HST observations of Cygnus A:  
circumnuclear effects of a powerful jet?

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Abstract. We present 340 nm continuum and [OIII] line images of the nuclear region of the radio galaxy Cygnus A at 0′′.1 resolution. At this high resolution the northwestern of the two nuclear components is resolved into two separate, line emitting subcomponents, and the radio jet points accurately between them. This suggests that the radio jet has blasted a path through emission-line clouds, and that the emission line clouds, having cooled after the passage of the shock, are being photoionized by a (presumably hidden) central source or by the shock itself. We confirm previous detections of a small component at a location corresponding to the radio nuclear position and discuss the evidence for a possible bifurcation of the emission region on the unseen “counterjet” side.

Key words: galaxies: active – galaxies: individual: Cygnus A – galaxies: jets – galaxies:nuclei

1. Introduction

Cygnus A is a radio galaxy at a redshift of 0.0567 (Spinrad & Stauffer 1982). Despite its relative closeness, it strongly resembles very distant (z≥1) objects in radio, optical and X-ray luminosity and in radio morphology. It therefore provides an ideal opportunity to study the phenomenon of high–power radio galaxies at a factor of 20 higher spatial resolution than we would otherwise be able to achieve.

Within the central few arcseconds of Cygnus A there lies a double optical object: the northwestern component radiates relatively more intense emission lines and the southeastern component stronger continuum emission (van den Bergh 1976). Early explanations for this double structure suggested that it represented the merger between two galaxies (Baade & Minkowski 1954) or that it was an effect produced by a central dust lane similar to that in the nearby active galaxy Centaurus A (e.g. Osterbrock & Miller 1975; Osterbrock 1983). Thompson (1984) rejected the dust lane hypothesis because his images of the nuclear region showed a central component located between the two brighter emission regions. He commented that “Cygnus A shows only a cursory resemblance to Centaurus A” and that “the double nucleus is, most likely, a true physical double rather than an illusion caused by dust”. In addition, Pierce & Stockton (1986) found a north–south reddening gradient and commented that their reddening distribution tended towards inconsistency with that of Cen A, although they did not investigate the reddening distribution across the central region corresponding to the proposed dust lane. They suggested that a scattering process produces much of the observed continuum emission. This was supported by the discovery (Djorgovski et al. 1991; Ward et al. 1991) of a mid–infra–red component at the nuclear position whose inferred optical obscuration is A_V ≈ 50, and also by the discovery (Tadhunter et al. 1991) of 2% continuum polarization in the extended optical emission and the southeastern blob, whose E–vectors lie perpendicular to lines of sight from the nucleus. Both observations suggest the existence of a nucleus which is not directly visible in the optical.

The distribution of absorption within the source, however, is still controversial and the dust lane model is certainly not ruled out (but see also Vestergaard & Barthel 1993, hereafter VB, for a contrary argument). In particular, the reddening distribution between the two components requires more detailed investigation at high resolution. However, if the dust lane idea is accepted we are left with the problem of the central component seen by Thompson (1984) and VB. It would have to lie on the near surface of the dust region, been seen along an unobscured line of sight through the dust lane, or else be intrinsically extremely luminous to penetrate the high optical depth.

Tadhunter et al.’s interpretation of the polarization, that at least some of the extended continuum is scattered radiation from an active nucleus, is also not universally accepted and it has been claimed (Goodrich & Miller 1989) that at least some of the polarized emission is due to foreground effects such as polarization.

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of starlight by aligned grains in our galaxy or the host galaxy of Cygnus A. The idea that more than one polarizing mechanism is at work finds support in a recent spectropolarimetry study (Jackson & Tadhunter 1993) in which no polarized broad line is found. Such a broad line would be expected if the polarization in this radio galaxy were due entirely to scattering of a hidden quasar (Scheuer 1987; Peacock 1987; Barthel 1989).

The picture is further complicated by the discovery (Tadhunter 1991) that the spectrum of Cygnus A contains a high-velocity, separate peak in the [OIII] lines, which is probably spatially separated from the continuum source. Tadhunter (1991) interpreted this as a moving component, possibly within or near to the radio jet. Any successful model of Cygnus A, the prototype high-power radio galaxy, must thus involve several distinct emission components spatially separated from each other by no more than 1 kpc, which corresponds to about 1'' ($H_0=75\text{ km s}^{-1}\text{Mpc}^{-1}$).

Imaging studies at a resolution considerably better than the separation between the two major optical components are clearly needed in order to clarify the situation. After the 0''65 resolution image of Thompson (1984), Carilli et al. (1989) and Baum et al. (1989) imaged the central region in lines and continuum: Hα and [NiII] emitting filaments were found out to a distance of about 10 kpc from the nucleus. Two high–quality recent ground based images have been presented by Stockton (1993) using the CFHT and by VB using the Nordic Optical Telescope on La Palma, both based on imaging taken in subarcsecond seeing. Here we present an image of Cygnus A with a resolution of 0''2, with the aim of clarifying the structure of...
the object. The image was taken with the Faint Object Camera (FOC, Paresce 1990) on the Hubble Space Telescope (HST).

2. Observations

The observations were taken using the f/96 configuration of the FOC on 1991 July 4 using the F342W and F372M filters. These filters have central wavelengths of 340 nm and 370 nm, and the latter filter included the redshifted [OII] emission line. The parameters of the observations are summarized in Table 1. Images at shorter wavelengths were also taken with the aim of spatially resolving the Lyα and CIV emission and investigating the distribution of the UV continuum, but no signal is visible on any of them despite heavy smoothing. This is not unexpected because galactic extinction at such a low galactic latitude (6°) has been estimated as E(B−V)=0.35 (van den Bergh 1976; Spinrad & Stauffer 1982). The images were processed by the standard data reduction "pipeline" to apply flatfields and correct for geometric distortion in the camera. Point spread functions for the appropriate wavelengths were obtained from the p.s.f. library, and removal of sky background and bright lines along the edge of the data frame was performed for both p.s.f. and object frames.

Figure 1a shows the 340 nm (continuum only) frame, Fig. 1b the 370 nm frame and Fig. 1c the continuum−subtracted [OIII] image. These images have all been deconvolved from the raw frames using 10 iterations of the Richardson−Lucy deconvolution algorithm. Use of more than 10 iterations was found to give unacceptable residuals and artefacts in the sky.

To obtain information about the spatial distribution of the [OIII] 372.7 nm emission the F372M image was subtracted from the F342W image, and the [OIII] image was multiplied by a factor of 3.1 to account for the fact that the [OIII] line lies on the red edge of the filter passband where the sensitivity is lower than the nominal sensitivity. In the subtraction of the continuum images, the assumption has been made that the flux of the continuum varies as $F(\lambda) \propto \lambda^0$ close to a wavelength of ≈350 nm (e.g. Osterbrock & Miller 1975). Before subtraction, the two images were shifted with respect to each other to minimize the area of negative regions in the subtracted frame. The small errors introduced in this procedure do not affect the appearance of the final line image appreciably. The above image processing was done using a combination of the NOAO/STScI IRAF/STSDAS and NRAO AIPS packages.

3. Results

The large scale morphology of the optical emission in our image resembles that seen previously in ground−based images. There are peaks in the optical emission corresponding to the NW emission−line component and the SE continuum component. There is also a central “blob” corresponding to the feature visible in the V and R−band optical images of VB. Both of the major components appear to be spatially extended in a direction roughly perpendicular to the axis of the radio jet, which lies at PA≈285°.

The HST images presented here reveal for the first time that each of the major components contain a number of separate subcomponents. The northwestern component, which lies on the same side of the source as the VLBI and arcsecond−scale radio
jet (Perley et al. 1984; Carilli et al. 1989, 1991a), is particularly interesting. Our 340 nm image shows that it is really double, and consists of two subcomponents about 0\textquoteleft 8 apart: this is not apparent on ground based images, the best of which were taken in ~0\textquoteleft 8 seeing, although hints of the structure can be seen on the VB image. The northern of the two subcomponents is the more prominent in [OIII]. Figure 2a shows a slice through the northwestern component along a position angle of 26\textdegree, roughly perpendicular to the radio jet, and it can be seen that a ~0\textquoteleft 5 wide channel is visible which cuts through the centre of this component.

Is this channel a void between two clouds which lie either side of it along a line in the sky plane, or is it the projection of a doughnut-shaped structure around the radio jet? A regular doughnut structure with a ratio of outer to inner radius \( r \) produces a central depression of \( \sqrt{(r-1)/(r+1)} \) of the peak flux. Our estimate of this quantity from Fig. 2a is about 1/3, so the doughnut would need to be thin in order to reproduce the observed profile. A more sensitive HST exposure would help in this regard.

A faint bar connects the southern side of the northwest component to the northern side of the southeastern component. In the middle of this bar we find, as do VB, a component at almost the same position as the radio nucleus: 19\textdegree59\textsec28.344\textsec, 40\textdegree44\textsec 2\textsec25 (J2000.0) although this is subject to pointing uncertainties of a few tenths of an arcsecond. This is close to the nuclear radio position (Carilli & Perley, private communication to VB) of 19\textdegree59\textsec28.348\textsec, 40\textdegree44\textsec 02\textsec17 (see Sect. 4.3). Moreover, Thompson (1984) finds that the central optical knot is coincident to an accuracy of 0\textquoteleft 2 with the radio nucleus. If we assume that either of these positions correspond to the nucleus, and overlay the 0\textquoteleft 4 resolution radio image\footnote{This image was extracted from the CD-ROM “Images of the Radio Universe”, available from the U.S. National Radio Astronomy Observatory} of Perley et al. 1984, we find in both cases that \textit{the radio jet lies between the two northwestern subcomponents, along the channel of lower optical brightness} (Fig. 3) which separates the two northwestern subcomponents. The first radio knot visible to the VLA, Perley et al.’s knot 2, occupies a hollow at the outer edge of the two optical subcomponents. Between the optical subcomponents lies the inter-knot space between the major radio features visible on this angular scale: the core and knot 2.

Table 2 shows the measured fluxes of the components, corrected by the factor of 3.1 in the case of the [OIII] image. The fluxes were derived using the PHOTFLAM keywords in the file headers and are subject to errors of ~25\%. The central (C) component corresponds to the object identified by VB as the nucleus. The northwest and southeast components are divided into northern and southern parts. It can be seen that by far the greatest ratio of line to continuum emission is displayed by the northern of the two subcomponents within the northwestern component (NW:N) and by the central component.

In some objects, most notably NGC 5252 (Tadhunter & Tsvetanov 1989) the extended line emission appears cone-shaped, suggesting that photoionizing radiation escapes from the central object along an unobscured range of solid angle. This may also be the case in Cygnus A, but the resemblance of the extended optical emission to a cone is not compelling.

4. Discussion

4.1. Models for extended line and continuum emission

Several explanations have been proposed for extended optical emission in radio galaxies. In the case of extended line emission there are often strong indications that interaction with radio plasma is exciting the line emitting gas (see Whittle 1989 for a review). In 3C120, for example (Axon et al. 1989) the [OIII] line is double on each side of the nucleus, indicating that the gas is being pushed to either side of the radio jet. The standard interpretation is that the gas, as it expands away from the radio jet and cools, is photoionized by the central object. In 3C277.3
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4.2. Comparison of the HST image with models

4.2.1. Pure jet/ISM interaction model

The new data make it quite clear that the radio and optical emission are not co-spatial. A detailed correspondence between radio and optical data would support models involving in situ radio jet induced star formation: this has been argued, for example, from HST observations of 4C41.17 (Miley et al. 1993) in which the optical emission appears to bend around a corner at the same place as the radio emission does. These models depend on the timescale for star formation being short enough that the radio structure has not moved during the star formation timescale, or that the synchrotron lifetime is long enough that radio emission is still observed at the interaction point. In the case of the present Cygnus A data, however, such a model is not strongly supported.

4.2.2. Pure reflection model

Another possible picture is the "pure reflection model". In this model, the continuum emission is due to the reflected light of a nuclear continuum source and the line emission is due to photoionization of ISM clouds within a cone defined by the unobscured solid angle of this photoionizing source. In this case, the optical line emission traces the ionization cone of the central ionizing source, convolved with the distribution of gas clouds which provide the scattering material. One would need to explain our inner channels by postulating that the radio jet has, during its passage, cleared material that could scatter the nuclear light away from the inner part of the cone solid angle.

4.2.3. Application to Cygnus A

Given the bright line emission immediately around the radio jet, it seems likely that an interaction took place in the past around the Perley et al. knot 2, about 1.′′ from the nucleus. The lack of optical emission along the position angle of the radio jet suggests it has created a hole in the surrounding gas, may have driven shocks into it and may possibly have been bent slightly in the process (see Fig. 3 and Perley et al. 1984). The gas, as it cools, condenses from the ambient density, estimated from X-ray observations as 0.02 cm$^{-3}$ at 10 kpc (Arnaud et al. 1984) and probably a little more at 1 kpc, into clouds of density 400 cm$^{-3}$ (estimated from Osterbrock & Miller's 1975 [SII] $\lambda 6717/\lambda 6731$ line ratio combined with Fig. 5.3 of Osterbrock 1989: see also Pedlar et al. 1985, 1989; Taylor et al. 1989 for exposition and applications of this model to Seyfert galaxies).

In the case of Cygnus A, this model is constrained by the time taken for the gas to cool to the temperature required to emit emission lines ($\sim 10^{4}$ K), which is given by (Whittle et al. 1986)

$$t_c < 1.7 \times 10^5 (4n)^{-1} V_s^2 \text{sec}$$

where $n$ is the density of the ambient medium and $V_s$ is the speed of the shock driven into the ambient material. The number is a lower limit because the active nucleus may hinder the cooling process by reheating the gas (see Whittle et al. 1986), although this may not be true under all circumstances (e.g. Forbes et al. 1990; Fabian & Crawford 1990). Using the value for the density of Arnaud et al., we obtain an upper limit of

$$V_s < (1.4 \times 10^3 d_{pc})^{1/4}$$

where $d$ is the distance that the shock has propagated perpendicular to the radio jet since the collision. Since the emission line region extends about 0.′′7 $\approx 700$ pc from the collision site, the shock speed is $\leq 320$ kms$^{-1}$. It follows that the time since the first interaction is $> 2.6$ Myr: assuming that the jet has constant speed out to the lobes, the core–lobe distance of $\sim 70$ kpc then implies a hotspot advance speed of $< 0.1 c$ (cf Roland et al. 1988).

Tadhunter (1991) found a blueshifted [OIII] emission line peak with a separation of up to 1800 kms$^{-1}$ from the main line. We remark that, because the [OIII] systemic wavelength is on the
red edge of our passband, we would be very much more sensitive to blueshifted [OII] emission than to [OIII] at the systemic velocity. It is therefore possible that the region responsible for the blueshifted [OII] is concentrated in the northern of the two northwestern subcomponents, which is the stronger in our [OIII] image, and that its motion is a result of the interaction with the radio jet.

4.3. Where is the nucleus?

VB claim that their line images show a central line–emitting "nucleus" which consists of that part of the central AGN which protrudes from the ~50 mag obscuration provided by the presumed torus of dust. In such a model (e.g. Scheuer 1987; Peacock 1987; Barthel 1989) the radio galaxy contains a hidden broad–line quasar nucleus, which we cannot see due to obscuration by a dusty torus. The size of the central component is small enough in the HST image that any obscuring torus is probably <150pc across.

We do see some emission in the continuum image at the nuclear position, although a considerable amount of line emission is also present. It is difficult, however, to rule out contamination by [NeV] λ3426 in our continuum image at this position: although it is weak in the integrated spectrum of the source (Osterbrock 1983) it would be expected to be stronger in the high–ionization conditions prevailing so close to the central ionizing source, although the details depend on the variation of density with radius. Moreover, since it is at least 15% of the strength of [OII] (Osterbrock & Miller 1975) and, unlike [OII] lies in the middle of the bandpass, it may make an appreciable contribution to our images. The results provide qualified support for the idea that at least some of the central ~200pc of Cygnus A is directly visible. On the "hidden–quasar" model, one would also predict that the immediate vicinity of this component would be the best place to search for scattered broad Hβ.

4.4. Detection of the counterjet?

In the radio, a possible arcsecond–scale counterjet appears in the map of Perley et al. (1984). Carilli et al. (1991b) find no counterjet in a VLBI map and conclude that if the milliarcsecond counterjet exists but is moving away from us at v ~ c and thereby hidden by Doppler beaming, their limit on its observed flux implies that the source's axis must lie at less than 63° to the line of sight. They therefore suggest intrinsic asymmetry between the two radio jets as an explanation for the difference in flux. Given that we have to detect the effects of the radio jet on one side of the source, it is therefore interesting to consider if the same effects are present on the other side and thus if we can see the effects of any counterjet: differences in optical properties, particularly line emission, ought to be independent of the Doppler beaming which may apply to the radio jet.

In Fig. 4 we show a continuum image of the source, scaled to show the lower grey levels more effectively. The channel through which the radio jet passes is visible at a position angle of 290° as a narrow channel. In addition, another channel is visible in the southeastern component exactly in a line with the northwestern channel (see Fig. 2b). We suggest that this corresponds to the passage of a counterjet which has cleared a path through the ISM in the same way as the northwestern jet. Caution is required in the interpretation of this channel as it is much less clearly visible on the 340 nm image. If it is real, however, one would expect it (and the northwestern channel) to point back to the true nucleus (ignoring complications to do with jet precession or bending). The VB/Thompson nucleus lies a little way to the north of the line defined by the two gaps, suggesting that it may not correspond to the true nucleus. Confirmation of the existence of the southeast channel is however required before any definite conclusions are reached.

5. Conclusion

This paper contains the highest resolution (~100 pc) optical images of a powerful radio galaxy so far made. One of the most striking features of the images is the evidence for structure indicating the passage of the radio jet. The northwest component, which has a larger line equivalent width and which lies along the line of the radio jet is shown to be double, and the radio jet passes between the two subcomponents. The southeastern component, on the side of the radio counterjet, may also have a channel of lower intensity optical emission passing through it.

In order to use the results presented here to make more definite statements about the physical conditions in Cygnus A, further high–resolution studies are needed. First, if the central component detected by Thompson (1984), VB and by us is the region around an obscured quasar nucleus, this region above all others should exhibit a scattered broad line: this can be tested by small– aperture spectroscopy with HST. High spatial resolution (~0") infra–red imaging of the region around this "nucleus"
will be of value in testing the dust–lane picture and comparing it to the other models discussed here. Spectroscopy of small regions in the northwestern component can give the line emission within the bright part of the northwestern components undulated by other regions of the source with different line ratios. This will help to determine whether the ionization source for the region around the channel we have discovered is photoionization or shock ionization, and thus whether the picture of a shock produced in the ISM by the passage of the radio jet is the correct one. Finally, blue spectropolarimetry is urgently required to clarify the nature of the blue continuum component in the extended optical emission.

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