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Scattered broad optical lines in the polarized flux spectrum of the FR II galaxy 3C 321

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ABSTRACT

We present optical/infrared broad-band filter polarimetry and optical spectropolarimetry of the powerful FR II galaxy 3C 321. The latter observations reveal a scattered broad component to the Hα emission line, detectable in polarized flux. This implies that 3C 321 is actually a quasar the continuum and broad-line region of which are obscured from direct view, possibly by the geometrically thick torus invoked in the unified theory of active galaxies.

Key words: polarization – scattering – galaxies: active – galaxies: individual: 3C 321.

1 INTRODUCTION

One of the chief goals of current research on active galactic nuclei (AGNs) is to identify possible unifying models which relate the seemingly disparate properties observed in the many classes of AGN. The most successful model has been a relatively simple relationship between the orientation of some fundamental axis of the AGN with respect to the observer.

Antonucci & Miller (1985) demonstrated that the archetypal Seyfert 2 galaxy, NGC 1068, shows prominent broad permitted lines, a Seyfert 1 property, in polarized flux. This observation was explained by a geometrical model where a type 1 nucleus, featureless continuum source and broad-line region (BLR) are surrounded by a geometrically and optically thick torus, together with a more extended narrow-line region (NLR). At small angles between the line of sight and the polar axis of the torus, the type 1 core can be viewed directly; at higher angles the torus blocks the view to these regions and only the NLR is observed directly, resulting in a type 2 object. However, radiation from the type 1 core can be scattered into the line of sight, and thus can be observed in polarized flux. This has since been observed in many objects with Seyfert 2 properties (e.g. Miller & Goodrich 1990; Tran, Miller & Kay 1992; Young et al. 1993, 1996a,b; Inglis et al. 1993; Hines & Wills 1993; Kay 1994).

Seyfert galaxies are radio-quiet, but similar orientation effects are also believed to play an important role in the appearance of radio-loud objects. Orr & Browne (1982) unified compact, core-dominated and extended, lobe-dominated quasars with a model that involves strongly forward-beamed radiation from a pair of relativisitc jets, and essentially isotropic emission from slow-moving plasma in two lobes fed by the jets. At low angles of inclination between the radio axis and the observer's line of sight, the Doppler-boosted jet emission dominates the lobe emission and a blazar or optically violent variable (OVV) is observed. As the angle increases, the object is observed as a core-dominated quasar and then a lobe-dominated quasar.

Barthel (1989) essentially combined the torus and Doppler beaming models to produce a model in which not only is the appearance of core- and lobe-dominated quasars explained, but also, at high angles of inclination, the torus blocks the view to the quasar core and a narrow-line radio galaxy (NLRG) results.

In the unified theory, NLRGs, like Seyfert 2s, should show scattered continuum and broad-line radiation in their polarized spectrum. The theory is supported by the observations that some radio galaxies show bright and highly polarized near-infrared emission (Bailey et al. 1986; Hough et al. 1987a; Antonucci & Barvainis 1990). Also, the radio galaxy 3C 234 shows a scattered quasar spectrum, including broad

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permitted emission lines, in polarized flux (Antonucci 1984). Scattered broad lines may also be present in two high-z radio galaxies, 3C 226 and 3C 277.2 (di Serego Alighieri, Cimatti & Fosbury 1994). Imaging polarimetry has also shown spatially extended regions of polarized light located along the radio axis (di Serego Alighieri et al. 1988; Tadhunter, Scarrott & Rolph 1990; Draper, Scarrott & Tadhunter 1993). Although scattering of nuclear radiation was considered untenable as an explanation of the observed polarization of Cyg A (Goodrich & Miller 1989), the discovery of broad Mg II (Antonucci, Hurt & Kinney 1994) reveals a hidden quasar nucleus.

Despite the observation of scattered broad lines in 3C 234, and a similar observation in the weak radio galaxy PKS 2048 – 57 (Inglis et al. 1993), in general spectropolarimetry has failed to detect scattered nuclear light (Antonucci & Barvainis 1990), with the possible exception of 3C 226 and 3C 277.2 (di Serego Alighieri et al. 1994). This has been attributed to the presence of kiloparsec-scale dust lanes that cover the nuclei of many of the radio sources, which may absorb a significant proportion of any scattered radiation. Such dust lanes are clearly evident in Cyg A and Cen A, and in the *Hubble Space Telescope* (*HST*) snapshot survey of 3C radio galaxies (Sparks, private communication). The near-infrared polarization of Cen A (Bailey et al. 1986), originally attributed to a misdirected blazar, has recently been successfully modelled as scattered quasar radiation which undergoes significant extinction (Packham et al. 1996). A similar situation may also apply for most radio galaxies. However, it should be noted that many powerful radio galaxies show evidence for a substantial scattered component in the form of high UV polarization (di Serego Alighieri et al. 1994).

The powerful FR II radio galaxy 3C 321 ($z = 0.096$) shows a clear double structure, with a separation of ~ 4 arcsec, originally described as a double nucleus or gravitational lens (Heckman et al. 1986; Filippenko 1987 and references therein), along with large-scale tails and fans, suggestive of a recent merger (Heckman et al. 1986). The double structure is clearly aligned with the radio axis (Baum et al. 1988), and Filippenko (1987) associated the brighter south-eastern component of the double with a flat-spectrum radio source, whilst the north-western source has a steep spectrum. Draper et al. (1993) showed, however, that both components exhibit centro-symmetric polarization, and hence may be regions of scattered radiation. Thus the true nucleus may lie between the two regions, and is obscured from view, in accordance with the unified model. Shaw, Tadhunter & Dickson (1996) demonstrated that the scattered, i.e. polarized, spectrum is completely consistent with that associated with quasars.

In this Letter we present optical spectropolarimetry and optical to near-infrared filter polarimetry of 3C 321, which reveal the presence of a hidden BLR. The observations are described in Section 2, with the results and discussion contained in Section 3, and conclusions are drawn in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

The optical and near-infrared broad-band filter polarimetric observations of 3C 321 (Table 1) were obtained using the 3.8-m United Kingdom Infrared Telescope (UKIRT), Hawaii, in conjunction with the optical/infrared polarimeter HATPOL, built by the University of Hertfordshire (Hough, Peacock & Bailey 1991), on the nights of 1993 February 19, 20 and 21. Observations were simultaneously made in U, B, V, R, I and K. The common-user photometer UKT9 was used on the infrared channel, and a 5-arcsec aperture was used throughout.

The optical spectropolarimetric observations (Table 1) were carried out at the 3.9-m Anglo-Australian Telescope (AAT) with the Royal Greenwich Observatory (RGO) spectrograph, in conjunction with the University of Hertfordshire waveplate modulator, on the night of 1993 July 16. A two-hole dekker, with 2.7×2.7 arcsec^2 apertures and a projected separation on the sky of 23 arcsec, was used, along with a 2 arcsec wide east–west slit, centred on the brighter component of 3D 321. The 1024×1024 Tek CCD was used with the 270R grating, giving a spectral coverage of 3380 Å. Observations were carried out in the usual spectropolarimetry mode: four exposures were made, one each at waveplate angles of 0°, 45°, 22.°5 and 67.°5, with the object in one of the two dekker apertures and the other aperture acting as a sky observation; then the object was switched to the other aperture.

2.2 Data reduction

For the broad-band filter polarimetry, the system functionality was checked by means of separate observations of an unpolarized star through a Glan prism, which gives 100 per cent polarization. These observations also provide a calibration for the position angle of polarization and the polarizing efficiency of the infrared channels. The UKIRT set of faint photometric standards (Casali & Hawarden 1992) was used for flux calibration, and observations of polarized standards (Serkowski 1974) were used as an additional check on the polarization calibrations. Airmass corrections were made using a multiplicative factor based on the zenith distance of the object at the time of the observation and the known extinction relationship for the observing site.

The optical spectropolarimetric data were reduced using FIGARO (Shortridge 1993) and the polarimetry reduction package TSP (Bailey 1992). Wavelength calibration was achieved from observations of the CuAr arc. Polarizing effi-

Table 1. Observation log.

Observation	Telescope	Date	Integration Time (s)
broad band	UKIRT	19,20,21 / 2 / 93	1334
spectropolarimetry	AAT	16 / 7 / 93	8000

ciency and the slight wavelength dependence of the position angle of polarization, resulting from the wavelength dependence of the fast axis of the superchromatic waveplate, were calibrated by observations of unpolarized stars through an HN22 Polaroid. Taylor spectrophotometric standards (Taylor 1984) were observed for flux calibration. The zero-point for the position angle of polarization was determined from observations of polarized standards (Serkowski 1974). Atmospheric absorption features were removed from the object data by dividing the data by normalized observations of smooth-spectrum atmospheric standards, after absorption features intrinsic to the stars had been interpolated over.

3 DISCUSSION

The broad-band filter polarimetric data for 3C 321 are presented in Table 2, and the optical spectropolarimetry is illustrated in Fig. 1. Both data sets show that the optical polarization is low, 0.74 per cent at V, consistent with previous measures (Cimatti et al. 1993; Draper et al. 1993), at a position angle that is approximately perpendicular to the radio axis. The filter data also show that the percentage polarization rises at U, consistent with the findings of Shaw et al. (1996), and also at near-infrared wavelengths. This U-shaped behaviour for the percentage polarization is typical of many of the Seyfert 2s that show scattered broad lines in their polarized flux spectra (e.g. Bailey et al. 1988; Young et al. 1996a).

The total flux spectrum shows a prominent type 2 spectrum, dominated by narrow-line emission. The measured emission-line strengths and widths from Gaussian fitting are listed in Table 3. Filippenko (1987) reports the detection of a broad component to Hα in total flux, FWZI > 6000 km s^{-1}. The line fitting to the current data does not indicate a requirement for such a line to account for the observed flux in the Hα + [N II] line complex. A polynomial fit to the continuum on either side of the line complex was used to reproduce the continuum under the line, and this may have contributed to the non-detection of broad Hα in total flux.

The polarized flux spectrum is consistent with an unreddened type 1 object, confirming the finding of Shaw et al. (1996). Also, there is a broad component to Hα in polarized flux, the properties of which are also listed in Table 3. The width and strength of this line were determined from a Gaussian fit to the binned polarized flux spectrum using the Starlink routines GAUSS from FIGARO (Shortridge 1993) and LONGSLIT (Wilkins & Axon 1991). After continuum fitting, itself difficult owing to the small spectral coverage on the red side of the line, a Gaussian was fitted to the wings of the broad component, and then narrow components were fitted to account for the remaining flux. There is also an increase in the percentage polarization around Hβ, which is tentative evidence for a scattered broad component to this line as well, although the noise is such that the line does not actually show in polarized flux.

The measured polarized broad Hα luminosity, $L_{\rm p}({\rm H}\alpha)$, is 2.7×10^{40} erg s^{-1} cm^{-2} ($H_0=75$ km s^{-1} Mpc^{-1}; $q_0=0$). If the scattering region is optically thin, then the total line luminosity, $L({\rm H}\alpha)$, can be simply related to $L_{\rm p}({\rm H}\alpha)$, following Miller & Goodrich (1990), by

$$L_{\rm p}({\rm H}\alpha)\approx L({\rm H}\alpha)(\Delta\Omega/4\pi)\,\tau P,$$

where $\Delta\Omega$ is the covering factor for the scatters in steradians, τ is the optical depth to scattering, and P is the intrinsic polarization of the scattered line. The value for the product of the covering factor and the scattering optical depth, $(\Delta\Omega/4\pi)\,\tau$, is not known. Therefore, in order to gain an estimate of the total broad Hα luminosity, we shall assume that 3C 321 is similar to previously modelled active galaxies. For the archetypal Seyfert 2 galaxy NGC 1068, modelling of the scattered flux indicates a value of $(\Delta\Omega/4\pi)\,\tau\sim0.003$ (Miller, Goodrich & Mathews 1991; Young et al. 1995), whilst for a group of *IRAS* type 2 objects an average value of ~0.006 is obtained (Young et al. 1996a). Here we shall assume $(\Delta\Omega/4\pi)\,\tau=0.006$, and, with $P\sim10$ per cent (Shaw et al. 1996), $L({\rm H}\alpha)$ is calculated to be 4.5×10^{43} erg s^{-1}, typical of quasars.

3C 321 is only the second powerful radio galaxy for which broad lines have been discovered spectropolarimetrically, the first such object being 3C 234 (Antonucci 1984). Unlike the latter object, the broad lines do not show in total flux, owing to the greater stellar fraction in 3C 321, as evidenced by the strength of the absorption features in total flux. This unpolarized flux component swamps the weak broad line in total flux.

3C 321 has the largest 60-μm flux of all the 3CR galaxies in the sample of Impey & Gregorini (1993). It has a 60-μm luminosity of 9.3×10^{44} erg s^{-1} ($H_0=75$ km s^{-1} Mpc^{-1}), which is exceeded only by the broad-line radio galaxy 3C 109, and is comparable to that of 3C 234; both of these galaxies have high optical polarizations. The far-infrared luminosity of 3C 321 far exceeds that of other NLRGs, with one exception, Cygnus A, which has a 60-μm luminosity almost identical to that of 3C 321, and falls within the range of quasars. This suggests that 3C 321 does indeed harbour a quasar nucleus.

The FIR/[O III] ratio is about an order of magnitude greater in 3C 321 than is typical for BLRGs, and several times higher than in Cygnus A (using the [O III] corrected for reddening). However, the reddening in the NLR of 3D 321, as calculated from the Balmer decrement (Table 3), is equivalent to an A_V of 2.2 mag. If the line flux is dereddened, then the FIR/[O III] ratio is within the range of BLRGs.

Table 2. Broad-band filter polarimetry data (5-arcsec apertures).

	U	B	V	R	I	K
P	4.10 ± 0.46	1.93 ± 0.29	0.74 ± 0.18	0.50 ± 0.10	0.47 ± 0.37	1.64 ± 0.54
θ	35 ± 3	34 ± 4	49 ± 7	37 ± 5	64 ± 22	18 ± 10
mag.	17.73 ± 0.02	17.69 ± 0.02	16.56 ± 0.02	16.18 ± 0.02	15.65 ± 0.02	13.13 ± 0.02

If we assume the presence of an obscured quasar, we can estimate its approximate luminosity from the strength of [O III]. Following the method of Simpson, Ward & Kotilainen (1994) and adopting the dereddened flux of [O III], we obtain $M_V \sim -25.5$ mag.

Inspection of Fig. 1 shows that the [O III] λ5007 line appears to be partially polarized. This raises the possibility that some of the observed polarization may be due to dichroism, which may arise in the narrow-line clouds and/or within dust lanes in the galaxy (the latter occurs, for

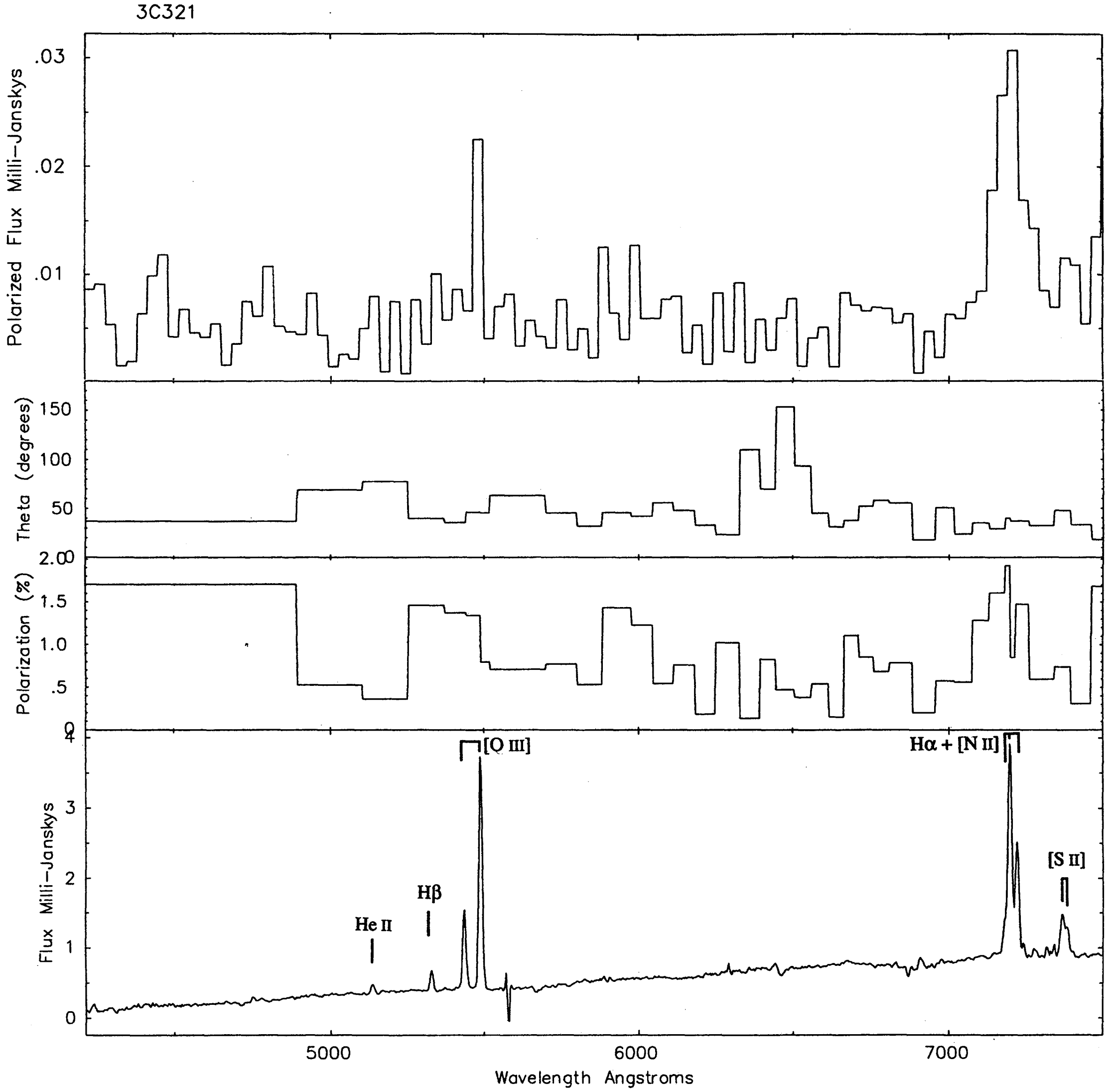

Figure 1. Spectropolarimetric data for 3C 321, showing, from bottom to top, the total flux, the percentage polarization, the position angle of polarization and the polarized flux spectrum. The data are binned at 0.35 per cent for the percentage polarization and 10 channels per bin for the polarized flux.

Table 3. Emission-line properties from Gaussian fits.

Line	FWHM	Flux	Line	FWHM	Flux
Hβ	729	4.0	Hα	620	25.7
[O III]λ4959	727	14.6	[N II]λ6583	629	13.8
[O III]λ5007	823	44.0	[S II]λ6717	620	4.8
[O I]λ6300	806	1.9	[S II]λ6734	599	2.9
[N II]λ6548	617	3.4	Hα *	9000	1.7

FWHM in units of km s^{-1}; flux in units of 10^{-15} erg s^{-1} cm^{-2}; slit width 2 arcsec.

*Broad Hα measured from the polarized flux spectrum.

example, in Cen A: Hough et al. 1987b; Packman et al. 1996). It is also possible to attribute some narrow-line polarization to scattering within the NLR itself, proposed for NGC 1068 (Inglis et al. 1995). The observed polarization is low if it is a result of dichroism through the extinction required to obscure the postulated quasar core at optical wavelengths. The narrow-line polarization may arise through scattering in the same regions where scattering of the nuclear radiation takes place.

4 CONCLUSIONS

The presence of broad polarized Hα, the polarization structure, the high far-infrared luminosity and the extremely strong He II line all point to 3C 321 harbouring an obscured quasar. We do not know the value of the line-of-sight extinction towards the putative quasar but, provided that it is not much in excess of that typical for the Seyfert 2s so far measured, a hard X-ray detection should be feasible, and would provide a value for the attenuating column density.

The observation of scattered broad lines stengthens support for the unified theory of active galaxies (Barthel 1989). The higher polarization measured at *K*, compared with the optical, may imply that the other NLRGs with high *K*-band polarization (Antonucci & Barvainis 1990) are also quasars observed at large angles between the radio axis and the line of sight.

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