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Near-infrared and millimetre polarimetry of Cen A

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ABSTRACT

We present near-infrared polarization images of the nuclear region of Cen A, and millimetre polarimetry of the nucleus.

In the near-infrared the polarization vectors mainly lie along the dust lane, with the polarization being produced by dichroic absorption of the radiation from stars embedded in the dust lane. At 2.2 μm the nucleus shows an additional larger polarized component, with position angle of polarization perpendicular to the inner radio and X-ray jet of Cen A. The millimetre observations at 800 and 1100 μm are consistent with the nucleus of Cen A being unpolarized at these wavelengths.

Modelling of the results suggests that the nuclear polarization observed at 2.2 μm is produced by scattering, with the scattered radiation observed through ~16 mag of extinction for a power-law central source with spectral index α of 1.3 ($F_\nu \propto \nu^{-\alpha}$). The central source is not observed directly in the near-infrared because of very high extinction to it along the line of sight. Our near-infrared results do not preclude the central source being a BL Lac type object, as several authors have suggested, although the zero polarization at ~1 mm is unexpected if the radiation at these wavelengths is dominated by non-thermal emission, as has been proposed. We present arguments which might explain the low polarization at these wavelengths while still allowing the central source to be a BL Lac type object. Based on our near-infrared model, the luminosity of the central source at 2.2 μm is weaker by a factor of 100 compared to that of BL Lac, approximately the same factor as at X-ray wavelengths.

There is no evidence for any additional polarization associated with the 'blue' infrared jet of Cen A. This suggests that the jet is not scattered radiation from the central source and is most likely free–free emission from gas shocked and heated by the jet of Cen A.

Key words: polarization – techniques: polarimetric – galaxies: active – galaxies: individual: NGC 5128 (Cen A) – galaxies: nuclei – infrared: galaxies.

1 INTRODUCTION

Although Cen A, the closest powerful active galaxy, is a well-known radio and X-ray variable, with a jet, inner and outer radio lobes, optical filaments, a dust lane, numerous H II regions and an extended X-ray halo, the true nature of the *central source*, which is hidden from direct view at optical wavelengths by several tens of magnitudes of extinction, remains elusive.

Near-infrared polarimetry (Bailey et al. 1986) showed that the nucleus, after correction for dilution by starlight and interstellar polarization in the dust lane (see also Hough et al. 1987), has an intrinsic polarization of 9 per cent at a position angle of 147°, perpendicular to the X-ray and radio jets. Bailey et al. suggested that the centre of Cen A contains a low-luminosity, 'misdirected' BL Lac, i.e. one

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viewed at a large angle to the jet axis. A number of authors (see for example, Urry, Padovani & Stickel 1991, and references therein), have proposed that the most likely parent (i.e. misaligned) objects for BL Lacs are Fanaroff–Riley type I radio galaxies, such as Cen A. Misdirected and/or intrinsically lower luminosity BL Lac objects will be difficult to observe for most radio galaxies, as the dilution by starlight will reduce the degree of polarization observed.

Further evidence that Cen A harbours a BL Lac object has recently been provided by the following observations. First, Morganti et al. (1991) concluded that the line-emitting filaments of the 'optical jet' are predominantly photoionized by the radiation field of a continuum source relativistically beamed in the direction of the optical jet, with a beam power similar to that of BL Lac itself. Secondly, Hawarden et al. (1993, hereafter HEA) have presented new submillimetre maps and multi-aperture photometry of Cen A at wavelengths between 350 and 2000 μm. They conclude that the nucleus appears as an unresolved central source (FWHM < 6 arcsec at 800 and 450 μm) and is evidently non-thermal in origin, with a *very flat spectrum*, at least down to 800 μm and possibly 350 μm, providing further support for the central source of Cen A being a BL Lac.

At X-ray wavelengths the nucleus is known to be variable on time-scales of a few minutes to years (Morini, Anselmo & Molteni 1989). In the radio it is variable at all wavelengths down to about 3 mm, where changes occur on a time-scale of days (Kellermann 1974). HEA report a 15 per cent change at both 1.3 and 2.0 mm. Turner et al. (1992) report that the nucleus had decreased in flux density by a factor of 2.5 at 3.26 μm over a time-scale $\leqslant 5$ yr. They argue that observing any variability at K will be difficult as the contribution to the total flux from starlight is a major, if not dominant, contributor to the brightness at K (in a 2.52-arcsec aperture).

Joy et al. (1991) reported the existence of a linear infrared (IR) structure to the north-east of the nucleus, 10 arcsec in extent, which they interpreted as an IR jet, as its location and position angle are the same as the radio and X-ray jets. However, as the jet is quite blue it cannot be produced, at least directly, by synchrotron emission from a beam of relativistic electrons.

In order to investigate further the origin of the nuclear polarization of Cen A, and to establish the nature of the IR jet, we have obtained high-resolution polarization images of the nuclear region of Cen A, made in the near-infrared, and aperture polarimetry at 800 and 1100 μm. These observations and the instrumentation we used are described in the next section of this paper, and our results are presented in Section 3. The implications of our results are analysed and discussed in Sections 4 to 6. Finally, our conclusions are presented in Section 7. In the rest of the paper the term *central source* refers to the power source at the centre of the galaxy, and the terms *nucleus/nuclear* refer to the position of the peak emission at near-IR wavelengths.

2 OBSERVATIONS

The near-IR observations were made using a new infrared imaging polarimeter constructed by the University of Hertfordshire for the Anglo-Australian Telescope. The polarimeter consists of a half-wave retarder, achromatic between 1.0 and 2.5 μm, which can be stepped to set angular positions. This is placed upstream of IRIS, the observatory's near infrared camera (Gillingham & Lankshear 1990), in which a magnesium fluoride Wollaston prism is used as an analyser. The prism is placed in the collimated beam of the camera. A focal plane mask (within IRIS) serves to blank out half the field so that the e- and o-rays from the Wollaston prism do not overlap when imaging extended objects. For linear polarization observations exposures are made with the half-wave retarder stepped to 0°, 22°.5, 45° and 67°.5. The telescope is then moved so that the other half of the field can be imaged.

The polarization images of a region 76 by 76 arcsec, centred on the nucleus of Cen A, were made at the *f*/15 focus of the AAT on the nights of 1993 May 15 and 1994 July 24. Images were taken in the *J*, *H* and K_n (2.0–2.32 μm) bands. 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 in Whittet et al. (1992). Instrumental polarization, determined by observing unpolarized standard stars, was <0.06 per cent.

The images were each flat-fielded, sky-subtracted and then cleaned by interpolating over dead pixels and cosmic rays. Next, the images were shifted by fractional amounts in order to account for slight image drift between frames, and then polarization images were constructed, using recently added software to the Starlink TSP package (Bailey 1992). Finally, the individual polarization maps were co-added in order to increase the signal-to-noise ratio.

The millimetre observations were made on the 15-m James Clerk Maxwell Telescope at Mauna Kea, Hawaii, on 1993 February 24 and 25, under relatively poor weather conditions, and on 1994 Jan 4–7, under very good conditions. The polarimetry was performed using the observatory polarimeter (Flett & Murray 1991) and the single-channel bolometer UKT14 (Duncan et al. 1990) with a chopping secondary. Filters at 1100 and 800 μm were used (1100 μm only for the first set of observations) with apertures of 19 and 15 arcsec respectively. The chopping throw was 90 arcsec. The instrumental polarization was carefully determined by measuring the polarization of Mars and Jupiter, and subtracted from the measured polarizations of Cen A. The polarization efficiency in each of the two bands is 100 per cent.

3 RESULTS

Polarization images at *J*, *H* and K_n, for the central 20 by 10 arcsec are presented in Figs 1, 2 and 3 respectively. Outside the nuclear region, the degrees of polarization at *J* and *H* are typically ~ 1 per cent, and the position angles of polarization lie generally along the dust lane (position angle $\sim 115°$), although there is a significant twisting or warping of the polarization vectors along the lane. As noted in Hough et al. (1987), the degree of polarization at optical wavelengths arising from interstellar polarization within our Galaxy is about 0.5 per cent; in the near-infrared the degrees of polarization will be less, and thus insignificant compared with the observed polarization of Cen A.

The polarization at *J* and *H* is most likely to arise from dichroic absorption of radiation from star formation regions

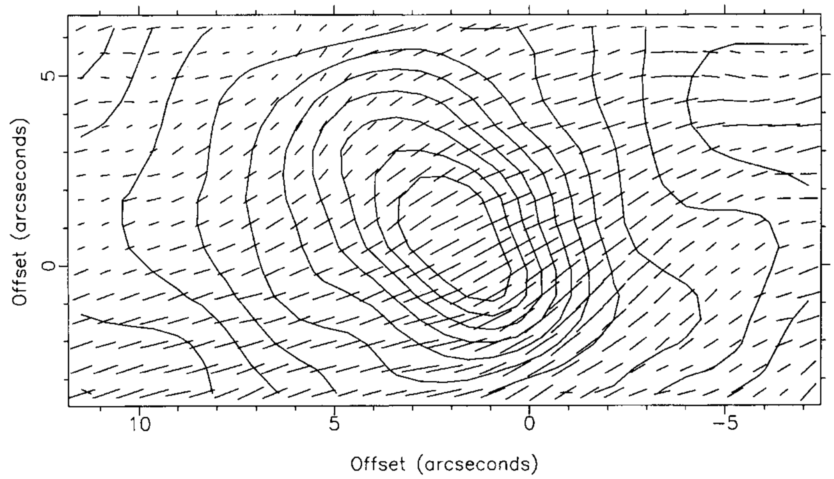

Figure 1. Polarization image of the central 20 by 10 arcsec in the J band. The zero of coordinates corresponds to the position of the nucleus of Cen A in the K_n band. 1.8 arcsec corresponds to 10 per cent polarization.

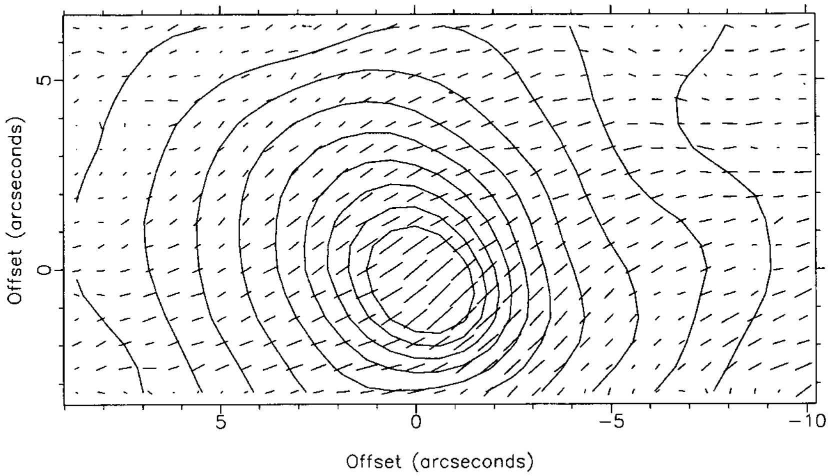

Figure 2. As in Fig. 1, for the H band.

embedded in the dust lane, with the central source not prominent at these shorter wavelengths. From polarization observations of the supernova (1986G) in Cen A, Hough et al. (1987) showed that the wavelength dependence of polarization in the optical and near-infrared is consistent with the standard form of interstellar polarization in our Galaxy, assumed to arise from the passage of starlight through a medium of elongated grains aligned by the interstellar magnetic field. Thus, as in our galaxy, the $\boldsymbol{E}$-vectors show the direction of the magnetic field in the dust lane, projected on to the plane of the sky. This interpretation of the large-scale polarization structure is in good agreement with the results of imaging polarimetry in the R and I bands obtained with the *HST* (Schreier et al. 1995). A more detailed analysis of the non-nuclear polarizations is the subject of a later paper.

At K_n the degrees of polarization along the dust lane are less, as would be expected for interstellar-type polarization. However, in the central few arcseconds there is an additional component, with a larger degree of polarization (5.4 per cent in a 2.25-arcsec aperture) and at a larger position angle (142°).

Fig. 4 shows a grey-scale image at J which clearly shows the 'infrared jet' extending to the north-east, as first identified by Joy et al. (1991).

The polarizations of the nucleus of Cen A at 1100 and 800 μm were measured to be (0.12 ± 0.20) per cent and (0.89 ± 0.46) per cent, respectively, for the 1994 observations, with the errors calculated from the spread in a large number of separate observations. The results indicate that at these wavelengths the nucleus of Cen A is unpolarized. The earlier 1993 observations gave a polarization of (0.36 ± 0.33) per cent at 1100 μm, again consistent with a zero polarization.

4 ANALYSIS

4.1 The nuclear near-IR flux density of Cen A

The K_n image clearly shows an additional nuclear contribution, presumed to arise from the central source,

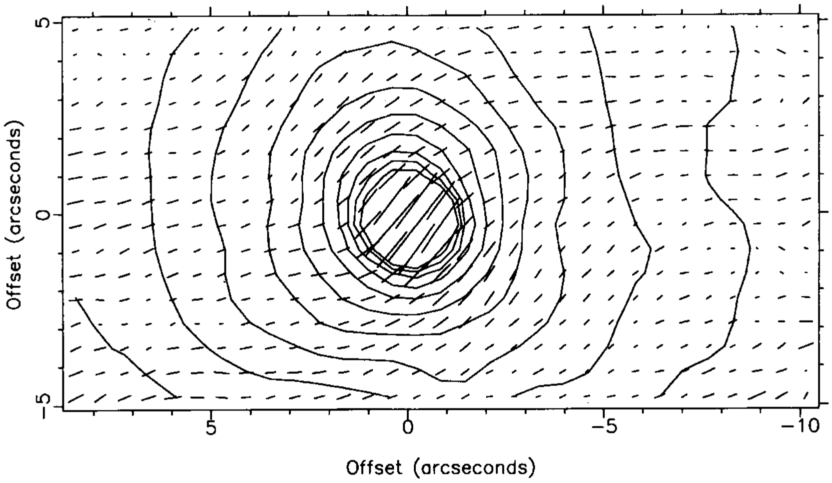

Figure 3. As in Fig. 1, for the K_n band.

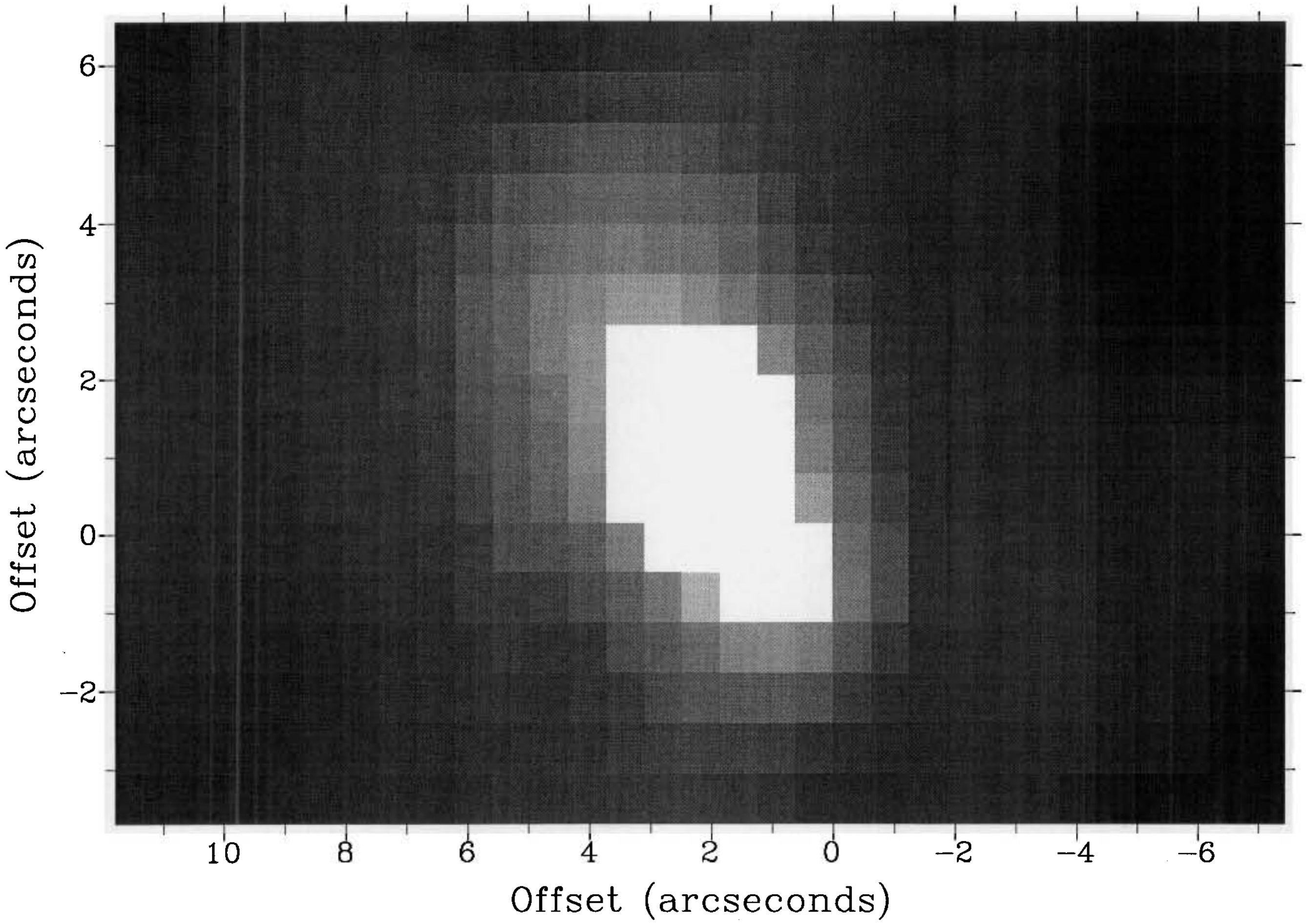

Figure 4. Grey-scale image at J of the central 20 by 10 arcsec.

superimposed on the diffuse emission from stars. To calculate its contribution we have followed the analysis of Turner et al. (1992) and taken cuts in H and K_n, along lines of constant $(J-H)$ colour, presumed to be lines of constant extinction, through the nucleus. An estimate of the point spread function (psf) was made from measurements of the star 15.21 arcsec south and 56.25 arcsec west of the nucleus. It was then assumed that the radial dependence of starlight is the same for K_n and H, and that the cut through the nucleus at K_n is composed of this starlight and the psf. Fig. 5 shows the one-dimensional surface brightness profiles at H and K_n, and the combined psf and H profile, matched to

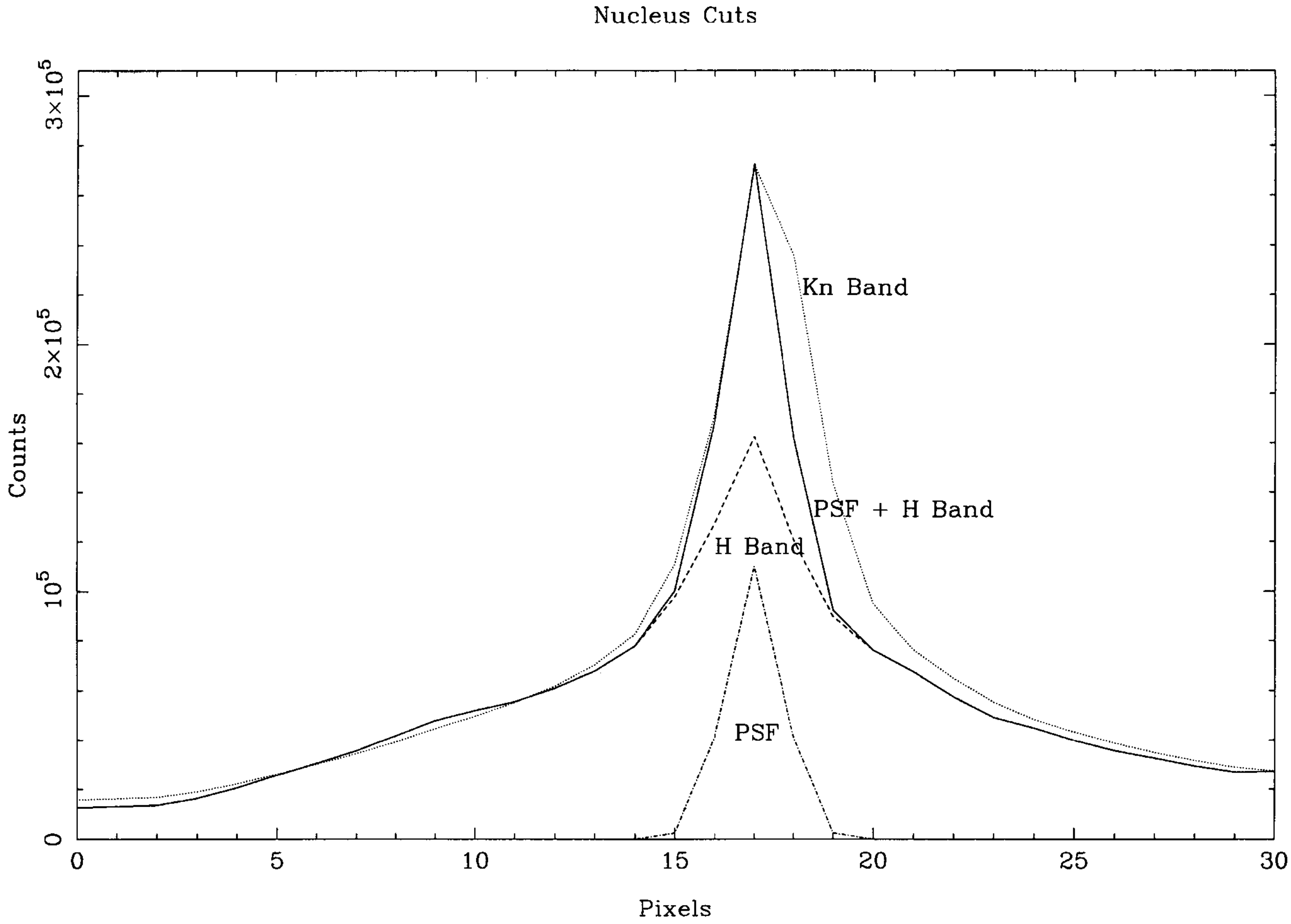

Figure 5. One-dimensional surface brightness profiles at H and K_n, and the combined psf and H profile, matched to the profile at K_n. 1 pixel corresponds to 0.6 arcsec.

the profile at K_n. Although the additional component makes a contribution to the total flux observed in the H band (see Section 5.3), it is not sufficient to significantly affect the above analysis.

In this way we calculate that the contribution from the central source to the total observed flux, in a 2.4-arcsec aperture, is ~ 30 per cent (with an estimated error of ~ 5 per cent). This is in excellent agreement with the value of 23 per cent in a 2.25-arcsec aperture calculated by Turner et al. (1992). Table 1 shows the observed J, H and K_n magnitudes for a number of different apertures measured at the position of the nucleus, as defined by the peak of the K_n flux density. The errors are derived from the spread of several observations. Transformation of the observed K_n magnitudes to the standard K band, using the known passbands of the filters and the spectral energy distributions of Cen A and the standard stars, gives K magnitudes which are ~ 0.09 mag brighter than at K_n.

We suspect that the differences in the J and H magnitudes, which are dominated by starlight, between the present data and that of Bailey et al. (1986) arise from incomplete sky subtraction for the latter, with the 'sky' also containing a contribution from the galaxy. Also, at J the peak brightness is not coincident with the peak brightness at K_n, and hence photometric comparisons at J require care to ensure that the measurements are taken at the same position in the galaxy.

The possibility of any variability of the central source, which might be observed at K_n is considered in Sections 4.2 and 5.3.1. However, at this point we note that seeing will affect the K_n photometry in small apertures, where there is a significant contribution from the central source.

4.2 The nuclear near-IR polarization of Cen A

Table 2 shows the nuclear polarizations for different aperture sizes, with the errors calculated from the spread of the results from several observations, together with the values of Bailey et al. (1986). Any differences in polarization between that observed in the K_n filter and in a standard K filter, arising from differences in starlight dilution, are negligible. At J and H the polarizations are dependent on aperture, but far less so than at K_n, and much of the aperture dependence, particularly at J, is likely to be caused by the warping of the position angles of polarization along the dust lane. Thus the nuclear polarizations at these wavelengths will be mainly produced by the passage of starlight through aligned grains in the dust lane, as suggested by Bailey et al. (1986), although, as shown in Section 5.3, a small contribution from the central source is likely at H.

Table 1. The observed *J, H* and K_n magnitudes for five different aperture sizes.

J BAND MAGNITUDES

Aperture arcsec	Bailey et al 26 June, 1985	Turner et al 9 February, 1992	Present Data 5 May, 1993
2.25	12.60	---	11.95±0.01
2.52	---	12.07	11.87±0.01
3.57	---	11.32	11.49±0.01
4.5	11.48	---	11.15±0.01
5.04	---	10.69	10.97±0.01

H BAND MAGNITUDES

Aperture arcsec	Bailey et al 26 June, 1985	Turner et al 9 February, 1992	Present Data 5 May, 1993
2.25	10.96	---	10.41±0.03
2.52	---	10.53	10.34±0.03
3.57	---	9.83	10.03±0.02
4.5	9.95	---	9.74±0.01
5.04	---	9.22	9.57±0.01

K_n BAND MAGNITUDES

Aperture arcsec	Bailey et al 26 June, 1985	Turner et al 9 Feb, 1992	Present Data 5 May, 1993	Present Data 24 Jul., 1994
2.25	9.60	---	9.48±0.01	9.67±0.03
2.52	---	9.61	9.43±0.01	9.57±0.03
3.57	---	9.04	9.10±0.01	9.17±0.02
4.5	8.98	---	8.83±0.01	8.88±0.02
5.04	---	8.53	8.68±0.01	8.73±0.02

Table 2. Nuclear polarizations for different aperture sizes.

J BAND POLARIZATIONS

Aperture	Bailey et al 1985		Present Data 5 May 1993		Present Data 24 July 1994	
	Pol. (%)	P.A. (°)	Pol (%)	P.A. (°)	Pol (%)	P.A. (°)
2.25	4.94±0.42	123.9±2.3	3.57±0.07	123.5±1.4	3.61±0.18	128.5±1.95
4.5	4.43±0.14	119.3±1.2	3.12±0.06	120.3±0.7	3.25±0.11	122.6±1.64
8.0	2.99±0.14	118.4±0.8	2.53±0.03	118.7±0.6	2.50±0.09	118.4±1.09

H BAND POLARIZATIONS

Aperture	Bailey et al 1985		Present Data 5 May 1993		Present Data 24 July 1994	
	Pol. (%)	P.A. (°)	Pol (%)	P.A. (°)	Pol (%)	P.A. (°)
2.25	4.63±0.20	136.4±1.3	2.28±0.13	122.6±1.5	3.45±0.27	129.7±4.36
4.5	2.80±0.08	128.6±0.8	1.99±0.01	123.5±1.5	2.33±0.14	124.1±1.71
8.0	1.94±0.06	124.9±0.8	1.49±0.03	121.8±2.4	1.74±0.07	121.7±1.05

K_n BAND POLARIZATIONS

Aperture	Bailey et al 1985		Present Data 5 May 1993		Present Data 24 July 1994	
	Pol. (%)	P.A. (°)	Pol (%)	P.A. (°)	Pol (%)	P.A. (°)
2.25	6.63±0.14	144.8±0.3	3.70±0.18	140.26±0.52	5.43±0.10	142.16±0.35
4.5	4.22±0.10	144.4±1.4	2.82±0.07	137.85±0.23	3.26±0.02	138.70±0.13
8.0	2.39±0.11	139.6±1.5	1.75±0.04	134.15±0.28	1.97±0.01	135.09±0.16

At K_n the additional component of polarization can be clearly seen with the polarization in a 2.25-arcsec much higher than that at *J* or *H*, and with a position angle of polarization significantly different to that in the dust lane.

The observed K_n polarization can be corrected for dilution by starlight (see Section 4.1), and for the contribution from polarization produced by aligned grains in the dust lane in the following way. To determine the contribution from the dust lane, the *J*-band polarization in an 8.0-arcsec aperture was taken, centred on the nucleus, as a measure of

Table 3. The results of our poor-seeing simulations, performed in an attempt to compensate for the seeing differences between 1993 May and 1994 July.

Date	Gaussian Filter	Width of Central Peak (pixels)	Polarization (%)	Position Angle (°)
5 May, 1993	None	3.73	3.70±0.18	140.26±0.52
24 Jul., 1994	None	~1.5	5.43±0.10	142.16±0.35
24 Jul., 1994	2 FWHM	2.08	4.91±0.09	141.33±0.15
24 Jul., 1994	3 FWHM	3.98	4.39±0.07	140.71±0.15
24 Jul., 1994	4 FWHM	5.94	3.89±0.05	140.02±0.15
24 Jul., 1994	5 FWHM	7.77	3.45±0.03	139.29±0.16

the interstellar polarization at that wavelength (2.50 per cent: this is likely to be an underestimate, as not all the starlight will pass through the full depth of the dust lane; however, even if the interstellar contribution is doubled it has only a small effect on the results of the calculation). Using the Serkowski formula (Serkowski 1973), and a value of λ_{max} of 0.43 μm (Hough et al. 1987), the interstellar polarization at K_n is calculated to be 0.39 per cent, at a position angle of 115° (the corresponding value at H is 1.2 per cent). Knowing from Section 4.1 that the central source contributes 30 per cent of the flux in a 2.25-arcsec aperture we calculate that the central source has an intrinsic polarization of 17 per cent at a position angle of 144°, which is perpendicular to the inner radio and X-ray jet of Cen A.

From Table 2 it would appear that the polarization at K_n has varied between the observations made in 1993 May, 1994 July and in 1985 June. However, the measured degree of polarization will depend on the seeing, and it is clear that there is a far better agreement between the 1993 May and 1994 July data for the 4.5- and 8.0-arcsec apertures, consistent with the seeing causing less of a problem in the larger apertures. Certainly the seeing was quite different between the two sets of observations, with the seeing in 1993 May being much worse than that in 1994 July (see Table 3). We have therefore attempted to match our two data sets by simulating poor seeing. This was achieved by convolving the 1994 July data with Gaussian filters of different widths, and then recalculating the polarization, with the results shown in Table 3.

As can be seen, to obtain good agreement for the polarization data taken in 1993 May and 1994 July, the simulated seeing for the more recent data has to significantly exceed the actual seeing of the earlier data. With the same seeing, the polarization for 1993 May and 1994 July are (3.70 ± 0.18) and (4.40 ± 0.07) per cent, respectively. Whilst the difference is significant, the formal errors do not take into account uncertainties in simulating the poor seeing, and thus the results are not conclusive. We further consider variability in Section 5.3.1.

5 DISCUSSION

There are three possible mechanisms which may explain the nuclear polarization of Cen A at K: directly observed synchrotron emission from a blazar, as originally proposed by Bailey et al. (1986), or the dichroic absorption or the scattering of radiation from a central source, which could still of course be a BL Lac object.

5.1 Synchrotron emission from a blazar

Bailey et al. (1986) interpreted the nuclear polarized emission as synchrotron radiation from a BL Lac object with a magnetic field parallel to the inner ratio and X-ray jet. However, for most BL Lacs, where a preferred position angle of polarization can be identified, the optical and infrared polarization is parallel (i.e. magnetic fields perpendicular) to the VLBI radio position angle (Impey, Lawrence & Tapia 1991; Smith et al. 1987). Another characteristic of BL Lacs is their variability on different time-scales. Whilst there does appear to be some evidence of variability in the degree of polarization in Cen A (see Section 5.3.1), as yet it is not conclusive because of the very small number of observations made to date.

While the calculated intrinsic polarization of the central source in the near-infrared (17 per cent) is certainly consistent with that of BL Lacs (although we show below in Section 5.3 that we are unlikely to be observing the central source directly at these wavelengths) the millimetre polarization is not. Typically, the polarization of BL Lacs (and more generally blazars) at 1100 μm is 5 per cent, with some sources, such as 3C279 and OJ287 reaching 10–15 per cent (Gear, private communication), and if the near-IR polarization of 17 per cent is the intrinsic polarization of a BL Lac then a polarization of at least several per cent would be expected at $\sim$1000 μm. Even one of the least polarized sources at 1100 μm, 3C273, has a polarization which is always larger than $\sim$1 per cent whereas we have observed no polarization for Cen A.

HEA observe a very flat spectrum for the nucleus of Cen A from a wavelength of 2000 μm down to 800 μm, and possibly to 350 μm, and they suggest that the nuclear flux, even in a 10-arcsec aperture, is dominated by non-thermal emission. The zero polarization at $\sim$1000 μm appears to be even more of a problem. As we will argue in Section 5.3, even if the near-IR polarization is most likely to be caused by scattering, with the central source obscured from direct view by very high extinction, this in itself does not preclude the central source from being a 'misdirected' BL Lac, and at millimetre wavelengths the central source should be observed directly. As noted in Section 1 there is a large body of evidence for high nuclear activity associated with the central source, and the HEA data would indicate the central source is indeed non-thermal in nature, and therefore most likely to be intrinsically polarized.

A further consideration is that for a BL Lac viewed pole-on, the blazar radiation is likely to be highly blue-shifted, and thus the millimetre polarimetry observed for Cen A (assuming a jet viewed at a large angle to the line of sight) should really be compared with the longer wavelength polarization of BL Lac objects (e.g. centimetre wavelengths for an assumed Doppler shift of 10). Saikia, Swarup & Kodali (1985) found, from a sample of 20 BL Lacs, that the median value of polarization at a wavelength of 6 cm was 2.7 per cent. While this polarization is significantly less than that at shorter wavelengths, there would still appear to be a problem in explaining the zero polarization observed for Cen A at ~ 1000 μm.

We propose two explanations for the zero polarization at millimetre wavelengths. First, the interpretation of the flat spectrum as being entirely non-thermal is incorrect. In fact the spectrum of HEA is unusually flat, with a spectral index α of ~ 0.0 ($F_\nu \sim \nu^{-\alpha}$) from 2000 to 800 μm, whereas a spectral index of 0.8 is more typical for synchrotron sources at wavelengths shorter than about 3000 μm (Impey & Neugebauer 1988). Also, the variability at 1100 μm reported by HEA is not high for a non-thermal source (probably less than 15 per cent), although observations at these wavelengths are relatively sparse. Thus there is the possibility that other sources of radiation contribute to the flux at ~ 1000 μm, although HEA suggest that there is no significant contribution from free–free emission or dust emission. In principle, it should be relatively easy to significantly reduce the observed degrees of polarization for a BL Lac type object viewed at a large angle to the jet, as is suggested to be the case for Cen A. Although the intrinsic degrees of polarization will be the same, the Doppler boosting of the polarized flux will be much lower along our line of sight, and thus dilution of the polarization from other emission processes within the galaxy could be large.

Secondly, the luminosity of Cen A at submillimetre wavelengths is very low compared to normal blazars (HEA). While some of this low luminosity could result from the large angle between the (supposed) BL Lac jet and the line of sight, it could also imply an intrinsically low luminosity (see Section 5.3.2), and it is possible that low-luminosity BL Lacs have lower degrees of polarization. For example, BL Lac itself had its lowest recorded optical polarization (4.5 per cent) while in a historical low state (Corbett et al. 1995). The low state corresponds to a reduction in the beamed emission, and the low polarization could result from a less ordered magnetic field in the jet caused by a reduced number of shocks being driven down the jet. Thus it might be possible for the flat spectrum to be that of a non-thermal source while the polarization of the source is low.

5.2 Dichroic absorption

There is strong evidence for a circumnuclear torus around the nucleus of Cen A that has its symmetry axis parallel to the inner radio and X-ray jet (HEA, and references therein). The total extinction to the nucleus, however, is uncertain. The X-ray emission is almost certainly nuclear, extending out to energies of about 1 MeV, and is highly variable (Morini, Anselmo & Molteni 1989). The same authors give a column density $N_{\rm H}$ of $\sim 1.5 \times 10^{23}$ cm^{-2}, which converts to an A_v of 70 mag assuming that a standard dust-to-gas ratio of $A_v = 4.5 \times 10^{-22} N_{\rm H}$ applies (Blanco, Ward & Wright 1990). Turner et al. (1992), re-examining extinction estimates from the depth of the 9.7-μm silicate absorption feature estimate A_v as between 38 and 55 mag. We note that the warm dust foreground of sources can often cause an underestimate of the extinction to the source from 10-μm observations, and thus we take an A_v of at least 50 mag as the most likely total visual extinction to the central source.

With an A_v of 50 mag to the central source, it should be possible to produce the nuclear polarization at $K_{\rm n}$ by dichroism, as proposed by Young et al. (1995) for NGC 1068. For example, the polarization to the centre of our Galaxy, $A_v = 30$ mag (Becklin et al. 1978), is 6.4 per cent at K (Bailey, Hough & Axon 1983), and therefore a polarization of 5.4 per cent is not inconsistent with an A_v of over 50 mag for Cen A, although it would mean that the efficiency of grain alignment or the polarizing efficiency of the grains is less than that found along the line of sight to the Galactic Centre.

If the polarization in the near-IR arises from dichroism then it might be expected that polarization would be seen in emission from aligned grains at millimetre wavelengths. For a K polarization of 5.4 per cent and an A_v of 50 mag, the polarization expected in emission, assuming the same grain conditions, is given by $P_{\rm e} \sim P_K/\tau$ (Hildebrand 1988) or ~ 1 per cent, much higher than the observed polarization. However, if the flux at 1100 μm is dominated by the (unpolarized) non-thermal source (see Section 5.1), then polarization produced by emission from aligned grains should not be observable.

While the above discussion would suggest that dichroism is a plausible mechanism for producing the K polarization of the nucleus, we will show in the next section that this is unlikely to be the case.

5.3 Scattering

In order to examine the case for scattering, we first look again at the estimate of the extinction to the central source, by comparing a reddened power-law source ($F_\nu \propto \nu^{-\alpha}$) and starlight, with the observed nuclear flux density at J, H, K (see Section 4.1) and at L. In order to have near-IR data (at different wavelengths), taken at the same time, we have used the observations of Turner et al. (1992), although the differences between Turner et al. and the present data sets at J and H are minimal. The contribution from starlight at the different wavelengths was determined by using the nuclear bulge of M31 as a template (Coleman, Wu & Weedman 1980) and constraining the contribution from the central source at $K_{\rm n}$ to be 30 per cent (in a 2.4-arcsec aperture). The starlight contribution at J and H, calculated in this way, actually exceeds the observed flux by 290 per cent at J and 144 per cent at H. This problem can easily be overcome by reddening the starlight, as would be expected, as the stars are embedded in the dust lane.

The model thus consists of a power law, reddened by a local extinction $A_v(1)$, perhaps arising from an obscuring torus, and $A_v(2)$, arising from the dust lane, together with reddened starlight [whose extinction is $A_v(2)$], with the latter contributing 70 per cent at $K_{\rm n}$ (see Section 4.1). Assuming a power-law spectral index of $\alpha = 1.3$, typical of blazars in the near-IR (Smith et al. 1987) and also of Seyfert I nuclei (McAlary & Rieke 1988), and the reddening law of

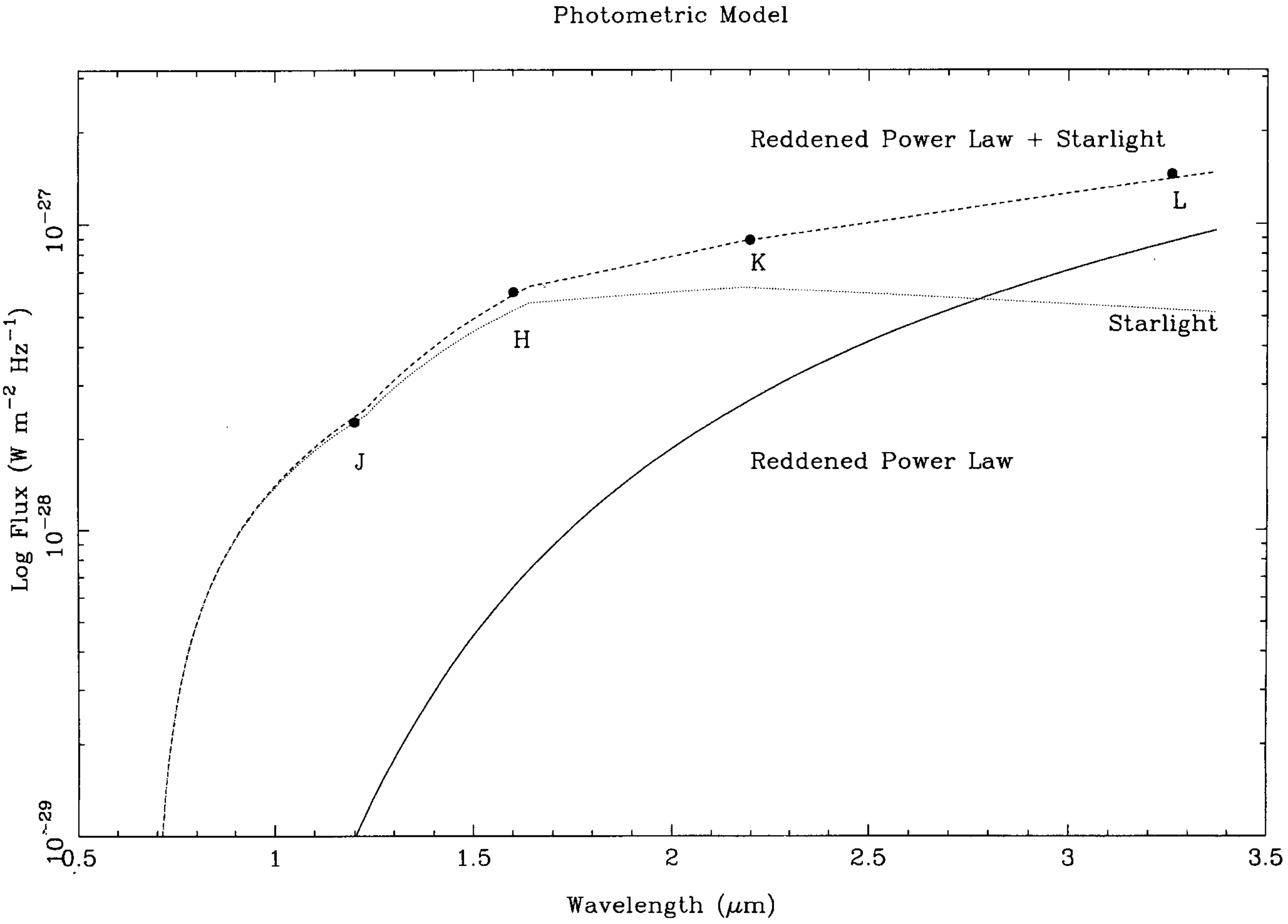

Figure 6. Model fit to the observed flux densities. For model details, see Section 5.3.

Landini et al. (1984), a good fit to the *J, H,* K_n and *L* observed flux densities is obtained with $A_v(1) = 9$ mag and $A_v(2) = 7$ mag (see Fig. 6). Different power laws can be equally well fitted with, for example, an $A_v(1)$ of 20 mag for $\alpha = 0.7$ and an $A_v(1)$ of 5 mag for $\alpha = 2.0$. As a spectral index of 0.7 is much flatter than that typically observed (Smith et al. 1987; McAlary & Rieke 1988) we can take 20 mag as an upper limit for $A_v(1)$, and 9 mag as the most likely value.

The value of $A_v(2) = 7$ mag, for the reddening of the starlight in the dust lane, agrees well with the A_v of (3.8 ± 0.6) mag calculated for the supernova SN1986G (Hough et al. 1987), especially as such observations are unlikely to measure the extinction through the whole of the dust lane. The total extinction to the central source $[A_v(1) + A_v(2) = 16$ mag], however, is substantially less than the 50 mag, or more, suggested in Section 5.2. If an A_v of 50 mag is used then the power law of the central source would have to be inverted, in order to get any reasonable fit to the data. If we assume that the observed *L* flux density has a contribution from hot dust, then the calculated A_v (for an α of 1.3) will be even lower than the 9 mag we calculated above, making it even harder to reconcile the difference between this value and the proposed 50 mag.

We suggest that the only way to explain the apparent discrepancies between A_v and the central source is to assume that the observed K_n nuclear flux from this central source arises entirely from scattering and that it is the scattered component which is seen through an A_v of ~ 16 mag. In the near-infrared the central source is not seen directly and dichroism alone cannot be responsible for producing the polarization (see previous section).

A polarization of 17 per cent in the near-infrared is quite easily produced by scattering, assuming that the scatterers are electrons, or small dust grains. For example, assuming that the scattering takes place in a cone-like geometry, filled with scatterers, then a polarization of 17 per cent is consistent with a cone axis inclined at 33° to our line of sight, with a cone half-opening angle of about 20° (Young et al. 1995).

From our model, the contribution at *H* due to the central source in a 2.25-arcsec aperture is ~ 10 per cent (see Fig. 6). Assuming the same intrinsic polarization of 17 per cent at *H*, and with an interstellar polarization contribution of 1.3 per cent (see Section 4.2), we expect an observed polarization at *H* of about 2.6 per cent at a position angle of $\sim 135°$, which is comparable with the measured values of (3.5 ± 0.3) per cent at $(130 \pm 4)°$.

Of course, the radiation that is scattered towards us could arise from a jet associated with a BL Lac object at the centre of Cen A. While electrons will also scatter millimetre radiation, the resulting polarized flux will be substantially diluted by the direct view of the central source at these wavelengths, giving low degrees of polarization.

5.3.1 Variability

If the central source of Cen A is variable then the amount of scattered light, and thus the observed degrees of polarization, will also vary. Taking a 30 per cent contribution from the central source, in a 2.25-arcsec aperture, and an intrinsic polarization of 17 per cent, a change in source luminosity of ± 30 per cent will lead to a change in observed polarization of ± 1 per cent, but only a change of ± 0.1 mag in the luminosity. The data at three different epochs do show what appear to be significant changes in the degrees of polarization. However, the measurements of Bailey et al. (1986) used an aperture polarimeter, whereas the two sets of observations reported here used an imaging polarimeter. The present data sets clearly show that different seeing conditions can produce marked changes in the measured degrees of polarization, since the flux contribution from the central source, even in a small aperture of 2.25 arcsec, accounts for only 30 per cent of the total flux (see Section 4.2). Although our correction of the polarization for the poor seeing of 1993 May does suggest that there is a difference in polarization between that date and 1994 July, we believe that far more observations are required before variability at IR wavelengths can be confirmed. With the availability of high-accuracy IR imaging polarimeters such a series of observations ought now to be made.

5.3.2 Source luminosity

Taking the distance of Cen A as 3.1 Mpc (Tonry & Schechter 1990), we calculate the luminosity at 2.2 μm as $\sim 2 \times 10^{43}$ erg s^{-1}. This is calculated from the measured K_n flux of the nucleus in a 2.25-arcsec aperture (with 30 per cent of that flux coming from the central source), assumes that 1 per cent of the radiation from the central source is scattered to us by electrons, and is viewed through a total visual extinction of ~ 16 mag. We have found, from the modelling of a number of obscured type I Seyfert galaxies, that 1 per cent is typically the fraction of light, from the obscured source, scattered to us (Young et al. 1995). If we are seeing scattered light from a relativistically beamed BL Lac, then we should be measuring, albeit indirectly, the power of that beam. If so, the luminosity is ~ 100 times than that of BL Lac [2.2-μm luminosity $= 2.5 \times 10^{45}$ erg s^{-1} (Impey & Neugebauer 1988)], which is similar to the factor of 200 for the BL Lac-to-Cen A luminosity ratio for hard X-rays (Morini, Anselmo & Molteni 1989). Thus the IR and X-ray luminosities are not inconsistent with Cen A containing a low-luminosity BL Lac.

6 THE INFRARED JET

We see no evidence for any enhanced polarization associated with the infrared jet. Thus it is unlikely that the blue colour of the jet (observed spectral index $\alpha = +1.3$, $F_\nu \propto \nu^\alpha$, Joy et al. 1991) can be produced by (dust) scattering. Also, as noted by Joy et al. (1991), the blue colours are inconsistent with a synchrotron spectrum, and this would be supported by the lack of any intrinsic polarization. The most likely explanation is that we are observing free–free emission from gas shocked and heated by the jet of Cen A. A similar conclusion has been reached on the basis of *HST* imaging polarimetry at optical wavelengths (Schreier et al. 1995). Recently, extended continuum – directly associated with the radio jets of a number of Seyfert galaxies – has been found, e.g. Mrk 3 (Capetti et al. 1995), and it is thought that this is a result of free–free radiation from a cocoon of shocked and heated interstellar medium around the jet.

7 CONCLUSIONS

We have used near-infrared imaging polarimetry and millimetre polarimetry of the nucleus of Cen A to construct a model in which the central source is seen only through scattered light at near-infrared wavelengths, with a likely extinction of ~ 16 mag along the of sight to the scattering region. We note that with this level of extinction any broad lines present, which might be scattered to us, will only be observed using infrared rather than optical spectropolarimetry. The relatively high extinction suffered by the scattered light, if common, has important consequences for the detection of obscured BLRs in polarized flux, since most spectropolarimetry to date, for both radio-quiet and radio-loud narrow-line galaxies, has been at optical wavelengths. We calculate that the intrinsic polarization, produced by scattering of radiation from the central source, is 17 per cent. The luminosity of the central source at 2.2 μm is estimated to be 2×10^{43} erg s^{-1}, ~ 100 times lower than that of BL Lac itself, approximately the same factor as at X-ray wavelengths. If the millimetre radiation is dominated by non-thermal emission, the absence of any polarization at these wavelengths is unexpected, although we suggest that low polarizations might well be associated with low-luminosity sources.

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