THE ASTROPHYSICAL JOURNAL, 512:L91–L94, 1999 February 20
© 1999. The American Astronomical Society. All rights reserved. Printed in U.S.A.

AN EDGE-BRIGHTENED BICONE IN THE NUCLEAR REGIONS OF CYGNUS A

C. N. TADHUNTER,[1] C. PACKHAM,[2] D. J. AXON,[3] N. J. JACKSON,[3] J. H. HOUGH,[4] A. ROBINSON,[4]
S. YOUNG,[4] AND W. SPARKS[5]

Received 1998 October 26; accepted 1998 December 16; published 1999 January 14

ABSTRACT

Infrared-imaging observations that span the wavelength range of 0.8–2.35 μm have been obtained for the archetypal powerful radio galaxy Cygnus A using the Near-Infrared Camera and Multiobject Spectrograph on board the *Hubble Space Telescope*. At 2.25 μm, the images are dominated by the presence of a nuclear point source (FWHM < 0.″21), whose flux is a factor of ~4 times less than the limits deduced from previous ground-based studies. The observations also reveal an edge-brightened biconical structure centered on the point source, which is strikingly similar to those observed around young stellar objects. The high polarization and orientation of the bicone relative to the radio axis lead us to conclude that it is an illuminated structure, while the edge brightening 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. A further implication of our observations is that not all of the anisotropy in the nuclear radiation field is caused by extinction on a scale less than 100 pc in the torus; some of the anisotropy must be generated by absorption and scattering in the dust lane on a 1 kpc scale.

Subject headings: galaxies: active — galaxies: individual (3C 405) — galaxies: nuclei — infrared: galaxies

1. INTRODUCTION

The extragalactic radio source Cygnus A holds a unique position in the study of powerful radio galaxies: one of the first radio sources to be optically identified (Baade & Minkowski 1954), it is the most powerful extragalactic radio source in the local universe and the only nearby radio galaxy to have a power comparable to those at high redshifts ($z > 0.5$).

In recent years, Cygnus A has been studied extensively across the electromagnetic spectrum (see Carilli & Barthel 1996 for review). A major theme of many of these studies has been to use Cygnus A to test the anisotropy-based unified schemes in which quasars and radio galaxies are deemed to be the same objects viewed from different directions, with the quasar nuclei in radio galaxies hidden from our direct view by a central obscuring torus (see, e.g., Barthel 1989). The hidden quasar hypothesis is supported in the case of Cygnus A by the detection of an ionization cone in long-slit spectra (Tadhunter, Metz, & Robinson 1994) and narrowband images (Jackson, Tadhunter, & Sparks 1998), by the detection of an obscured hard X-ray source (Ueno et al. 1994), and, most impressively, by the clear detection by Ogle et al. (1997) of scattered quasar features in spectropolarimetry observations of the large-scale optical reflection nebulosity (Tadhunter, Scarrott, & Rolph 1990).

More controversial in its relevance to the unified schemes is the detection of a compact nuclear source at infrared wavelengths. Imaging observations presented by Djorgovski et al. (1991) show a clear progression from the double structure originally detected by Baade & Minkowski (1954) at optical wavelengths (0.55 μm) to a compact nuclear source at infrared wavelengths (3.7 μm). Djorgovski et al. interpreted the compact nuclear source in terms of the quasar nucleus shining through the obscuring torus, which becomes less opaque at infrared wavelengths. Making assumptions about the spectral energy distribution (SED) of the quasar, they deduce an extinction through the torus of $36 < A_v < 70$.

Despite the suggestive nature of the detection of a compact nuclear source at infrared wavelengths, the interpretation of this source in terms of a direct view of the quasar nucleus has recently been called into question: first, it has been recognized that contamination of the core source by starlight, emission lines, and hot dust emission from the torus may be significant (Simpson 1995; Stockton & Ridgway 1996); second, high-resolution ground-based imaging observations have provided evidence that the infrared core source is resolved in the K' band (FWHM ~ 0.″3; Stockton, Ridgway, & Lilly 1994); and third, Packham et al. (1998) have found the nucleus to be highly polarized in the K band—a possible sign that the nuclear source represents a near-nuclear reflection nebulosity rather than the quasar shining through the torus, although these authors favor a dichroic origin for the nuclear polarization.

In this Letter, we present new diffraction-limited infrared-imaging observations of Cygnus A that were made with the Near-Infrared Imaging Camera and Multiobject Spectrograph (NICMOS; MacKenty et al. 1997) on the *Hubble Space Telescope* (*HST*). These observations have a direct bearing on the controversy surrounding the nature of the infrared core, and they provide important new information about the circumnuclear outflows and the causes of the radiation field anisotropy in this key source.

2. OBSERVATIONS AND RESULTS

The infrared-imaging observations were taken on 1997 December 15. The use of Camera 2 of NICMOS resulted in a pixel scale of 0.″075 and a total field of 19.″4 × 19.″4. Details of the filters, exposure times, and potential emission-line contamination are given in Table 1. For observations with the longer wavelength medium-band filters, regular chops were made to the offset fields in order to facilitate accurate background subtraction. The data were reduced using the standard

[1] Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, England, UK.
[2] Isaac Newton Group of Telescopes, Sea Level Office, Apartado de Correos 321, Santa Cruz de La Palma, Canary Islands, E-38780, Spain.
[3] Nuffield Radio Astronomy Laboratories, Jodrell Bank, University of Manchester, Cheshire, 5K11 9DL, England, UK.
[4] Division of Physics and Astronomy, Department of Physical Sciences, University of Hertfordshire, College Lane, Hatfield, Hertfordshire, AL10 9AB, England, UK.
[5] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

TABLE 1
DETAILS OF NICMOS IMAGING OBSERVATIONS FOR CYGNUS A

Filter	λ_0 (μm)	$\Delta\lambda$ (μm)	Total Exposure (s)	Contamination[a]
F110W	1.10	0.6	1344	He I
F160W	1.60	0.4	1344	[Fe II]
POL0L	2.00	0.2	14 × 192	Paα, H_2, [Si VI]
POL120L	2.00	0.2	14 × 192	Paα, H_2, [Si VI]
POL240L	2.00	0.2	14 × 192	Paα, H_2, [Si VI]
F222M	2.25	0.15	5 × 192	Brγ, H_2

[a] Potential emission-line contaminants.

pipeline reduction software (see, e.g., Kulkarni et al. 1998), and the data taken with the three long-wavelength polarization filters were co-added to form a deep 2.0 μm image.

The final co-added images—presented in Figure 1—show a striking change in the structures from the shorter to the longer infrared wavelengths. The changes follow the trend first noted by Djorgovski et al. (1991) toward increased dominance of the core at the longer wavelengths, but several important new details become apparent at the higher resolution of the NICMOS images.

At 1.1 μm, the IR images resemble the optical high-resolution images described by Jackson et al. (1998): the extended complexes 1.″2 to the northwest and 0.″5 to the southeast are relatively bright, and the effects of patchy dust obscuration by the kiloparsec-scale dust lane remain visible. However, by 2.25 μm, the images are dominated by a nuclear point source (FWHM < 0.″21), with the first Airy ring clearly detected. Note that the images are consistent with the conclusions of Stockton et al. (1994) in the sense that the nucleus is clearly resolved at 2.0 μm (covered by the Stockton et al. K' observations).

The flux in the nuclear point source at 2.25 μm was estimated using a trial and error subtraction of a point-spread function that was generated using the Tiny Tim software (Krist & Hook 1997). The best subtraction was obtained for a nuclear point-source flux of $F_{2.25\,\mu\mathrm{m}} = (4.9 \pm 1.0) \times 10^{-31}$ W m^{-2} Hz^{-1}. The fact that this is ~4 times smaller than the nuclear flux estimated on the basis of the K-band photometry of Djorgovski et al. (1991) is likely to reflect a greater degree of contamination of the lower resolution Djorgovski et al. data by starlight and illuminated structures close to the nucleus. In estimating this flux, we have assumed that the point source at 2.25 μm is dominated by continuum light, whereas the degree of emission-line contamination remains to be established. Thus, the flux represents an upper limit on the true continuum flux of the point source at this wavelength.

An intriguing feature of the NICMOS images is the subarcsecond-scale biconical structure centered on the nucleus, which is most clearly detected in the 2.0 μm image (Fig. 1, *bottom left*). One-half of the bicone—comprising the sharp V-shaped structure on the northwest side of the nucleus—is visible in shorter wavelength optical and infrared images, whereas the other (southeast) half only becomes prominent relative to the extended structures at the longer infrared wavelengths. The improved visibility of the southeast cone at longer wavelengths is consistent with the idea that the near-nuclear structures to the southeast suffer greater extinction than those to the northwest (see also Fosbury et al. 1998). The opening angle of the bicone is 116° ± 8°, and its axis is aligned to within 15° of the axes of both the large-scale radio jets and the emission-line cones visible in the optical images. The fact that the V shapes persist to the longer infrared wavelengths shows that they are genuinely edge-brightened structures rather than filled cones that are extinguished along the cone axes by patchy dust obscuration associated with the dust lane. Detailed analysis of the polarization of the core structure will be presented elsewhere (Tadhunter et al. 1998), but it is clear from a simple comparison of the three long-wavelength polarization filter images that the bicone is highly polarized at a level of several tens of percent. Thus, it is likely that the bicone represents an illuminated structure—an inner reflection nebulosity.

3. DISCUSSION

3.1. *The Nuclear Point Source*

Our observations provide the first unambiguous detection of a nuclear point source at infrared wavelengths in Cygnus A. Nuclear point sources have also been detected with NICMOS in the much lower power radio galaxies: IC 5063 (Kulkarni et al. 1998) and Centaurus A (Schreier et al. 1998). However, in none of these cases is the nature of the nuclear point source understood with any certainty.

If we assume that the point source represents the quasar nucleus "shining through" the obscuring torus, we can place limits on the extinction to the nucleus. From the tight correlation between near-IR and hard X-ray fluxes for quasars, and the measured hard X-ray flux of Arnaud et al. (1987), Ward et al. (1991) have estimated an intrinsic flux for the active galactic nucleus of Cygnus A at 2.2 μm of 5.8×10^{-28} W m^{-2} Hz^{-1}. Comparing this with our upper limit on the core flux at 2.25 μm, we derive an extinction to the nucleus of $A_k = 7.7$ mag, corresponding to $A_v = 94$ mag. Assuming that the intrinsic shape of the quasar SED is a power law ($F_\nu \propto \nu^{-\alpha}$), a further estimate of the extinction can be obtained by comparing our 2.25 μm flux with the 3.7 μm flux of Djorgovski et al. (1991), as corrected for stellar contamination by Simpson (1995). For $\alpha = 0.18$—corresponding to the spectral index obtained by fitting a power law to the high-frequency radio core data—we obtain $A_v = 85$ mag,[6] whereas for $\alpha = 1.5$—corresponding to a typical spectral index for a quasar SED in the infrared—we obtain $A_v = 70$ mag. These estimates are higher than many of the previous estimates of the nuclear extinction based on near-IR data, but they remain significantly lower than estimates based on fits to the X-ray spectrum by Ueno et al. (1994), who obtained $A_v = 170 \pm 30$.

One interpretation of the discrepancy between the X-ray and near-IR extinction estimates is that the X-ray extinction represents the true extinction to the quasar nucleus of Cygnus A, but that the point-source emission at 2.25 μm is dominated by the emission line and/or the hot dust emission from the near-nuclear regions (see, e.g., Stockton et al. 1994 and Kulkarni et al. 1998) rather than direct quasar continuum light.

3.2. *Outflows and Anisotropy in the Central Regions*

The edge-brightened bipolar structure is strikingly similar to the structures observed around young stellar objects (YSOs; see, e.g., Velusamy & Langer 1998). In the case of YSOs, the edge brightening is explained as a hollowing out of material from the circumstellar disk by an outflow driven along the rotation axis of the disk. We can envisage a similar scenario for the central regions of Cygnus A: the outflows that are driven by the central quasar will hollow out funnels on opposite sides of the nucleus in the kiloparsec-scale disk that is responsible

[6] We have used the extinction law of Landini et al. (1984), and we have assumed that the Galactic contribution to the extinction is negligible.

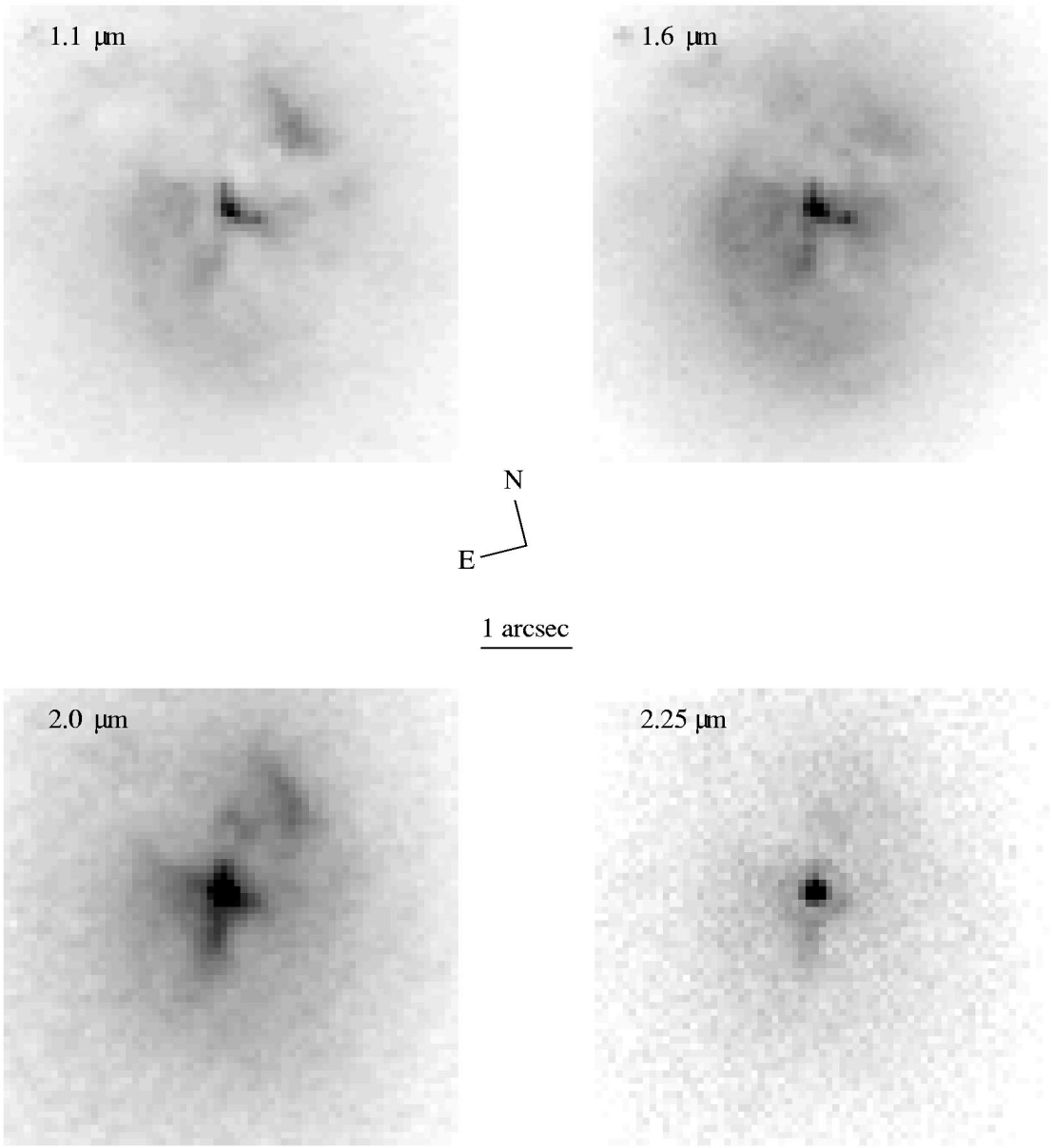

FIG. 1.—Co-added infrared images of Cygnus A: F110W image (1.1 μm) (*top left*); F160W image (1.6 μm) (*top right*); combined polarization filter image (2.0 μm) (*bottom left*); and F222M image (2.25 μm) (*bottom right*). At the redshift of Cygnus A, 1″.0 corresponds to 1.0 kpc for $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.0$.

for the dust lane; the lateral expansion of the outflows may also lead to a density enhancement in the walls of the funnel; and the structures are illuminated by the anisotropic radiation field of the quasar. In order for this scenario to work, the opening angles of the illumination cones produced by the parsec-scale torus surrounding the quasar must be larger than the opening angles of the funnel structures produced by the outflows, as illustrated in Figure 2.

The nature of the outflows that hollow out the funnels in Cygnus A is unclear. One possibility is that, as the plasma jets and lobes expanded out of the central regions of the galaxy in the early stages of the formation of the radio source, they swept aside material in the dust lane. The shape of the funnels then reflects the pressure gradient in the central regions of the galaxy at the time of the formation of the radio source. Alternatively, there may exist a radiation-driven wind that is associated with the nucleus, which sweeps material out of the central regions.

3.3. *Significance for the General Population of Radio Galaxies*

The fact that we see an illuminated, edge-brightened structure implies that the kiloparsec-scale dust lane must present a significant scattering/absorption optical depth to the quasar at 2.0 μm. If the scattering medium is dust, the optical depth will be even larger at shorter wavelengths, in the optical. Thus, at least some of the radiation field anisotropy in Cygnus A is likely to be caused by the kiloparsec-scale dust lane rather than in the less than 100 pc scale torus surrounding the nucleus. If the opening half-angle of the funnel hollowed out by the outflows is ϕ, the opening half-angle of the radiation cones caused by the torus is θ, and we view the object at an inclination angle i to the radio axis, then the quasar will appear partially obscured for inclinations in the range $\phi < i < \theta$. We speculate that the redder quasars in the sample of Baker (1997), and the classic

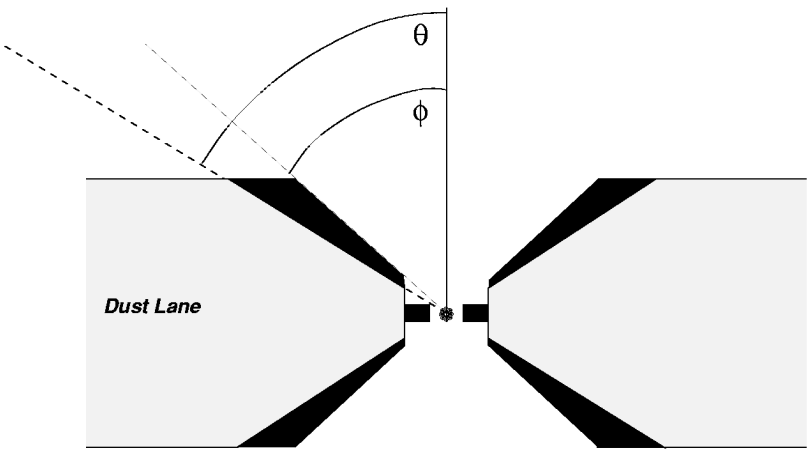

FIG. 2.—Schematic diagram showing a possible model for the edge-brightened bicone structure in Cygnus A: the outflows associated with the nuclear activity hollow out the funnels in the dust lane (funnel-opening half-angle, ϕ), the funnels are then illuminated by the radiation cones of the central quasar + obscuring torus (radiation cone–opening half-angle, θ). The illuminated regions are shaded black.

broad-line radio galaxies (Osterbrock, Koski, & Phillips 1976), which also show clear signs of reddening, are objects for which $\phi < i < \theta$. If this is the case, then the fraction of broad-line objects detected in a given sample of radio sources will depend on ϕ and θ, which in turn are likely to be related to the strength of the outflows and the power of the radio jets.

4. CONCLUSIONS AND FUTURE WORK

Our NICMOS observations of Cygnus A demonstrate the rich potential of high-resolution, near-IR observations for the study of powerful radio galaxies. In particular, they provide evidence that the structures in the central kiloparsecs of powerful radio galaxies are shaped as much by outflows in the near-nuclear regions as they are by the radiation cones of the central obscuring tori, and that at least some of the radiation field anisotropy is produced on a kiloparsec scale in the dust lane.

It is now important to follow up these observations with high-resolution infrared observations of a larger sample of powerful radio galaxies. Such data will yield valuable information on both the optical depths of the dust lanes and the polar diagrams of the illuminating radiation fields, thus leading to further refinement of the unified schemes for powerful radio galaxies.

The information in this Letter is based on observations made with the ESA/NASA *HST*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. A. Robinson acknowledges support from the Royal Society.

REFERENCES

Arnaud, K. A., Johnstone, R. M., Fabian, A. C., Crawford, C. S., Nulsen, P. E. J., Shafer, R. A., & Mushotsky, R. F. 1987, MNRAS, 227, 241
Baade, W., & Minkowski, R. 1954, ApJ, 119, 215
Baker, J. C. 1997, MNRAS, 286, 23
Barthel, P. D. 1989, ApJ, 336, 606
Carilli, C., & Barthel, P. D. 1996, A&A Rev., 7, 1
Djorgovski, S., Weir, N., Matthews, K., & Graham, J. R. 1991, ApJ, 372, L67
Fosbury, R. A. E., Vernet, J., Villar-Martin, M., Cohen, M. H., Ogle, P. M., Tran, H. D., & Hook, R. N. 1998, in Proc. Amsterdam Conf. on High-z Radio Galaxies, in press
Jackson, N., Tadhunter, C., & Sparks, B. 1998, MNRAS, in press
Krist, J. E., & Hook, R. 1997, Tiny Tim User Guide, Version 4.4 (Baltimore: STScI)
Kulkarni V. P., et al. 1998, ApJ, 492, L121
Landini, M., Natta, A., Oliva, E., Salinari, P., & Moorwood, A. F. M. 1984, A&A, 134, 284
MacKenty, J. W., et al. 1997, NICMOS Instrument Handbook, Version 2.0 (Baltimore: STScI)
Ogle, P. M., Cohen, M. H., Miller, J. S., Tran, H. D., Fosbury, R. A. E., & Goodrich, R. W. 1997, ApJ, 482, L37
Osterbrock, D. E., Koski, A. T., & Phillips, M. M. 1976, ApJ, 206, 898
Packham, C., Young, S., Hough, J. H., Tadhunter, C. N., & Axon, D. J. 1998, MNRAS, 297, 936
Schreier, E. J., et al. 1998, ApJ, 499, L43
Simpson, C. 1995, DPh thesis, Univ. Oxford
Stockton, A., & Ridgway, S. E. 1996, in Cygnus A—Study of a Radio Galaxy, ed. C. L. Carilli & D. E. Harris (Cambridge: Cambridge Univ. Press), 1
Stockton, A., Ridgway, S. E., & Lilly, S. 1994, AJ, 108, 414
Tadhunter, C. N., Metz, S., & Robinson, A. 1994, MNRAS, 268, 989
Tadhunter, C. N., Scarrott, S. M., & Rolph, C. D. 1990, MNRAS, 246, 163
Tadhunter, C. N., et al. 1998, in preparation
Ueno, S., Katsuji, K., Minoru, N., Yamauchi, S., & Ward, M. J. 1994, ApJ, 431, L1
Velusamy, T., & Langer, W. D. 1998, Nature, 392, 685
Ward, M. J., Blanco, P. R., Wilson, A. S., & Nishida, M. 1991, ApJ, 382, 115