Highly polarized structures in the near-nuclear regions of Cygnus A: intrinsic anisotropy within the cones?

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ABSTRACT

We present near-infrared imaging polarimetry observations of the nucleus of Cygnus A ($z = 0.0567$), taken with the NICMOS camera of the *Hubble Space Telescope* (*HST*) at a wavelength of $2.0\,\mu$m. These maps reveal a highly collimated region of polarized emission straddling the nucleus and extending to a radius of 1.2 arcsec. Remarkably, this feature coincides with one, but only one, limb of the edge-brightened bicone structure seen in the total intensity image. The high degree ($P_k \sim 25$ per cent) and orientation of the extended polarization feature are consistent with a scattering origin. Most plausibly, the detection of polarization along only one limb of the bicone is a consequence of *intrinsic anisotropy* of the near-infrared continuum within the radiation cones, with the direction of maximum intensity of the near-infrared radiation field significantly displaced from the direction of the radio axis. The unresolved nuclear core source is also highly polarized ($P_k > 28$ per cent), with a position angle close to perpendicular to the radio axis. Given that this high degree of nuclear polarization can only be explained in terms of dichroic extinction if the dichroic mechanism is unusually efficient in Cygnus A, it is more likely that the nuclear polarization is caused by the scattering of nuclear light in an unresolved scattering region close to the active galactic nucleus. In this case, the flux of the core source in the K band is dominated by scattered rather than transmitted quasar light, and previous extinction estimates based on K-band photometry of the core substantially underestimate the true nuclear extinction.

Key words: polarization – scattering – infrared: galaxies.

1 INTRODUCTION

As yet, little is known about the structure of the inner regions of powerful radio galaxies and the impact of the activity on circum-nuclear regions. The high resolution and sensitivity afforded by imaging observations using the *Hubble Space Telescope* (*HST*) has revealed a wealth of complex structures in such objects, with dust lanes, jets and large regions of scattered emission from hidden nuclei. One of the key targets in studies that aim to elucidate the interplay between active nuclei and their host galaxies, and between galactic activity of different types, is the archetypal powerful radio galaxy Cygnus A (see Carilli & Barthel 1996 for a review).

HST infrared imaging observations of Cygnus A by Tadhunter et al. (1999) revealed an edge-brightened biconical structure

centred on the nuclear point source, which is strikingly similar to those observed around young stellar objects. The edge-brightening of this structure provides evidence that the bicone is defined as much by outflows in the nuclear regions as by the polar diagram of the illuminating quasar radiation field. The *HST* observations also show an unresolved nuclear source at 2.0 and $2.25\,\mu$m. However, from the imaging observations alone it is unclear whether this unresolved source represents the highly extinguished quasar nucleus seen directly through the obscuring torus (Djorgovski et al. 1991), or emission from a less highly extinguished extended region around the nucleus.

Near-infrared polarization observations have the potential to remove the uncertainties surrounding the nature of the unresolved nuclear sources and, in addition, to provide further important information about the obscuration and anisotropy in the near-nuclear regions of powerful radio galaxies. Previous ground-based polarimetric observations of Cygnus A by Packham et al. (1998)

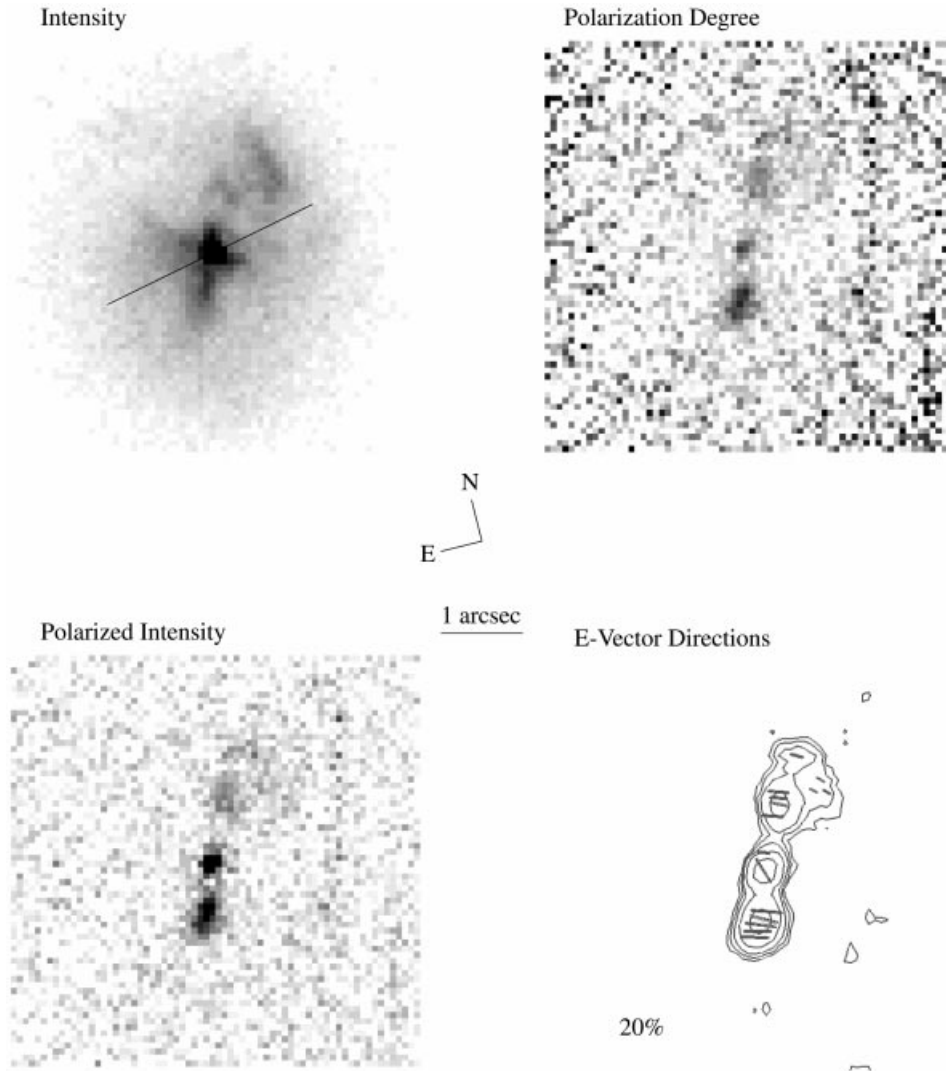★ E-mail: c.tadhunter@sheffield.ac.uk

Intensity

Polarization Degree

Polarized Intensity

E-Vector Directions

1 arcsec

20%

N

E

Figure 1. Infrared (2.0-μm) polarization images of Cygnus A. Top left: total intensity (Stokes *I*) at full resolution; top right: polarization degree at full resolution; bottom left: polarized intensity at full resolution; bottom right: polarization vectors plotted on a contour map of the polarized intensity image derived from the data smoothed with a 5×5 pixel box filter, with length of vectors proportional to the percentage polarization. The line segment in the intensity image shows the direction of the radio axis. At the redshift of Cygnus A, 1.0 arcsec corresponds to 1.0 kpc for $H_0 = 75 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$ and $q_0 = 0.0$.

demonstrate that the nuclear regions are highly polarized in the *K* band, with a measured polarization of $P_k \sim 4$ per cent for a 1-arcsec diameter aperture centred on the compact infrared nucleus. However, the resolution of the ground-based observations is insufficient to resolve the structures and determine the polarization mechanism unambiguously. In this letter we present new diffraction-limited infrared imaging polarimetry observations of Cygnus A made with the Near Infrared Imaging Camera and Multi-Object Spectrometer (NICMOS: MacKenty et al. 1997) on the *HST*. These observations resolve the polarized structures, and raise new questions about the nature of the anisotropy in the near-nuclear regions of this key source.

2 OBSERVATIONS AND DATA REDUCTION

NICMOS Camera 2 'long-wavelength' infrared imaging polarization observations were taken in 1997 December and 1998 August, giving a pixel scale of 0.075 arcsec and a total field of

19.4×19.4 arcsec. The NICMOS polarizers are self-contained spectral elements, with the three long-wavelength polarizers effective from $\lambda \approx 1.9$–2.1 μm, resulting in an effective central wavelength of ≈ 2.0 μm (MacKenty et al. 1997). The polarizers are oriented at approximately 60° intervals and have characteristics as presented by Hines (1998). Each exposure consisted of a number of non-destructive reads of the detector, which were optimally combined in the reduction software to remove cosmic rays. Regular chops were made to offset fields in order to facilitate accurate background subtraction. The total integration time was 2400 s per polarizer.

The reduction of the data used standard IRAF/STSDAS pipeline processing together with pedestal removal as given by van der Marel (1998). The three final, clean polarization images were combined following the prescription of Sparks & Axon (1999), using the pipeline-produced variance data. The output data comprised a set of images containing each of the Stokes parameters I, Q, U, their variances and covariances, a debiased estimate of the polarization intensity and polarization degree using the method of

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Serkowski (1958), and also position angle and uncertainty estimates on each of those images, as described in detail in Sparks & Axon (1999).

The two epochs of observation were acquired with different instrumental orientation, and were analysed independently to provide a robust check on our estimated uncertainties and on the possibility of systematic errors. A variety of spatial resolutions were used, from full diffraction-limited NICMOS resolution down to ≈ 1 arcsec by smoothing the input three images prior to polarization analysis. Both epochs were fully consistent within the estimated statistical errors, implying that there are no significant sources of systematic uncertainty. Measurements of several Galactic stars in the field of Cygnus A give 2.0 µm polarizations of $P_{2.0\,\mu m} < 2.0$ per cent for 5 pixel diameter apertures. This can be regarded as an upper limit on the level of systematic error in estimates of P. The typical statistical uncertainties for the most highly polarized regions measured in our full resolution images are ± 1.5 per cent for P and $\pm 3°$ for the polarization angle. In the following, we will present the data for the December 1997 observations only, as these have a higher signal-to-noise ratio (S/N) as a consequence of longer exposure times.

3   RESULTS

Fig. 1 shows the first epoch polarization results. As expected, the total intensity image (Stokes I) is very similar to the direct images published previously by Tadhunter et al. (1999). In particular, it shows an apparent edge-brightened, reasonably symmetric, biconical structure centred on the nucleus with an opening angle of 116°. The axis of the bicone is closely aligned with the radio jet.

The image of polarized intensity, however, reveals intriguing differences compared with total intensity. The only regions of strongly polarized emission (apart from the nucleus discussed below) are confined to a quasi-linear structure running along the north-west–south-east limb of the biconical structure. This feature shows approximate reflection symmetry about the nucleus, as opposed to the axial symmetry about the radio axis in the total intensity image. The brightness ratio of the two limbs of the cone to the east of the nucleus is approximately 2:1 in the total intensity image, while in the polarized intensity image it is $>12:1$. Note that the polarization structure visible in our 2.0-µm image is strikingly different from that of the optical V- and B-band polarization images (Tadhunter, Scarrott & Rolph 1990; Ogle et al. 1997), in which the polarized emission appears uniformly distributed across the kpc-scale ionization cones and shows no clear preference for the north-west–south-east limb of the bicone.

Typical *measured* degrees of polarization are in excess of 10 per cent, up to a maximum of ≈ 25 per cent in the polarized region to the south-east of the nucleus. However, these measures underestimate the true degree of *intrinsic* polarization in the extended structures, because starlight from the host galaxy makes a substantial contribution to the total flux. For example, using the azimuthal intensity profile measured in an annulus with 4-pixel inner radius and 12-pixel outer radius, we estimate that the diffuse starlight from the host galaxy contributes 50–70 per cent of the total flux in the south-east arm of the bicone. Assuming that the starlight is unpolarized, the degree of intrinsic polarization in the south-east arm is $P^{intr}_{2.0\,\mu m} \sim 50–70$ per cent. Such high degrees of measured and intrinsic infrared polarization are unprecedented in observations of active galaxies in which the synchrotron-emitting jets are not observed directly at infrared wavelengths.

3.1   The nucleus

The nuclear point source, discussed in detail by Tadhunter et al. (1999), is also highly polarized. In the polarized intensity image the main nuclear component is unresolved (FWHM = 2.24 pixel) and its position agrees with that of the nucleus in the total intensity image to within 0.5 pixel (0.04 arcsec). Thus, it appears likely that the bulk of the polarization is associated with the compact nucleus rather than a more extended region around the nucleus. The core does, however, show a faint extension to the north-west in the polarized intensity image. This extension is aligned with the larger scale polarization structures, and its polarization E-vector is close to perpendicular to the radius vector from the nucleus.

From our full resolution polarization images, the measured degree of polarization at the peak flux of the nuclear point source is $P^m_{2.0\,\mu m} \sim 20$ per cent. However, spurious polarization can arise because of small misalignments between the polarization images, especially in the nuclear regions where there are sharp gradients in the light distribution. To guard against such effects we have smoothed the polarization data using a 5×5 pixel boxcar filter $(0.375 \times 0.375 \text{ arcsec}^2)$ and remeasured the polarization in the nuclear regions. As expected, the measured degree of polarization in the nucleus in the smoothed image is less ($P^m_{2.0\,\mu m} \sim 10$ per cent) than in the full resolution image, because of the greater degree of contamination by unpolarized starlight and extended structures around the nucleus. In order to determine the intrinsic polarization of the point source it is first necessary to determine the proportion of flux contributed by the point source to the total flux in the nuclear regions. Experiments involving the subtraction of a TINYTIM-generated point spread function (Krist & Hook 1997) suggest that an upper limit on the fractional contribution of the nucleus to the total flux in a 5×5 pixel box centred on the nucleus is $f_{nuc} < 0.35$. Thus, assuming that *all* the polarization in the near-nuclear regions is caused by the unresolved compact core, and that the remainder of the light is unpolarized, the intrinsic polarization of the unresolved core source is $P^{intr}_{2.0\,\mu m} = P^m_{2.0\,\mu m}/f_{nuc} > 28$ per cent.

The position angle of the polarization E-vector of the core source measured in our full resolution polarization map (PA = 201 ± 3), is close to perpendicular to the radio jet axis (PA = 105 ± 5). This is similar to the situation seen in other active galactic nuclei (AGN), and in particular Cen A, where, towards longer wavelengths and smaller apertures, the infrared polarization becomes more and more closely perpendicular to the radio jet (Bailey et al. 1986).

4   DISCUSSION

4.1   The nature of the unresolved core source

A major motivation for the *HST* observations was to investigate the nature of the compact core source and the cause of the relatively large polarization measured in the core by Packham et al. (1998). The explanation favoured by Packham et al. is that the compact core source represents transmitted quasar light, while the high polarization is caused by dichroic absorption by aligned dust grains in the central obscuring torus. Because the dichroic mechanism is relatively inefficient, a high polarization implies a large extinction: from observations of Galactic stars it is known that *at least* 55 magnitudes of visual extinction is required to produce a K-band polarization of 28 per cent for optimum grain

alignment (Jones 1989). More typically, the correlation between *K*-band polarization and extinction deduced for Galactic stars by Jones (1989) implies that an extinction of $A_v \sim 350$ mag would be required for $P_k = 28$ per cent. For comparison, an upper limit on the *K*-band extinction in Cygnus A, estimated by comparing the 2.25-μm core flux with mid-infrared and X-ray fluxes, is $A_v < 94$ mag (see Tadhunter et al. 1999 for details). Thus, the dichroic mechanism is only feasible if the efficiency of the mechanism in Cygnus A is greater than it is along most lines of sight in our Galaxy. Such enhanced efficiency cannot be entirely ruled out, given that the Galactic dichroic polarization involves a randomly oriented magnetic field component, whereas the magnetic fields in the central obscuring regions of AGN may be more coherent. In this context it is notable that near- and mid-infrared polarization measurements of the central regions of the nearby Seyfert galaxy NGC 1068 provide evidence for a greater dichroic efficiency than predicted by the Jones (1989) correlation, with $P_k = 5$ per cent produced by $A_v \sim 20$–40 mag (Lumsden et al. 1999). However, even the greater dichroic efficiency deduced for NGC 1068 would not be sufficient to produce the high polarization measured in the core of Cygnus A if $A_v < 94$ mag.

The efficiency problem might be resolved if the extinction to the core source in the *K* band is higher than the $A_v < 94$ estimated on the basis of comparisons of the *K*-band flux with the mid-infrared and X-ray fluxes. Indeed, substantially higher extinctions have been deduced for Cygnus A, both from modelling the X-ray spectrum of the core ($A_v = 170 \pm 30$: Ueno et al. 1994) and from comparisons between hard-X-ray continuum, [O III] emission-line and mid-infrared continuum fluxes ($A_v = 143 \pm 35$: Ward 1996, Simpson 1995). If such high extinctions also apply to the quasar nucleus in the *K* band, the low efficiency of the dichroic mechanism would be less of a problem. However, for any reasonable quasar spectral energy distribution, the contribution of such a highly obscured quasar nucleus to the flux and the polarization of the *detected* 2.0-μm core source would be negligible (i.e. we would not expect to detect the quasar nucleus directly in the *K* band). Thus, it is more likely that the relatively low extinction deduced from the *K*-band flux measurements reflects contamination of the *K*-band core by emission from a less highly obscured region, which is close enough to the central AGN to remain unresolved at the resolution of our *HST* observations. Although it has been proposed that the contaminating radiation in the *K* band may include hot dust emission and/or line emission from quasar-illuminated regions close to the nucleus (e.g. Stockton & Ridgway 1996), such emission would have a low intrinsic polarization, and a large dichroic efficiency would still be required in order to produce the polarization of this component by dichroism.

The most plausible alternative to dichroic extinction is that the *K*-band core source represents scattered, rather than transmitted, quasar light. In this case, the polarization is a consequence of scattering in an unresolved region close to the illuminating quasar; we do not detect the quasar nucleus directly in the *K* band, and previous extinction estimates based on the *K*-band fluxes substantially underestimate the true nuclear extinction. Note that the presence of such a scattered component would resolve the discrepancy between the extinction estimates based on *K*-band flux measurements, and those based on fluxes measured at other wavelengths.

Finally, we must also consider the possibility that the core polarization is caused by synchrotron radiation associated with the pc-scale jet visible in very long baseline interferometry (VLBI) radio images (Krichbaum, Alef & Witzel 1996). Although the *integrated* polarization of the radio core is small even at high radio

frequencies ($P_{22\,GHz} < 5$ per cent : Dreher 1979), we cannot entirely rule out the possibility that we are observing a highly polarized subcomponent of the jet that suffers a relatively low extinction, or alternatively that the radio core source as a whole suffers large Faraday depolarization at radio wavelengths, and would appear more highly polarized at infrared wavelengths. Polarization observations at submillimetre wavelengths will be required to investigate this latter possibility.

4.2   The extended polarization structures

An intriguing feature of our *HST* observations is the high degree of polarization measured along, and only along, the north-west–south-east limb of the bicone. The orientation of the polarization measured along the limb is consistent with the scattering of light from a compact illuminating source in the nucleus, while the high degree of polarization is consistent with the edge-brightened bicone geometry of Tadhunter et al. (1999), in the sense that the scattering angle for the edge-brightened region will be close to the optimal 90° required for maximal polarization. However, the fact that the polarization is measured along only one limb is difficult to reconcile with the simplest bicone model in which the illuminating infrared radiation field is azimuthally isotropic, and the scattering medium is uniformly distributed around the walls of the funnels hollowed out by the circumnuclear outflows. In this simplest model both limbs would be highly polarized in the direction perpendicular to the radius vector of the source, and this is clearly inconsistent with the observations.

Our observations require that one or more of the assumptions implicit in the simple model must be relaxed. In general terms, this requires either invoking specific matter distributions within the cone and/or an anisotropic illumination pattern of the central source itself.

Perhaps the simplest way of reconciling the polarization characteristics with the bicone geometry is to adjust the relative importance of scattering and intrinsic emission with azimuth around the cone, so that one limb of the cone is dominated by scattered radiation, while the other is predominantly intrinsic radiation. As the band-pass of the NICMOS polarizers contains the Paschen alpha line, this provides an obvious potential source of the diluting radiation for the unpolarized regions. Unfortunately there is no obvious reason why such an asymmetry should exist. Furthermore, direct images with the F222M filter show that there is no radical change in the relative brightness of the two limbs of the eastern cone between 2.0 and 2.25 μm. This is an argument against the Paschen alpha model for the intrinsic emission, since the F222M filter admits no emission lines as strong as Paschen alpha.

An alternative possibility is that the north-west–south-east limb is brighter because the near-infrared radiation field of the illuminating AGN is more intense in that direction (i.e. the illuminating radiation field is azimuthally anisotropic within the cones). In this case, the clear difference in structure between the optical and near-infrared reflection nebulae suggests that the sources of illumination at the two wavelengths are different: while the source of the shorter wavelength continuum must produce a radiation field that is azimuthally isotropic within cones defined by the obscuring torus, the source of illumination at the longer wavelengths is required to display considerable degree of azimuthal anisotropy. The near-infrared continuum source must also have a relatively red spectrum, in order to avoid producing similar structures at optical and infrared wavelengths. The near-infrared anisotropy might arise in the following ways.

(i) Beamed radiation from the inner radio jet. The near-infrared continuum is emitted by a component of the inner synchrotron jet that has a direction of bulk relativistic motion significantly displaced from the axis of the large-scale radio jet, such that the radiation is beamed towards the north-west–south-east limb of the bicone. However, given the remarkable degree of collimation, and the lack of bending, observed in the Cygnus A jet on scales beteem 1 pc and 100 kpc, a major difficulty with this model is that the the jet would have to bend through a large angle on a scale smaller than ∼1 pc (the resolution of the VLBI maps), whilst retaining the rotational symmetry in the jet structure about the nucleus. A further requirement of this model is that, if the inner jet is precessing, the precession time-scale must be greater than the light travel time (∼5000 yr) across the bicone structure.

(ii) Anisotropic hot dust emission. The near-infrared continuum is emitted by hot dust in the inner regions of the galaxy, with a larger projected area of the emitting region visible from one limb of the bicone than from the other. For example, if the near-infrared radiation is emitted by dust in a warped disc close to the central AGN – perhaps an outer part of the accretion disc – the warp could be oriented such that the north-west–south-east limb has an almost face-on view of the emitting region, whereas the the north-east–south-west limb has a more oblique view. There is already direct observational evidence for a warped outer accretion disc in at least one active galaxy (Miyoshi et al. 1995). Given that this mechanism would produce a relatively mild, broad-beam aniso-tropy, an optically thick torus on scales larger than the hot dust emitting region would still be required in order to produce the sharp edges to the illuminated bicone structure.

Note that regardless of how any anisotropy in the infrared radiation field might be produced, such anisotropy would not by itself explain the nature of the unpolarized emission along the south-west–north-east limb of the bicone, and the lack of variation in the brightness ratio of the two limbs of the eastern cone between 2.0 and 2.25 μm. It may also be difficult to reconcile the anisotropic illumination model with the polarization properties of the unresolved core source: if the core polarization is caused by scattering, the orientation of the core polarization vector implies that a substantial flux of illuminating photons must escape at large angles to the north-west–south-east limb of the bicone.

We expect future spectropolarimetry observations to resolve the uncertainties concerning the origin of the near-infrared polarization structures in Cygnus A. For example, in the case of the anisotropic illumination mechanisms considered above, the anisotropy is in the *continuum* flux rather than the broad lines associated with the AGN. Thus, if this model is correct, the broad lines will be relatively weak or absent in the polarized spectrum of the extended structures. In contrast, for a non-uniform distribution of scattering material but isotropic illumination within the cones, the broad lines and continuum will be scattered equally, and the equivalent widths of the broad lines in the polarized spectrum should fall within the range measured for steep-spectrum radio quasars.

5　CONCLUSIONS AND FUTURE WORK

Our NICMOS polarimetry observations of Cygnus A have demonstrated the existence of a compact reflection nebula around the hidden core, but one with polarization properties that are inconsistent with the simplest illumination model suggested by the imaging data. The predominantly axial symmetry of the total intensity imaging is replaced by axial asymmetry and reflection symmetry about the nucleus in polarized light.

We have discussed several mechanisms to explain the near-infrared polarization structures. While none of these is entirely satisfactory, it is clear that the near-infrared polarization properties have the potential to provide key information about the geometries of the central emitting regions in AGN, and the near-infrared continuum emission mechanism(s). In this context, it will be interesting in future to make similar observations of a large sample of powerful radio galaxies in order to determine whether the extraordinary infrared polarization properties of Cygnus A are a common feature of the general population of such objects.

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