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DISCOVERY OF AN INFRARED NUCLEUS IN CYGNUS A: AN OBSCURED QUASAR REVEALED?

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ABSTRACT

We report on the discovery of a compact, unresolved infrared nucleus, coincident with the radio core, in the prototypical powerful radio galaxy Cygnus A (3C 405). The infrared colors and magnitudes of the nucleus can be explained as a highly reddened extension of the radio continuum. The implied restframe extinction is $A_V \simeq 50 \pm 30$ magnitudes. The extinction-corrected luminosity of the object is in the quasar range. This discovery gives some support to the unification models for quasars and powerful radio galaxies.

Subject headings: galaxies: individual (Cygnus A) — infrared: sources — quasars — radio sources: general

1. INTRODUCTION

Cygnus A (3C 405) is an archetypical powerful radio galaxy, the most luminous radio source in this end of the universe. It has served for numerous studies of radio sources, and its large radio power, strong line emission, and peculiar morphology make it perhaps the best local analog of the powerful radio galaxies at large redshifts. Yet, ever since its identification by Baade & Minkowski (1954), there has been an ongoing debate about its nature, and the cause of its peculiar central two-lobe optical morphology: a merger of two galaxies, an object intersected by a dust lane, or a bipolar scattering nebula. As we shall argue, the truth may contain elements of all three explanations. Previous detailed studies of Cyg A including those by Kronberg, van den Bergh, & Button (1977), Osterbrock (1983), Wright & Birkinshaw (1984), Perley, Dreher, & Cowan (1984), Alexander, Brown, & Scott (1984), Pierce & Stockton (1986), Salter et al. (1989), and Tadhunter, Scarrott, & Rolph (1990), who give additional references.

One widely accepted model (Pierce & Stockton 1986) at present is that at least some of the optical central morphology is due to the scattering from a hidden nonthermal source, which can presumably be identified with the central radio core. This is also consistent with the interpretation of the optical spectra by Osterbrock & Miller (1975) and Osterbrock (1983), and is strongly supported by the polarimetric results by Tadhunter et al. (1990) (however, see Goodrich & Miller 1989). The X-ray spectrum of Cyg A also indicates the presence of a nonthermal component (Arnaud et al. 1987). Optical high-resolution imaging by Thompson (1984) revealed a hint of a compact component coincident with the radio core. We present here infrared images which clearly show the presence of a very red, unresolved infrared source coincident to better than 1″ with the radio core. A peliminary report was presented by Weir et al. (1990).

2. IMAGING AND PHOTOMETRY

The infrared images of Cyg A were obtained on UT 1989 August 20 with the *f*/70 Cassegrain IR camera (using an SBRC InSb array detector) at the Palomar 200 inch Hale telescope, giving the pixel scale of 0″.313. Standard infrared observing and calibration procedures were followed. Multiple images of Cyg A were obtained while moving it on the detector, in the *JHKL′* bands. Standard stars from Elias et al. (1982) were used for photometric calibration (their *L* band magnitudes were used to calibrate our *L′* images). Optical images were obtained on UT 1988 September 10 and UT 1989 September 07, using the 4-Shooter imager at the Palomar 200 inch telescope, with the pixel scale 0″.334. Multiple images in Gunn-Thuan *gri* bands were obtained, and standard stars from Kent (1985) were used for the magnitude calibrations. The weather was photometric throughout the observations, with the typical standard stars residuals at a level of 0.02 and 0.05 mag, and the seeing FWHM about 0″.6 and 0″.9 in the best images in the IR and optical, respectively.

Images of the object are shown in Figure 1. The optical images show the well known two-lobe structure, with the *g* and *r* images containing some line emission (stronger in the NW lobe), and the *i* image being dominated by the continuum. The IR images reveal an interesting trend: as the wavelength increases, the center becomes both rounder and sharper. What appears to be an unresolved source shows clearly in the *K* band, and in the *L′*, nothing but the point source is detected. This infrared nucleus is at the apparent center of the galaxy isophotes, and it coincides positionally to better than 1″ with the radio core (see Kronberg et al. 1977). Its very red color suggests that it is a highly obscured IR counterpart of the central radio source. A hint of a similar feature was already seen in the high-resolution red images by Thompson (1984).

The measurement of the *L′* magnitude of the object is straightforward, since the underlying galaxy is not even detected; we obtain $L'_{\rm nuc} = 12.05 \pm 0.4$. Other bands present a problem in deblending the unresolved nucleus from the peaked light of the galaxy. The surface brightness profiles show an almost flat core in the *J* band, and become unresolved in the *K*. We tried two approximate methods to estimate the contribution from the nucleus alone. In the first, we assume that within some radius, the underlying galaxy surface brightness can be assumed to be flat; everything above that level is assumed to be the signal from the nucleus. While at larger radii this method would always overestimate the brightness of the nucleus (since the starlight actually is peaked), at very small radii some light from the nucleus would be lost, because of the finite seeing.

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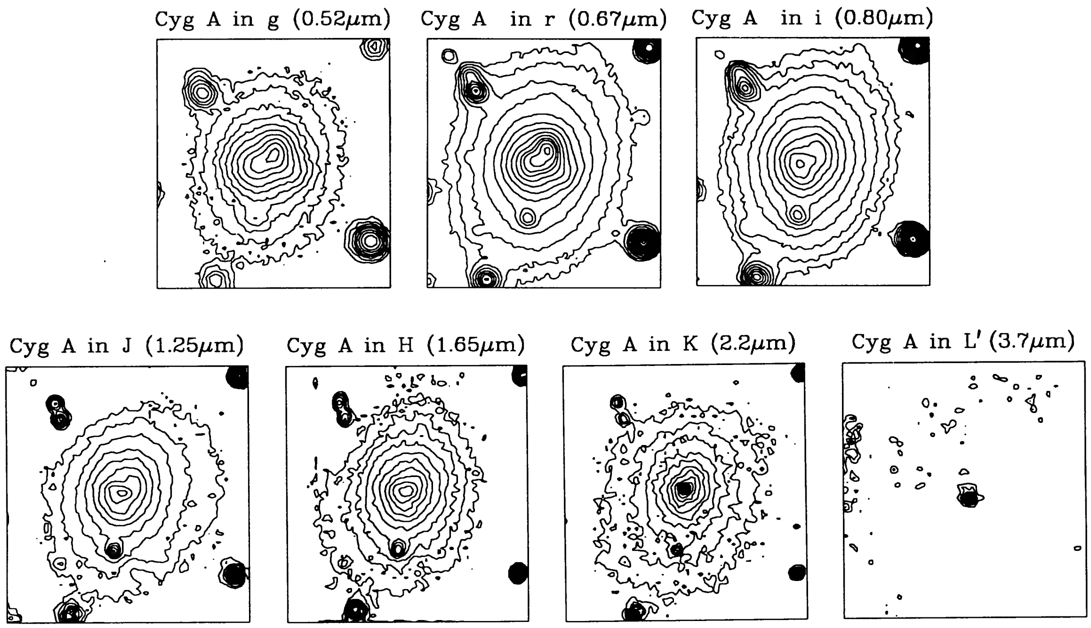

FIG. 1.—Images of Cyg A obtained at Palomar. *Top row:* sections of the 4-Shooter images; the field size is 18″.7 × 20″.0. *Bottom row:* co-added stacks of the IR images; the field size is 18″.2 × 19″.4. North is at the top, east is to the left. The contour spacing is approximately equidistant in log intensity. The *g* and *r* images contain line emission from [O III], and Hα, respectively. The central isophotes become rounder in the *H* band, and a (quasi?) stellar nucleus shows in the *K* band. The underlying galaxy is not even detected in the *L′*, and only the nucleus is seen.

After some experimentation, we decided that aperture radii between 1″ and 1″.5 give the best compromise values. In the second method, we assume that the nucleus is not present at the shortest wavelength (*J*), scale the *J* profile to match the profiles in the *H* or *K* at some intermediate radial range (about 2″ to 4″), and subtract it from the *H* or *K* profile. The residual signal in the center is then attributed to the nucleus. We think that this is a superior technique, and give it a higher weight. Our final estimates (weighted averages of the two methods) give for the nucleus: $K_{\rm nuc} = 16.2 \pm 0.5$, and $H_{\rm nuc} = 18.4 \pm 1.0$, not including any extinction corrections.

For comparison, the integrated magnitudes of the galaxy (mostly starlight, but including any possible nonthermal contributions) in the aperture of 3″ diameter (comparable to the effective apertures for the IR nucleus measurements) are: $g = 18.36 \pm 0.09$, $r = 17.56 \pm 0.10$, $i = 17.72 \pm 0.07$, $J = 15.46 \pm 0.06$, $H = 14.53 \pm 0.05$, $K = 13.78 \pm 0.06$. These values do not include the extinction corrections. It should be noted that the *g* and *r* bands includes the line emission of [O III] and Hα, respectively, and that the *K* band may also include some extended Brγ emission (in addition to the nucleus itself). The seeing differences make the optical magnitudes slightly too dim relative to the IR magnitudes. Our optical photometry is in a very good agreement with the photometry from van den Bergh (1976) in the corresponding apertures, assuming the typical color for brightest cluster galaxies $(g - V) \simeq 0.28$, and with the spectrophotometry from Osterbrock & Miller (1975).

3. EXTINCTION ESTIMATES

The key to the interpretation of the IR nucleus is the total line of sight extinction. The Galactic contribution is relatively modest: from the measurements by van den Bergh (1976) and Spinrad & Stauffer (1982), we estimate $A_V = 1.2 \pm 0.1$. In order to estimate the in situ extinction, we must consider the data on Cyg A obtained at other wavelengths. As a working hypothesis, we assume that the IR nucleus can be identified with the radio core.

Figure 2 shows our measurements, and a compilation of other data available in the literature. The radio spectrum shows a shallow turnover near 10 GHz, and at higher frequencies is well fitted by a power law, $S_\nu \sim \nu^{-0.18 \pm 0.03}$, with $S_{10\,\rm GHz} \simeq 1$ Jy. This power law diverges in energy at high frequencies, and in any case must turn over at some point due to the energy losses of high-energy electrons, but it probably presents a useful upper limit for the extrapolated flux at the IR wavelengths. An alternative and equally good fit to the radio data is a parabola in the log-log space, following Landau et al. (1986), and our best-fit parameters are in excellent agreement with the modes of the distributions found by Landau et al. (1986). We note that the total integrated energy under this spectrum does not provide enough power to support the observed FIR emission, and thus the parabolic fit probably provides a lower limit to the extrapolated IR fluxes. In the *KL′* region, the effective power-law slope implied by this spectrum is about -1.0.

We then estimate the total extinction in two ways. We use the interstellar extinction curve from Rieke & Lebofsky (1985), and take care to use the rest-frame wavelengths where necessary, and accounting for the foreground Galactic extinction. We use this solar-neighborhood extinction curve simply because nothing better is available; it should be remembered that the extinction law in a galaxy with a presumably different enrichment history, and in different physical conditions, i.e., near an active nucleus, may be somewhat different.

We convert magnitudes to fluxes assuming that $K = 0^m$ corresponds to 630 Jy, and that $L' = 0^m$ corresponds to 250 Jy (Johnson 1966; Neugebauer et al. 1987).

First, we consider our IR data alone. The observed color is $(K - L') = 4.15 \pm 0.9$. If the effective power-law index is -0.18, the intrinsic color is $(K - L') = 0.36$, the net reddening is $E_{K-L'} = 3.8 \pm 1.0$, and the implied extinction at the source is

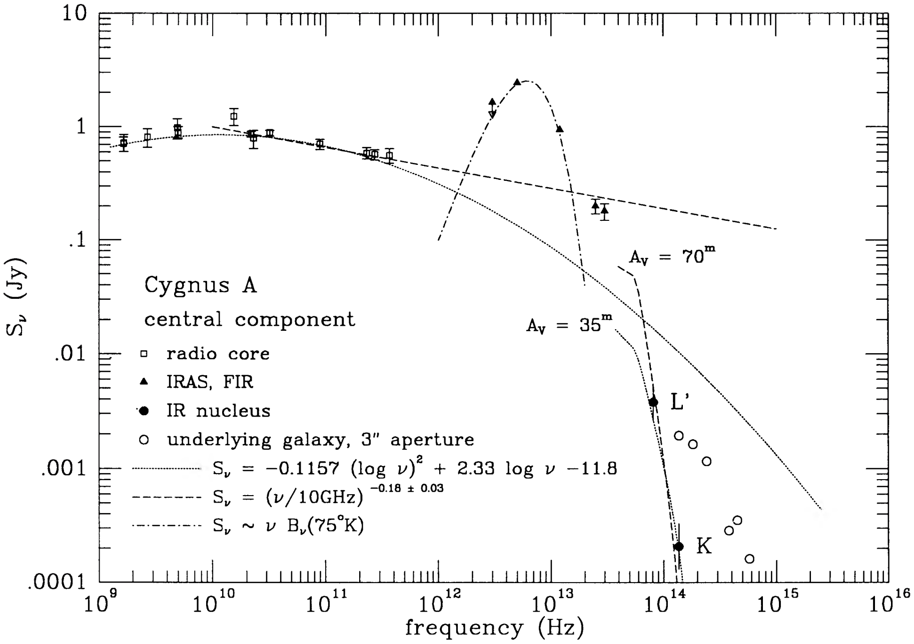

FIG. 2.—Spectral energy distribution for the central component of Cyg A. The radio data are taken from the compilations by Wright & Birkinshaw (1984), Alexander et al. (1984), Salter et al. (1989), and references therein. The *IRAS* data are from Knapp et al. (1990), and are supplemented with the 10 μm point from Rieke & Low (1972). The dot-dashed line is a gray body fit to the FIR data, after the estimated continuum subtraction; the dust emissivity index $n = 1$ was assumed. The dashed line is a power-law fit to the radio core continuum for $\nu > 10$ GHz, and the dotted line is the log-parabolic fit to all radio data with $\nu > 1$ GHz. The corresponding curves, filtered with the extinction as indicated, are the nearly vertical segments going through the KL' points. Solid and open circles are our own measurements.

$A_V = 56 \pm 15$ mag. If the effective power-law index is -1.0, the intrinsic color is $(K-L') = 1.55$, the net reddening is $E_{K-L'} = 2.6 \pm 1.0$, and the implied extinction at the source is $A_V = 38 \pm 15$ mag. Since the K band might contain some Brγ emission, the true extinction might be even higher.

Second, we simply use the observed L' magnitude, and the extrapolated radio spectra. For the power-law fit, we estimate the extinction $A_{L'} = 4.3 \pm 0.7$ mag in the observed frame, and $A_V = 83 \pm 13$ mag in the galaxy restframe. For the parabolic fit, we get $A_{L'} = 2.0 \pm 0.8$ mag (observed frame), and $A_V = 35 \pm 14$ mag in the rest frame.

Thus, in the power-law extrapolation we obtain $A_V \simeq 70 \pm 20$ mag, and in the parabolic extrapolation $A_V \simeq 36 \pm 15$ mag. We give slightly more credence to the latter, and conclude that the IR nucleus in Cyg A is seen through $\sim 50 \pm 30$ mag of visual extinction. To the best of our knowledge, this is the first direct measurement of the extinction towards an obscured active nucleus, possibly hidden by a circumnuclear torus.

We note that some contribution to the nuclear KL' flux may come from a possible hot dust component (this is *not* the cooler dust responsible for the FIR bump), but we have no way of checking for its presence with the data in hand. If such a component were present, the net extinction would have been higher.

4. DISCUSSION

Probably the simplest interpretation of our data is that we have detected an obscured active nucleus in Cyg A, which corresponds to the radio core, and is seen through $\sim 50^m$ of visual extinction. The implied IR extinction ($A_{L'} = 2.9 \pm 1.7$, $A_K = 5.6 \pm 3.3$ at the source) brings the IR luminosity of the object ($L'_0 = 9.1 \pm 2.1$, $K_0 = 10.5 \pm 3.8$) up to the range of the more luminous PG quasars at comparable redshifts (Sanders et al. 1989; Neugebauer 1990, private communication). Even without *any* extinction, the observed L' magnitude of the object is close to the lower luminosity PG quasars in this redshift range. Thus, taking into the account the independent evidence from polarimetry (Tadhunter et al. 1990), and optical and X-ray spectroscopy (Osterbrock 1983; Pierce & Stockton 1986; Arnaud et al. 1987), we conclude that the radio/IR nucleus of Cyg A is a quasar, seen along an obscured line of sight. Were we to observe this source from the direction along the radio axis, its brightness would likely be even higher. This discovery gives considerable support to at least some "grand unified schemes" for active galactic nuclei (Barthel 1989, and references therein).

Other powerful radio galaxies at low redshifts may harbor such hidden nuclei (e.g., 3C 465; De Robertis & Yee 1990). Lilly, Longair, & Miller (1985) detected an "excess" at 3.5 μm in several other low-redshift 3CR radio galaxies. There is accumulating evidence that many of the high-redshift 3CR galaxies also contain hidden nonthermal nuclei (Scarrott, Rolph, & Tadhunter 1990; McCarthy et al. 1990; Djorgovski et al. 1990).

Finally, we address the FIR excess in Cyg A (Golombek et al. 1988; Knapp, Bies, & van Gorkom 1990). After subtracting the interpolated estimated continuum from under the *IRAS* measurements, we obtain a fair fit for $T_{\rm dust} = 75$ K (in the observed frame), and the dust emissivity index $n = 1$ (as shown in Fig. 2). Such relatively high dust temperatures are often seen in quasars and Seyferts detected by *IRAS* (Soifer, Houck, & Neugebauer 1987, and references therein). The integrated luminosity in the FIR component is $L_{\rm FIR} \simeq 1.6 \times 10^{11} h_{100}^{-2}\ L_{\odot}$, which is approaching the range of ultraluminous *IRAS* sources. The implied dust mass for this temperature is $M_{\rm dust} \simeq$

$5.3 \times 10^5 h_{100}^{-2} M_{\odot}$. However, some fraction of the FIR flux may be from the powerful radio lobes, which would lower these estimates.

Mergers have been implied in triggering the activity of both powerful radio galaxies and quasars, perhaps with an intermediate, dusty, FIR–ultraluminous starburst phase (Sanders et al. 1988). It is possible that the nucleus of Cyg A is an example of such a recently born quasar, still shrouded in the remnants of its placental dust. This system also resembles Arp 220, where similar extinction to an active nucleus was implied (Graham et al. 1990).

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