HIGH-RESOLUTION $K'$ IMAGING OF THE $z = 1.786$ RADIO GALAXY 3C 294

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Received 1999 April 20; accepted 1999 May 11; published 1999 May 28

ABSTRACT

We have obtained imaging in the $K'$ band ($\sim$I-band rest frame) of the $z = 1.786$ radio galaxy 3C 294 with the 36-element curvature-sensing adaptive optics system Hokupa’a and the Canada-France-Hawaii Telescope. At a resolution of $\approx 0.15$, the galaxy is seen as a group of small but resolved knots distributed over a roughly triangular region $\sim 1.4$ across. The interpretation of the structure depends on the location of the nucleus, as indicated by the compact radio core. Its position is uncertain by $\approx 0.5$ (2 $\sigma$) because of uncertainties in the optical astrometry, but our best estimate places it at or near the southern apex of the distribution. If this location is correct, the most likely interpretation is that of a hidden quasar nucleus illuminating dusty infalling dwarf galaxy–like clumps that have characteristic sizes of $\sim 1.5$ kpc.

Subject headings: galaxies: active — galaxies: evolution — galaxies: formation — galaxies: individual (3C 294) — radio continuum: galaxies

1. INTRODUCTION

High-redshift radio galaxies probably mark out regions of higher than average density in the early universe, and they give us a window into formation processes for at least one kind of massive galaxy. Recent Hubble Space Telescope (HST) imaging of radio galaxies with redshifts greater than 2 in the rest-frame ultraviolet show that most comprise several components and that the ultraviolet flux from these components is apparently dominated by recent star formation (van Breugel et al. 1998; Pentericci et al. 1998, 1999).

As one of the dozen radio galaxies in the 3CR catalog (Bennett 1962) with $z > 1.5$, 3C 294, at $z = 1.786$, is not only one of the most powerful radio sources in the observed universe, but also a likely example of a massive galaxy in its youth. It has strong Ly$\alpha$ emission extending over $\sim 10''$, roughly aligned with the radio structure (McCarthy et al. 1990). It also has a $V = 12$ star less than 10'' to the west (Kristian, Sandage, & Katem 1974), which initially hampered optical and IR observations, but which now can be put to good use as an adaptive optics (AO) reference. In this Letter, we describe the results of an initial AO imaging investigation of 3C 294.

2. OBSERVATIONS AND DATA REDUCTION

The AO observations were obtained with the University of Hawaii AO system Hokupa’a (Graves et al. 1998) mounted at the f/36 focus of the Canada-France-Hawaii Telescope (CFHT). This system uses the curvature-sensing approach pioneered by F. Roddier (Roddier, Northcott, & Graves 1991). Briefly, an image of the telescope primary is formed on a 36-element deformable mirror. Light from this mirror shortward of $\sim 1$ $\mu$m is sent by a beam splitter to a membrane mirror, which is driven at 2.6 kHz to image extrafocal images on both sides of focus onto a 36-element avalanche-photodiode array. Corrections for the wavefront errors derived from the difference of these extrafocal images are sent back to the deformable bimorph mirror, which is updated at 1.3 kHz. Under typical seeing conditions at CFHT and for sufficiently bright ($R \sim 12$) stars, diffraction-limited imaging can be achieved as short as $I$ band (Graves et al. 1998). Our imaging of 3C 294 was in the $K'$ band (Wainscoat & Cowie 1992), so the correction was excellent and quite stable over the course of the observations. The detector system was the University of Hawaii Quick Infrared Camera (QUIRC), which uses a $1024 \times 1024$ HAWAII array (Hodapp et al. 1996). We obtained eight 300 s exposures on 1998 July 3 UT and 14 300 s exposures on 1998 July 4 UT. Unusually rapid variation of the airglow emission compromised the reduction of data from the first night, and we use here only the data from the second night. The individual exposures were dithered in a pattern that kept the bright guide star off the edge of the detector for all exposures.

The images were reduced using our standard iterative procedure (Stockton, Canalizo, & Close 1998). Briefly, we make a bad-pixel mask from a combination of hot pixels (from dark frames) and low-response pixels (from flat-field frames); these pixels are excluded from all sums and averages. For each dark-subtracted frame, 3 or 4 time-adjacent dithered frames were median averaged to make a sky frame, which was normalized to the sky value of the frame in question and subtracted; then the residual was divided by a flat-field frame. These first-pass images were registered to the nearest pixel and median averaged. After a slight smoothing, this rough combined frame was used to generate object masks for each frame, which were then combined with the bad-pixel mask. This process was repeated to give better sky frames, better offsets for alignment, and a new combined image. This new image was used to replace bad pixels in each flattened frame with the median from the other frames, so that bad pixels would not affect the centering algorithm used to calculate the offsets. The final combined image was a straight average of the corrected, subpixel-registered frames, using a sigma-clipping algorithm in addition to the bad-pixel mask to eliminate deviant pixel values. Normally we use field stars for registration, but in this case we had to use the ghost image of the guide star, since there were no other objects visible on individual frames. This ghost image was produced...
by a secondary reflection in the AO system optics; it was about 10 mag fainter than the guide star, and it was positioned 0\,\textdegree114 south and 7\,\textdegree85 east of the star. The image scale with the $K'$ filter was determined to be $0\text{.03537} \pm 0\text{.00005}$ pixel$^{-1}$, based on an accurate measurement of the scale in the $J$ filter by C. Roddier and a determination of the ratio of the $K'$ to $J$ scales for QUIRC from contemporaneous imaging data obtained with the University of Hawaii 2.2 m telescope.

3. RESULTS

Our $K'$ band image of 3C 294 samples the rest-frame spectrum from 6850 to 8300 Å, a region unlikely to be dominated by emission lines (the strongest expected lines in this bandpass are [Ar III] $\lambda\lambda 7136, 7751$ and [O II] $\lambda\lambda 7320, 7330$). This region is also close to the peak of the spectral energy distribution for a stellar population with an age of $\approx 2$ Gyr. If the luminosity at the center of this galaxy is dominated by a central bulge of relatively old stars, we should be able to see it. What we actually do see is shown in Figure 1. Scattered light and a diffraction spike from the guide star extend from the lower right across the lower middle of the frame, and the ghost image of the guide star lies just above the diffraction spike. The radio galaxy 3C 294 is at the middle of the frame. The structure is knotty and filamentary, comprising several distinct components within a roughly triangular region about 1\,arcsec across ($\sim$10 kpc for $H_0 = 75$, $q_0 = 0.3$, and $\Lambda = 0$, which we assume throughout this Letter), no one of which is clearly dominant. The data from the first night, although of lower quality, confirm the main features seen in Figure 1.

Since, at larger scales, both the inner radio structure and the extended Ly$\alpha$ emission are aligned along P.A. $\sim 20^\circ$ (McCarthy et al. 1990), one possible interpretation is that we are seeing a dust-scattering nebula centered on this same axis (Chambers 1999a, 1999b). If this is the case, the hidden nucleus must lie somewhere near the faint southern tip of the “triangle.” However, it is also possible that we are seeing an assemblage of small merging components and that the active nucleus is coincident with one of the peaks in our image. Thus, the interpretation of the observed structure is critically dependent on the location of the nucleus.

McCarthy et al. (1990) found a flat-spectrum central compact radio component, presumably to be identified with the nucleus, and they determined its position to a precision of $\sim 50$ mas. Because we have determined the position of the ghost image and the image scale quite accurately, we can relate any point in our field to the position of the guide star to a similar precision. However, in order to relate our image to the radio position, we need to have high-quality astrometric positions for both the guide star and the radio nucleus in the same reference frame. There are two problems with accomplishing this task: (1) the McCarthy et al. (1990) radio data is referenced to the equinox B1950, epoch 1979.9 VLA calibrator reference frame, and converting to the equinox J2000, epoch 2000.0 FK5 frame is not completely straightforward; and (2) as McCarthy et al. (1990) point out, the positions for our guide star given by Veron (1966), Kristian et al. (1974), and Riley et al. (1980) do not agree very well. Our separate AO imaging of the guide star itself shows an added minor complication: the star is a double with a separation of 0\,\textdegree15 (see inset in Fig. 1).

We have converted the position of the central radio component to the FK5 frame by an empirical mapping of the B1950 VLA calibrator reference frame in the region of the source to the J2000 VLA calibrator frame. We first do a standard pre-

2 Available at http://www.nofs.navy.mil.
Fig. 1.—Image of 3C 294 (centered) in the $K'$ filter obtained with the University of Hawaii AO system Hokupa’a at the CFHT. The wings and diffraction spike from the AO guide star (placed outside the field of the detector) are visible to the right. The compact bright spot just below and to the left of 3C 294 is a $10^{-4}$ intensity ghost image of the guide star produced by the optics of the AO system. The FWHM of the image is $\sim 0.15$. The upper right inset shows 3C 294 at lower contrast, and the upper left inset shows a short exposure on the AO guide star, which is found to be double, with a separation of 0.13 and an intensity ratio at $K'$ of 1.5:1. The large lower left inset reproduces the region around and to the east of 3C 294, with estimates of the position of the radio nucleus shown. The large cross indicates the position and 2 $\sigma$ internal error range of the radio core based on a position for the AO guide star from an astrometric fit to 12 USNO-A2.0 stars. The three crosses show the position of the radio core from positions for the AO guide star given by Kristian et al. (1974), Veron (1966), and Riley et al. (1980) (left to right, respectively). Assuming that the radio core actually lies near the southern apex of the optical structure, the short arrows in the main panel are at the locations of the inner knots of the radio jets and point toward the directions of the hot spots, as seen on the 6 cm VLA map of McCarthy et al. (1990).
we see, the emission is most likely due either to stars or to scattering from a hidden quasar. The position we obtain for the flat-spectrum radio component of 3C 294 favors a location at or near the southern apex of the observed distribution of bright knots, and it therefore supports (although it cannot prove) the interpretation of the observed structure as an illumination cone, most likely due to dust scattering of radiation from a quasar nucleus. Figure 1 can be compared with Figure 2 of McCarthy et al. (1990), which shows contours of the Lyα and radio emission (the short arrows in our Fig. 1 are at the positions of the radio knots $K_s$ and $K_b$ shown in their figure). The extended Lyα emission also shows a well-defined triangular structure extending to the north, which McCarthy et al. (1990) suggest is due to anisotropic emission of ionizing radiation from a central nonthermal source. While the inferred Lyα and $K'$ cones are fairly well aligned, the Lyα material extends $\sim 4''$, or roughly 4 times as far as does the continuum emission in our $K'$ AO image. The Lyα emission also extends to the other side of the radio nucleus, in a weak and somewhat poorly defined "counter cone." We do not see a corresponding feature at $K'$, but our dynamic range is not sufficient to put very strong limits on the presence of such material. If the illumination is truly biconical and intrinsically fairly symmetric, the southern cone must suffer significant extinction along our line of sight.

However, granting that the morphology we see in our AO image is likely to be at least partly determined by illumination effects, the material being illuminated also does seem to have an intrinsic distribution in small ($\sim 0''2$ $\approx 1.5$ kpc) coherent bodies, which (on the not unreasonable assumption that they contain stars as well as dust) must shortly merge together. In fact, the tendency of these objects to show elongation roughly aligned in the direction of the apex may well be caused by tidal stretching. Thus, the alternatives of illuminating effects and merging subunits need not be starkly opposed to each other in this case, although the presence of an illumination cone, if confirmed (say, by polarization measurements), means that we are likely seeing only part of the action.

In summary, 3C 294 appears to be a particularly good example of several aspects of a emerging picture of high-redshift radio galaxies. The observations suggest the following scenario: A quasar nucleus, hidden along our line of sight, is responsible for the jets that power the radio source as well as for the illumination of material in the immediate environment of the radio galaxy that falls within a biconical region. This illumination is made evident to us by scattering by dust and by emission from the large Lyα nebula that is aligned with the radio axis (McCarthy et al. 1990). The bulge is apparently still in the process of being assembled from small ($\sim 1.5$ kpc = 0''2), merging, dusty objects (e.g., Baron & White 1987; Passerini et al. 1996), which, at the depth of our current images, are visible only by scattered light, when they happen to fall within the illumination cone of the central source. Deeper high-resolution imaging might pick up intrinsic emission from similar objects in regions not illuminated by the quasar.

We are grateful for the support of the University of Hawaii Adaptive Optics group: François Roddier, Claude Roddier, Buzz Graves, Malcolm Northcott, and Laird Close, without which these observations would not have been possible. We also thank Laird Close and Claude Roddier for helpful discussions and for information on the image scale, Dave Monet and Dave Tholen for discussions on astrometric matters, and Rob Whitely for obtaining short exposures on the 3C 294 field. This research was supported in part by NSF grant AST 95-29078.

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