained using a 0.2” slit. Our extraction of the spectrum covers a 5 pixel (0.25”) region centered on the nucleus. Before comparing the Keck and STIS data, we removed the continuum from each spectrum. To model the Keck continuum, we combined a spiral galaxy bulge template (that of M31) with a power-law component. The continuum in the STIS spectrum, which contains little or no starlight because of the small effective aperture, was removed by subtracting a constant. We rescaled the continuum-subtracted STIS spectrum to match the strength of the narrow H\( \alpha \) line in the Keck spectrum.

The results of our comparison are displayed in Figure 3. The narrow emission lines exhibit somewhat different velocity widths and flux ratios in the Keck and STIS data; this is a reflection of density stratification in the narrow-line region of NGC 2110 (e.g., Filippenko & Halpern 1984), which has been sampled by different apertures. The blue peak of the broad H\( \alpha \) line, clearly visible in the Keck spectrum near 6425 Å, is completely absent in the high signal-to-noise ratio STIS spectrum.
Given the lower amount of diluting starlight in the small 0.2° × 0.25° STIS aperture, the blue peak would be at least as prominent in the STIS spectrum if it were present. We conclude, therefore, that the double-peaked Hα line in the nucleus of NGC 2110 has appeared rather recently. Moreover, additional spectropolarimetric observations in 2007 February by H. Tran have shown that the line profile has varied significantly over an interval of 14 months. The transient nature of this feature and its subsequent variations are not without precedent; the double-peaked line profile (e.g., Storchi-Bergmann 1999), and numerous other objects exhibit variability of the double-peaked line profile (e.g., Storchi-Bergmann et al. 1995; Gezari et al. 2007).

6. CONCLUSIONS

Beginning with observations of NGC 1068 (Antonucci & Miller 1985), spectropolarimetry has played a crucial role in our understanding of the physical nature of AGNs, and it continues to provide valuable insight. Our results establish that NGC 2110 possesses a disk-like BLR, which expands the range of properties exhibited by Seyfert 2s. In addition, NGC 2110 presents some opportunities for interesting follow-up study. As noted above, the double-peaked feature is transient and variable, and it would be worthwhile to monitor its behavior. The observed variations may trace changes in the structure of the BLR or in the properties of the scattering medium. Also, the similarity of NGC 2110’s broad Hα profile to that of Arp 102B suggests that the line has not been distorted significantly in the scattering process. This has implications for the scattering geometry; e.g., the scattering medium may only see the line-emitting disk over a narrow range of inclination angles. High-resolution imaging polarimetry and detailed spectropolarimetric modeling (e.g., Smith et al. 2004, 2005) would clarify this issue. In the bigger picture, by demonstrating that at least one double-peaked emitter contains the type of nuclear obscuration believed to be present in most (if not all) classical Seyfert galaxies, we can now extend the concept of unification to the disk-emitting class of AGNs. On parsec scales, double-peaked AGNs may be structurally similar to other types of Seyfert nuclei. If so, this underscores the need to understand how physical differences might originate in their broad-line regions.

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