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Near-infrared imaging polarimetry of Cygnus A

C. Packham,[1] S. Young,[1] J. H. Hough,[1] C. N. Tadhunter[2] and D. J. Axon[3★]

[1]Department of Physical Sciences, University of Hertfordshire, Hatfield, Herfordshire AL10 9AB
[2]Department of Physics, University of Sheffield, Sheffield S3 7RH
[3]Nuffield Radio Astronomy Laboratory, University of Manchester, Jodrell Bank, Macclesfield, Cheshire SK11 9DR

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ABSTRACT

We present a 2.2-μm polarization image of the nuclear regions of Cygnus A. The degree of polarization in the central 1 arcsec is (4.1 ± 0.50) per cent, at a position angle of $(23.6 \pm 3.6)°$, approximately perpendicular to the axis of the radio jet.

Modelling of the results suggests that at this wavelength the polarization along the line of sight to the central source is most likely produced by dichroism, through an $A_v \sim 40$ mag, with the polarization in surrounding regions produced by scattering. For this model, the *K*-band luminosity of the central source is calculated to be $\sim 2 \times 10^{44}$ erg s^{-1}.

Key words: polarization – methods: observational – techniques: polarimetric – galaxies: individual: Cygnus A – galaxies: nuclei – infrared: galaxies.

1 INTRODUCTION

The true nature of the central source in Cygnus A (3C 405) has proved controversial since the optical component to the intense radio source was first identified (Baade & Minkowski 1954). At optical wavelengths there is a dual nuclear morphology showing components separated by ~2 arcsec, initially attributed to a recent merger. The proportion of line to continuum emission from these nuclear components is slightly different, with the north-west component showing a much greater contribution from line emission. Recently, high-resolution optical and near-infrared images reveal a third isolated component, positioned between the double optical nuclei, at a position very close to the central radio source (Vestergaard & Barthel 1993; Stockton, Ridgway & Lilly 1994).

At radio wavelengths, Cygnus A is the third brightest source in the sky (after the Sun and Cassiopeia A) and hence was one of the first radio-loud active galactic nuclei (AGN) to be intensively studied. Indeed, Cygnus A, with a redshift of $z = 0.0562$ (Stockton et al. 1994), is the most radio-luminous AGN to a redshift of $z \sim 1$. Thus, Cygnus A is assured the role as the archetypal radio-loud AGN at a non-cosmological redshift. Cygnus A shows the classic properties of a Fanaroff–Riley class II (FRII) radio source with an edge-brightened double-lobed morphology and a jet, revealed in high-dynamic-range Very Large Array (VLA) images (Perley, Dreher & Cowan 1984). Barthel (1989) suggested that powerful FRII galaxies contain a quasar at their centre, intensifying the efforts to form a coherent model to explain the nuclear emission from the central regions of Cygnus A. Evidence for a quasar at the centre of Cygnus A has been collected after intensive studies at various wavelengths including ultraviolet (UV), optical, infrared (IR) and X-ray regimes – see Carilli & Barthel (1996) for an excellent review.

At optical wavelengths, there is a distinct similarity between Cygnus A and Centaurus A (NGC 5128) arising from the obvious obscuration across the central regions of both galaxies. However, high-resolution images of the dust lane of Cygnus A show the obscuration to form numerous condensations, which make the morphology far more patchy than the dust lane of Centaurus A (Jackson et al. 1996). These high-resolution images have important implications for the suggestion that the dual nuclear morphology arose from a recent merger. At radii greater than 2 arcsec, a good fit to the $r^{1/4}$ surface brightness profile was found (Pierce & Stockton 1986; Vestergaard & Barthel 1993) and the lack of large-scale tidal features and host-galaxy distortion implies that the merger hypothesis for this morphology is incorrect. An alternative scenario suggests that the nuclear morphology largely arises from collimation of nuclear radiation (Pierce & Stockton 1986), possibly by the

★Affiliated to the Space Sciences Division of ESA, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA.

much-postulated torus (e.g. Antonucci & Miller 1985; Lawrence 1987), producing two areas of radiation scattered into our line of sight.

Tadhunter, Scarrott & Rolph (1990) found that the optical polarization formed an approximate centrosymmetric pattern, with the degree of polarization ~1.4 per cent at a position angle (PA) of $(18.1 \pm 4.5)°$ in an aperture of ~1.5 arcsec around the nucleus. Tadhunter et al. (1990) point out that the relatively low nuclear polarization can arise from integrating over an approximate circular polarization pattern, and from very high stellar and emission line dilution. For example, Vestergaard & Barthel (1993) estimate that the *V*-band nuclear contribution is only $\sim 27 \pm 7$ per cent in a 10 arcsec aperture. Further, Tadhunter (1996) finds that it is possible to model the spectral energy distribution entirely from the addition of scattered quasar continuum, stellar radiation and free–free emission. This model requires that the contribution of scattered quasar continuum (at 0.5 μm) is ~20 per cent, implying that the intrinsic polarization is ~7.5–10 per cent at optical wavelengths.

Polarimetry of Cygnus A has itself proved controversial because of its low Galactic latitude ($b = 5.8°$), implying that dichroism (the passage of light through magnetically aligned grains) from our Galaxy may significantly contribute to the measured degree of polarization. The first major spectropolarimetric study of Cygnus A (Goodrich & Miller 1989) measured a visual continuum polarization of 1.58 per cent at a PA of $(13 \pm 2)°$ and an [O III] line polarization of 1.25 per cent at a PA of $(33.5 \pm 3)°$. They claimed that the morphology of the [O III] emission, and the similarity of the [O III] and continuum polarization, strongly suggests that the polarization does not arise from scattering, but is a result of dichroism in our Galaxy, thereby challenging the conclusions of Tadhunter et al. (1990).

In order to investigate the polarizing mechanism further, Jackson & Tadhunter (1993) observed both Cygnus A and a bright field galaxy less than 60 arcsec from Cygnus A in spectropolarimetric mode. They measured the polarization of the field galaxy to be 0.5 per cent with a PA of polarization almost perpendicular to that measured for Cygnus A, at a similar wavelength. The Galactic magnetic field map of Axon & Ellis (1976) shows a fairly constant magnetic field in the line of sight to Cygnus A, with a PA of polarization similar to that of the field galaxy measured by Jackson & Tadhunter (1993), which would seem to suggest that the continuum polarization of Cygnus A is indeed intrinsic to the source.

Optical spectropolarimetric observations of Jackson & Tadhunter (1993) found the degree of polarization to be ~2 per cent in the blue, decreasing to ~1 per cent in the red. Despite careful searches, no evidence for polarized broad Hα was found. They suggest two possible models to account for the measured polarization of Cygnus A. Their first model consists of an optically and geometrically thick torus, which obscures the central engine and broad-line region (BLR), although the narrow-line region (NLR) remains unobscured by the torus. Polarization of the continuum and BLR arises entirely by scattering close to the torus, and the NLR is not polarized. Their second model is essentially the same as the first, but with the addition of scattering within the host galaxy of Cygnus A, resulting in polarization in the continuum, BLR and NLR. From their spectropolarimetric observations, the second model is favoured.

Two important observations of Cygnus A have recently been made, both from the *Hubble Space Telescope* (*HST*). Jackson et al. (1996) published *HST V*-band images of Cygnus A, which clearly show the dual-component optical nucleus as well as the central dusty channel in which a central component is observed. The image also shows a filamentary structure from the north-west component, which they suggest is [O III] line emission. The reddening is found to vary across the image, in agreement with the suggestion of Stockton et al. (1994), with the north-west component having a reddening of $A_v \sim 2$ mag more than the south-east component.

Antonucci, Hurt & Kinney (1994) report the detection in *total flux* of broad Mg II emission lines in Cygnus A. They suggest that at UV wavelengths there is a significant contribution from reflected quasar radiation whereas the optical radiation arises from *in situ* extended emission. The authors suggest that supporting evidence for this scenario may be drawn from the lack of optical broad emission lines in either the total or polarized flux spectra (but see the next paragraph). The observed featureless blue component observed in the nuclear regions of Cygnus A (Shaw & Tadhunter 1994) could therefore arise from a population of young stars or from a second spatially extended featureless continuum (FC2), already suggested to exist around several other AGN (e.g. Tran 1995 and references therein). Further support for the above ideas may be drawn from the tentative report by Antonucci et al. (1994), of a UV polarization of (6.0 ± 1.7) per cent at a PA of $(17 \pm 8)°$, measured from *HST* imaging polarimetry of Cygnus A.

Very recently, Ogle et al. (1997), using the Keck II telescope, report the discovery of scattered broad Hα in polarized flux from components on either side of the nucleus, and to a lesser extent from the nucleus. Also, a high signal-to-noise ratio *B*-band image shows a double fan of centrosymmetric polarization vectors indicative of a scattering origin. Their observations are consistent with the scattering of light from a hidden quasar and lends support to the detection of broad Mg II emission lines by Antonucci et al. (1994).

At near-IR wavelengths, Djorgovski et al. (1991) report an unresolved nucleus at the L' band (3.7 μm) and small-aperture photometry over several broad bands. By the use of simple models, they estimate an obscuration to the central source of $A_v = 50 \pm 30$ mag. From luminosity arguments, they claim that Cygnus A is indeed an obscured quasar, possibly the result of a recent merger, in which the central dust channel represents gas and dust still settling around the central engine. Ward et al. (1991) presented near-IR spectroscopic observations of the central regions of Cygnus A, and from observations of the Paα line estimate an obscuration to the NLR of $A_v = 2.4$ mag (of which $A_v = 1.2$ mag results from Galactic obscuration) and a lower limit to the BLR, derived from the non-detection of broad Paα lines, of $A_v = 24$ mag. Finally, they estimate the extinction to the central source from the good correlation between the *K*-band (2.2-μm) magnitude and the soft X-ray flux, for quasars, to be $A_v = 54 \pm 9$ mag, in good agreement with that of Djorgovski et al. (1991).

Ueno et al. (1994), from hard X-ray observations, estimate $N_H = 3.75 \pm 10^{23}$ cm^{-2} for the absorption column to the central engine, equivalent to an A_v of 170 mag when a standard dust-to-gas ratio is used. If the L' flux reported by Djorgovski et al. (1991) is corrected for stellar dilution, even at these relatively long wavelengths, and using an X-ray constrained model (*Ginga* data, Ueno et al. 1994), an obscuration to the central source of an A_v of 131 ± 27 mag is calculated (Ward 1996). If the true *V*-band flux is estimated from observations of the equivalent width of the [O III] and compared to that observed at L', an additional independent estimate of the extinction to the central source may be made (Simpson, Ward & Wilson 1995), the results of which give an A_v of 143 ± 30 mag.

In order to investigate further the origin of the nuclear polarization of Cygnus A, we have obtained a high-resolution near-IR polarization map of the nuclear regions of Cygnus A. The observations and the instrument used are outlined in the following section and our results presented in Section 3. Section 4 looks at a number of models for producing the nuclear polarization, followed by a discussion section and finally our conclusions are presented in Section 6. In the rest of this paper, the term *central source/engine* refers to the power source at the centre of the galaxy, and the terms *nucleus/nuclear* refer to the position of peak emission at near-IR wavelengths.

2 OBSERVATIONS

Observations of Cygnus A were obtained during commissioning of the new dual-beam near-IR polarimeter (IRPOL2), designed and built at the University of Hertfordshire (Hough et al., in preparation). This is placed upstream of the near-IR camera (IRCAM3) at the United Kingdom Infrared Telescope (UKIRT), Mauna Kea, Hawaii, in which a lithium niobate Wollaston prism is used as an analyser, placed in the collimated beam of the camera. For linear polarization, observations are made with the half-wave retarder stepped to 0°, 45°, 22.5° and 67.5°. The efficiency of the polarimeter was measured using a Glan polarizing prism (effectively 100 per cent efficient in all bands) and the zero of position angle was determined from polarized stars taken from the list of Whittet et al. (1992).

IRCAM3 uses a 256×256 InSb array, where each pixel corresponds to 0.286 arcsec as projected on to the sky. On-object exposures were made on two separate nights (1995 August 24 and 25) at the *K* band (2.2 μm) for 192 s each night; the seeing was ~ 1 arcsec for both nights. Observations of blank sky were interposed with the object observations and used for sky subtraction and construction of a flat field. The images were flat-fielded, sky-subtracted and cleaned by interpolating over dead or hot pixels and cosmic rays. Next the images were shifted by fractional pixel values in order to account for slight image drift between frames, and then polarization images were constructed using the TSP Starlink package (Bailey 1992). Eight polarization maps were constructed each night and were checked for consistency between the observations. These maps were co-added in order to increase the signal-to-noise ratio, resulting in one final map for each night's observations. The data for the two nights were in good agreement and both data sets were combined giving $\sim 8\sigma$ result for the polarization in a 1-arcsec aperture (see next section). No significant difference was found between determining the polarization image for each observation and then averaging (which are the data shown), and averaging each of the flux images, for each waveplate position, and then determining the polarization.

Observations of photometric standards were taken in polarimetry mode, from the UKIRT set of faint standards (Casali & Hawarden 1993), and reduced using the procedures described above.

3 RESULTS

The polarization image for the central 9×6 arcsec of Cygnus A in the *K* band is presented in Fig. 1. This image

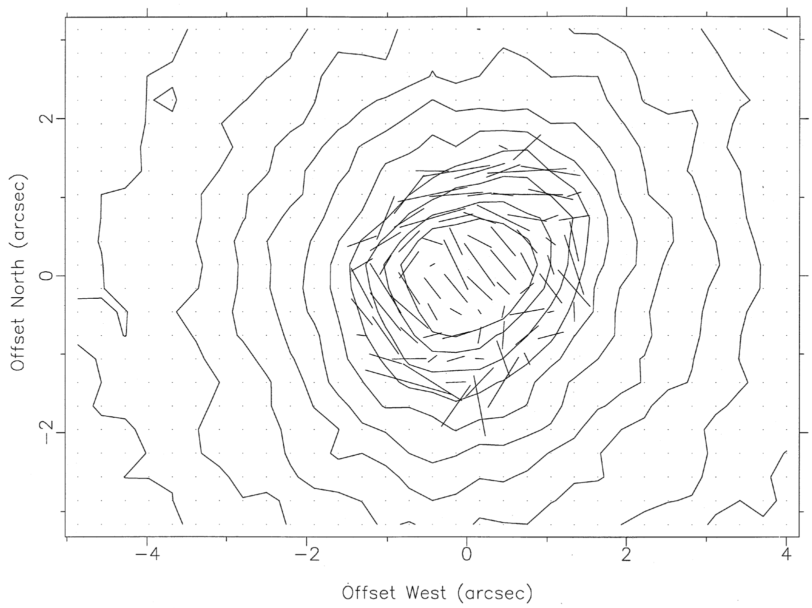

Figure 1. Polarization image of the central 9×6 arcsec of Cygnus A in the *K* band. The zero of coordinates corresponds to the centroid of the nuclear region at *K*. A 0.57-arcsec polarization vector corresponds to 10 per cent polarization.

(with no spatial binning) displays the total intensity contours whilst the overlaid vectors are proportional in length to the degree of polarization with their orientation showing the position angle of polarization. Only where the uncertainty in degree of polarization is less than 0.75 per cent, derived from the spread in polarization for each pixel, are the polarization vectors plotted. With typical degrees of polarization of 5 per cent this gives an uncertainty in the PA of polarization of 4°. Our observations are not of sufficient spatial resolution to observe a second *K*-band nucleus.

The polarization image shows approximately parallel vectors over the central 1–2 arcsec, surrounded by an approximately centrosymmetric pattern, which is similar to that seen by Ogle et al. (1997) in their *B*-band polarization image, although the IR observations are of lower signal-to-noise ratio. The polarization pattern, outside the central region, is inconsistent with the polarization being dominated by dichroic polarization in our Galaxy. Furthermore, measurements of a field star $\sim$20 arcsec from Cygnus A show a degree of polarization of (0.20 ± 0.06) per cent at a PA of $(106 \pm 4)°$. Whilst the observed field star is at an undetermined Galactic depth, and hence suffers an unknown amount of extinction, this result is in good agreement with optical obsevations of a nearby field galaxy whose degree of polarization was measured to be (0.52 ± 0.02) per cent (Jackson & Tadhunter 1993). If the optical polarization of the field galaxy arises entirely from dichroism, the degree of polarization at *K* would be $\sim$0.09 per cent (using the interstellar polarization law of Whittet et al. 1992, and assuming a λ_{max} of 0.55 μm), entirely consistent with our *K*-band observations of the field star, which is substantially less than the measured polarization of Cygnus A, and is also orthogonal in position angle (see below).

The degree of polarization in a 1-arcsec aperture, centred on the peak of the *K*-band emission for Cygnus A, is measured to be (4.1 ± 0.50) per cent at a position angle of $(23.6 \pm 3.6)°$, and in a 3-arcsec aperture is (1.58 ± 0.20) per cent at a PA of $(39.6 \pm 8.7)°$, where the errors are derived from the spread of several observations. The PA of polarization in the *K* band for the smaller aperture is approximately perpendicular to the radio jet axis [$(284 \pm 1)°$, Carilli et al. 1996], and is similar to that measured at optical (Tadhunter et al. 1990) and UV (Antonucci et al. 1994) wavelengths.

Photomeric calibration of the data was carried out in two different-sized apertures so that comparison with previously published data could be made, as shown in Table 1. Good agreement is found for both of the apertures.

The contribution of the central source to the total flux has been estimated by Djorgovski et al. (1991), who use two independent methods. Their first estimate assumed that within the central 1.5 arcsec the starlight surface brightness profile is flat and any deviation from this profile arises entirely from radiation from the central source. They confirm this estimate using an independent test by scaling the stellar bulge in an extended region around the central regions at the *J* band (1.2 μm) relative to the *H*-(1.6 μm) and *K*-band images. The scaled *J*-band image was then subtracted from the *H*- and *K*-band images so that starlight emission at these wavelengths is effectively removed, leaving only the contribution from the central source (if, however, there is a peaked stellar cusp, this estimate will be an upper limit to the central source contribution). This method has also proved successful in determining the central source contribution in Centaurus A (Packham et al. 1996; Turner et al. 1992). Djorgovski et al. (1991) conclude that the most likely contribution from the central source in the *K* band is $\sim$11 per cent, within a 3-arcsec aperture, whilst at the *H* band the contribution is ony $\sim$3 per cent in a 3-arcsec aperture. At wavelengths shorter than the *H* band, the central source makes a negligible contribution in an aperture of a few arcsec.

Using the Djorgovski et al. (1991) estimate that 89 per cent of the radiation in a 3-arcsec aperture is of stellar origin, the intrinsic nuclear polarization of Cygnus A is calculated to be $\sim(14 \pm 2)$ per cent. This does not, however, take into account the contribution from the polarization of the starlight. In the next section we present a model fit to the nuclear photometry, in which the starlight is viewed through an A_v of $\sim$5 mag. Assuming the typical polarization-to-extinction ratio found in our Galaxy (Serkowski, Mathewson & Ford 1975), the visual polarization of starlight should be $\sim$5 per cent, and in the *K* band $\sim$0.1 per cent (Whittet et al. 1992). Using these figures, we estimate the intrinsic nuclear polarization in the *K* band as $\sim$10 per cent.

4 MODELLING

There are three possible mechanisms that may explain the nuclear polarization of Cygnus A: (i) directly observed synchrotron emission from the central engine, (ii) dichroic absorption of nuclear and/or stellar radiation, and (iii) scattering of radiation from the central engine. These three possibilities are considered in Sections 4.1–4.3.

First we look at the likely extinction to the central source. The existence of a significant amount of dust in the nuclear regions of Cygnus A is well-documented (i.e. Stockton et al. 1994; Tadhunter, Metz & Robinson 1994; Pierce & Stockton 1986; Vestergaard & Barthel 1993) and the existence of a circumnuclear torus around the central engines of AGN has been postulated many times in unified schemes of AGN (i.e. Antonucci & Miller 1985; Lawrence 1987).

We have constructed a model in which a power-law source ($F_\nu \propto \nu^{-\alpha}$) is obscured, with a total visual extinction A_{v1}. The nuclear bulge of M31 was used as a stellar template for starlight from the host galaxy (Coleman, Wu & Weedman 1980), whose contribution to the total flux was constrained to be 89 per cent in a 3-arcsec aperture in the *K* band (see Section 3). Photometry, in a 3-arcsec aperture, was taken from Djorgovski et al. (1991), which provides data at a single epoch for the *r*, *i*, *J*, *H*, *K* and *L′* bands (the *r*-band data point has been corrected for a 46 per cent contribution from line emission as estimated by Vestergaard & Barthel (1993)). For this model the stellar contribution actually exceeds the observed flux by 82 per cent at *J* and 59 per cent at *H*, although this problem is easily

Table 1. Photometry of Cygnus A.

Aperture (arcsec)	Present data (mag)	Other data (mag)	Reference
3	13.73 ± 0.04	13.78 ± 0.06	Djorgovski et al. (1991)
8	12.40 ± 0.04	12.57 ± 0.05	Heckman et al. (1983)

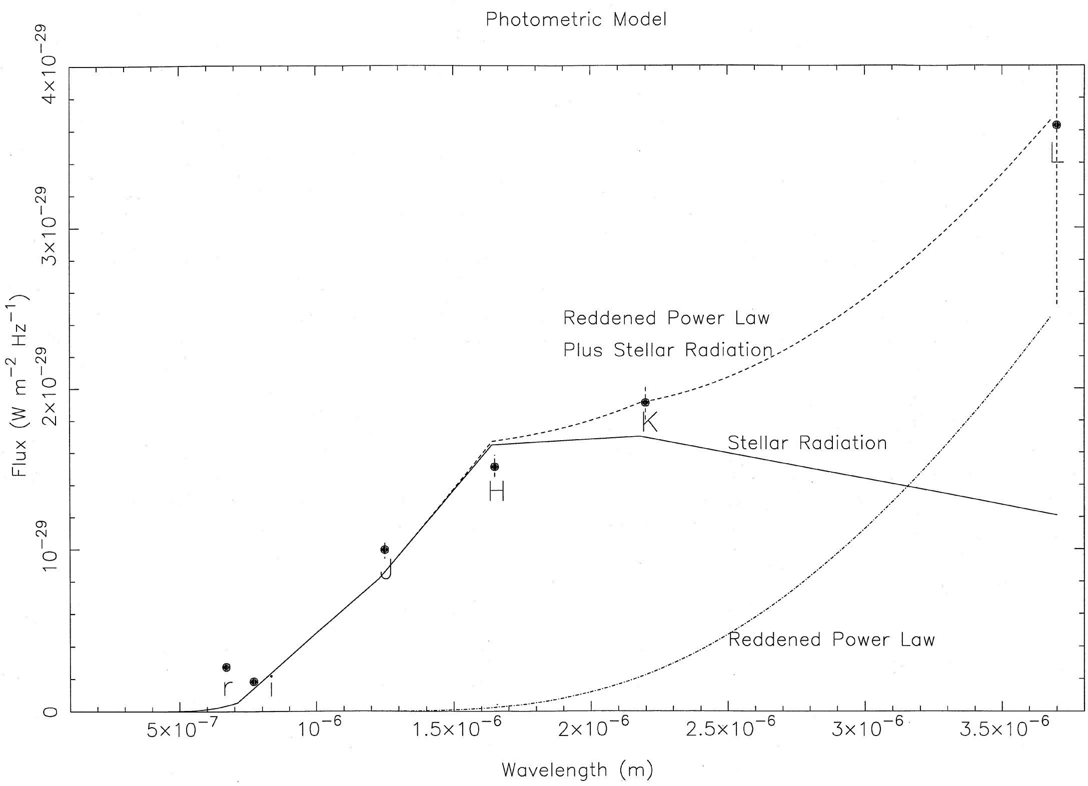

Figure 2. Model for the nucleus of Cygnus A, with an 11 per cent contribution from the central source in a 3-arcsec aperture. The solid line represents the reddened stellar radiation, the dashed line, the reddened power law ($F_\nu \propto \nu^{-\alpha}$, $\alpha=1.3$), and the dotted line is the addition of these two.

overcome by reddening of the stellar radiation, as indeed would be expected for a galaxy with a prominent dust lane.

The model therefore consists of a power law, reddened by an extinction A_{v1}, perhaps arising from local obscuration close to the central engine, and by an amount A_{v2} from the dust lane. Starlight, also with an extinction A_{v2} (which is much less than A_{v1}), is then added to this reddened power law, with the contribution from the central source fixed at 11 per cent of the total flux at *K* in a 3-arcsec aperture. A power-law spectral index of $\alpha=1.3$ was assumed, typical of blazars in the near-IR (Smith et al. 1987) and also of Seyfert 1 nuclei (McAlary & Rieke 1988), and the reddening law of Landini et al. 1984) was used. Fig. 2 shows the best visual fit to the Djorgovski et al. (1991) data, with $A_{v1}=34$ mag and $A_{v2}=5.5$ mag. The total A_v to the central source, of ~ 40 mag, is quite consistent with other estimates of the extinction using near-IR observations (Djorgovski et al. 1991; Ward et al. 1991).

Extinction estimates from X-ray observations are, however, much larger (see Section 1), with, for example, Ueno et al. (1994) estimating an A_v of 170 mag. Such differences are found for several other AGN when X-ray and near-IR obscuration estimates are compared and, as Ueno et al. (1994) suggest, are probably due to one or more of the following reasons: (i) the X-ray region is different from that observed in the near-IR and is probably significantly more compact than the near-IR feature (see also Young et al. 1995), (ii) different beam sizes for the two data sets preclude a valid comparison, or (iii) the standard (Galactic) dust-to-gas ratio is invalid in the nuclear regions of AGN, which could have the effect of reducing the value of extinction as measured from X-ray observations.

4.1 Synchrotron emission

It is possible that the observed polarization arises from synchrotron emission from the much-postulated quasar at the centre of Cygnus A. For most synchrotron-dominated sources, where a preferred PA of polarization can be identified, the optical and near-IR PA of polarization is similar to the PA of the radio jet [i.e. the magnetic field is perpendicular to the radio axis (Impey, Lawrence & Tapia 1991; Smith et al. 1987)]. Our present data show that the PA of polarization is perpendicular to the radio axis, suggesting that we are not directly observing synchrotron radiation from the jet.

The extended polarization pattern observed in the *K* band also argues against synchrotron emission being directly observed. Synchrotron radiation would produce a well-collimated jet of highly polarized emission (although unlikely to be resolved in these observations) and is hence inconsistent with the extended pattern of polarization we observe.

Lastly, assuming that most of the synchrotron emission at optical and near-IR wavelengths originates close to the central source, this emission will be obscured from direct views by the very large extinction (~ 170 mag) measured at X-ray wavelengths.

4.2 Dichroic absorption

Young et al. (1995) present a model to explain the polarization of NGC 1068, in which the near-IR nuclear polarization (in the *H* and *K* bands) arises from a dichroic view through the nuclear torus of the near-IR emission regions, which in their model arises from hot dust in the torus funnel. As this dust is ~ 1 pc from the nuclear continuum source, it is viewed through a smaller optical depth than is the central source. The BLR can only be observed in scattered flux, at both optical and near-IR wavelengths.

For Cygnus A, with an A_v of ~ 40 mag, as measured at near-IR wavelengths, it is possible to produce the *K*-band intrinsic nuclear polarization of ~ 10 per cent by dichroism. Estimates of the obscuration to the central source of our Galaxy suggests an A_v of ~ 30 mag (Becklin et al. 1978), whilst the measured polarization is 6.4 per cent at *K* (Bailey, Hough & Axon 1983). Although the polarization-to-extinction ratio in our Galaxy has a large scatter (Serkowski et al. 1975), a direct scaling with the Galactic Centre polarization would suggest that the polarization of Cygnus A should be ~ 8.5 per cent, close to the calculated 10 per cent.

If dichroism is contributing to the measured polarization, the polarization will be produced by aligned grains mainly within the nuclear torus, but also with a contribution from the dust lane. The measured PA of polarization would indicate that the magnetic field, along which the short axis of dust grains will preferentially align, has a PA of $\sim 24°$, approximately perpendicular to the radio axis. Assuming the radio axis is parallel to the polar axis of the torus, the magnetic field, as projected on to the sky plane, is approximately parallel to the plane of the torus. This is the same geometry as described by Young et al. (1995) for NGC 1068.

4.3 Scattering

The observed PA of polarization in the *K* band is also consistent with polarization produced by scattering of radiation from a central source that is obscured from direct view by an optically and geometrically thick torus, with the torus polar axis aligned with the radio axis. The scattering takes place off particles (electrons and/or dust) located along the poles of the torus.

A scattering model can easily explain the apparent discrepancy between the estimates of extinction made at X-ray and near-IR wavelengths. If the torus is optically thick at 2.2 μm, the near-IR extinction estimates are for the route taken by the scatterers, not for the direct route to the central source.

For Cygnus A an intrinsic polarization of ~ 10 per cent might be difficult to produce by scattering within a uniformly filled cone of scatters, since this implies a viewing angle within the cone. For example, a cone with an axis inclined to the plane of the sky at $\sim 35°$ (as suggested by Vestergaard & Barthel 1993) with a cone opening half-angle of $\sim 59°$ (Tadhunter et al. 1994) gives a degree of polarization of ~ 20 per cent. To match the intrinsic polarization of ~ 10 per cent, using this simple model, the cone axis will be inclined to the plane of the sky at an angle of $\sim 52°$. In either case, our line of sight lies within the forward-scattering cone, resulting in the central source being viewed directly. Relatively low degrees of intrinsic polarization can be produced with a cone axis closer to the plane of the sky if (i) there is some extinction through the cone, which preferentially absorbs scattered radiation from the far side of the cone, reducing the observed degree of polarization, or (ii) the proposed FC2, suggested to appear in some other AGN (Tran, 1995), dilutes the degree of observed polarization.

5 DISCUSSION

Both dichroism and a scattering model can account for the *K*-band polarization along the line of sight to the central source. However, even for the dichroic model, the pattern of polarization vectors at larger distances (out to 5 arcsec) most likely arises from scattering of radiation from the central source.

We feel, however, that scattering, seen through an A_v of ~ 40 mag, is a less likely explanation for the nuclear polarization, as the extinction along the scattering route would be so high. Although Packham et al. (1996) favour a scattering model to explain the near-IR nuclear polarization of Centaurus A, they calculate an A_v of only 16 mag for the scattering route, with approximately half the obscuration coming from the dust lane. Young et al. (1996), for the IR-luminous galaxy IRAS 23060 + 0505, calculate that the scattered radiation is obscured by an A_v of ~ 3 mag, far less than would be the case for Cygnus A. Also, a scattering model with high extinction would make it difficult to explain the UV polarization of (6.0 ± 1.7) per cent at a PA of $(17 \pm 8)°$, measured by Antonucci et al. (1994).

If the scattering model is correct, then it would not be possible to observe any broad emission lines in the polarized flux spectrum, at least at optical wavelengths, as the A_v of ~ 40 mag along the scattering route is simply too high for a detection to be made. If the dichroic model for the near-IR polarization is correct, then it might be possible to see scattered broad emission lines at both optical and near-IR wavelengths, as observed for many other type II AGN, although the dust lane of the galaxy will still contribute some extinction.

We note that Jackson & Tadhunter (1993) did not observe any broad Hα in their spectropolarimetry of Cygnus A, while Ogle et al. (1997) clearly observe broad Hα in their data, and broad Mg II emission lines are seen in the total flux spectrum of Antonucci et al. (1994). These results can be reconciled if the obscuration produced by the dust lane is patchy, as then it might be possible to see scattered broad lines, depending on the positioning of the slit. Indeed, Ogle et al. (1997) report that less-scattered broad Hα is seen at the position of the nucleus. Furthermore, if the scattered component is quite large, as might occur at short wavelengths if the scatterers are dust grains rather than electrons, then the broad line can be observed in the total flux spectrum, as reported by Antonucci et al. (1994).

The optical polarization is most likely produced by dichroism of radiation from stars embedded in the dust lane (or from an extended featureless continuum, FC2) and scattered radiation from the central source. Dichroism of starlight is the explanation presented by Packham et al. (1996) for the polarization of NGC 5128 (Centaurus A) at wavelengths shorter than 1.6 μm. With an A_v for the dust lane of

Cygnus A of 5–7 mag, most stars might be obscured with an A_v of 2.5–3.5 mag, leading to polarizations of typically 2–3 per cent at optical wavelengths (Whittet et al. 1992) consistent with the $\sim$1.5 per cent observed (Tadhunter et al. 1990). The UV polarization of (6.0 ± 1.7) per cent at a PA of $(17 \pm 8)°$, measured by Antonucci et al. (1994), would suggest that scattered radiation can escape, even at quite short wavelengths, and that the dust-lane obscuration might indeed be patchy, as proposed above.

We can calculate the luminosity of the central source in the following ways. For the scattering model, we assume $\sim$1 per cent of the radiation from the central source is scattered to us by electrons, typical of that determined from the modelling of the polarization properties of Seyfert 2 galaxies (Young et al. 1995). Taking the distance to Cygnus A as 219 Mpc [using the value of $z = 0.0562$ (Stockton et al. 1994) and $H_0 = 75$ km s^{-1} Mpc^{-1}], and A_v along the scattering route of around 40 mag, and a central source contribution of 11 per cent in a 3-arcsec aperture, we calculate the *K*-band luminosity as $\sim 2 \times 10^{46}$ erg s^{-1}. For the dichroic model, the *K*-band luminosity will be 2×10^{44} erg s^{-1}. Although the estimated luminosities are very model-dependent, we can compare Cygnus A with the stellar-subtracted *K*-band luminosity of 2×10^{43} erg s^{-1} for the central source of Centaurus A (Packham et al. 1996) and 3×10^{46} erg s^{-1} for the luminous broad-line radio galaxy 3C 234 (Young et al. 1998).

6 CONCLUSIONS

A *K*-band polarization image of Cygnus A shows approximately parallel vectors over the cenral 2–3 arcsec, surrounded by an approximately centrosymmetric pattern. A model fit to the nuclear IR photometry provides a best estimate for the total visual extinction of $\sim$40 mag, consistent with other estimates at these wavelengths. This is substantially less than the 170 mag estimated from X-ray observations. Although a scattering model can be used to explain this difference, with the 40 mag being the extinction along the scattered route, we prefer to explain the *K*-band polarization by a direct view, through 40 mag of extinction, of the near-IR emission regions. The hot dust responsible for the near-IR emission will be $\sim$1 pc from the central source, and thus can be obscured far less. In this regard the model is very similar to that developed by Young et al. (1995) for NGC 1068.

This dichroic model, for the *K*-band polarization along the line of sight to the central source, is entirely consistent with the recent observation by Ogle et al. (1997) of broad Hα in the polarized flux spectrum of Cygnus A.

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REFERENCES

Antonucci R., Miller J. S., 1985, ApJ, 297, 621
Antonucci R. R., Hurt T., Kinney A., 1994, Nat, 371, 313
Axon D. J., Ellis R. S., 1976, MNRAS, 177, 499
Baade W., Minkowski R., 1954, ApJ, 119, 215
Bailey J. A., 1992, TSP – A Time Series/Polarimetry Package, Version 2.0, Starlink User Note 66.2
Bailey J. A., Hough J. H., Axon D. J., 1983, MNRAS, 203, 339
Barthel P. D., 1989, ApJ, 336, 606
Becklin E. E., Mathews K., Neugebauer G., Willner S. P., 1978, ApJ, 220, 831
Carilli C. L., Barthel P. D., 1996, A&AR, 7, 1
Carilli C. L., Perley R. A., Bartel N., Dreher J. W., 1996, in Carilli C. L., Harris D. E., eds, Cygnus A – Study of a Radio Galaxy. Cambridge Univ. Press, Cambridge
Casali M., Hawareden T., 1993, JCMT–UKIRT Newsl., 4, 33
Coleman G. D., Wu C.-C., Weedman D. W., 1980, ApJS, 43, 393
Djorgovski S., Weir N., Mathews K., Graham J. R., 1991, ApJ, 372, L67
Goodrich R., Miller J. S., 1989, ApJ, 346, L21
Heckman T. M., Lebofsky M. J., Rieke G. H., Van Breugel W., 1983, ApJ, 272, 400
Impey C. D., Lawrence C. R., Tapia S., 1991, ApJ, 375, 46
Jackson N., Tadhunter C. N., 1993, A&A, 272, 105
Jackson N., Tadhunter C. N., Sparks W. B., Miley G. K., Macchetto F., 1996, A&A, 307, L29
Landini M., Natta A., Oliva E., Salinari P., Moorwood A. F. M., 1984, A&A, 134, 284
Lawrence A., 1987, PASP, 99, 309
McAlary C. W., Rieke G. H., 1988, ApJ, 333, 1
Ogle P. M., Cohen M. H., Millker J. S., Tran H. D., Fosbury R. A. E., Goodrich R. W., 1997, ApJ, 482, L37
Packham C., Hough J. H., Young S., Chrysostomou A., Bailey J. A., Axon D. J., Ward M. J., 1996, MNRAS, 278, 406
Perley R. A., Dreher J. W., Cowan J. J., 1984, ApJ, 285, L35
Pierce M. J., Stockton A., 1986, ApJ, 305, 204
Serkowski K., Mathewson D. S., Ford V. L., 1975, ApJ, 196, 261
Shaw M., Tadhunter C. N., 1994, MNRAS, 267, 589
Simpson C., Ward M. J., Wilson A. S., 1995, AJ, 454, 683
Smith P. S., Balonek T. J., Elston R., Heckert P. A., 1987, ApJS, 64, 459
Stockton A., Ridgway S., Lilly S. J., 1994, AJ, 108, 414
Tadhunter C. N., 1996, in Carilli C. L., Harris D. E., eds, Cygnus A – Study of a Radio Galaxy. Cambridge Univ. Press, Cambridge
Tadhunter C. N., Scarrott S. M., Rolph C. D., 1990, MNRAS, 246, 163
Tadhunter C. N., Metz S., Robinson A., 1994, MNRAS, 268, 989
Tran H. D., 1995, ApJ, 440, 597
Turner P. C., Forrest W. J., Piphe J. L., Shure M. A., 1992, ApJ, 393, 648
Ueno S., Koyama K., Nishida M., Yamauchi S., Ward M. J., 1994, ApJ, 431, L1
Vestergaard V., Barthel P. D., 1993, AJ, 105, 456
Ward M. J., 1996, in Carilli C. L., Harris D. E., eds, Cygnus A – Study of a Radio Galaxy. Cambridge Univ. Press, Cambridge
Ward M. J., Blanco P. R., Wilson A. S., Nishida M., 1991, ApJ, 382, 115
Whittet D. C. B., Martin P. G., Hough J. H., Rouse M. F., Bailey J. A., Axon D. J., 1992, MNRAS, 386, 562
Young S., Hough J. H., Axon D. J., Bailey J. A., Ward M. J., 1995, MNRAS, 272, 513
Young S., Packham C., Hough J. H., Efstathiou A., 1996, MNRAS, 283, L1
Young S., Axon D. J., Hough J. H., Fabian A., Ward M. J., 1998, MNRAS, 294, 478