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A LUMINOUS COOL COMPONENT IN THE PROTOGALAXY CANDIDATE 3C 326.1

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ABSTRACT

A very deep K-band (2.2 μm) image of the protogalaxy candidate 3C 326.1 at $z = 1.82$ has shown that it is dominated by a faint condensed $K = 19$ source that is coincident with one of the optical continuum components. This object has a K magnitude and an $(R - K)$ color that are not anomalous when compared with the 20 or so other radio galaxies known at $z > 1$. We therefore suggest that 3C 326.1 contains a luminous old population of stars, and hence that it is unlikely to be a protogalaxy seen in the process of formation.

Subject headings: galaxies: evolution — galaxies: formation — radio sources: galaxies

I. INTRODUCTION

The radio galaxy 3C 326.1 at $z = 1.83$ has attracted considerable interest as a promising protogalaxy candidate since its discovery by McCarthy *et al.* (1987*a*). It, and 3C 294 at $z = 1.79$ which has similar properties (Spinrad 1988), represents one of the few pieces of evidence to support the notion that the formation of massive galaxies was occurring as late as $z \sim 2$. As such, 3C 326.1 has frequently been cited both to support theories of late formation for massive galaxies and as a possible prototype for the appearance of forming galaxies (e.g., Baron and White 1987).

Nevertheless, the majority of radio galaxies at $z \leq 2$ are thought to be old "well-formed" systems (e.g., Lilly and Longair 1984) and the few radio galaxies now known at $z > 3$ (Lilly 1988; K. Chambers and G. Miley, private communication) have also generally been interpreted as being relatively mature systems. The evidence for old stellar populations comes from observations in the near-infrared waveband. At $z \sim 2$, the K band at 2.2 μm samples light emitted in the rest-frame R band. The continuum spectral energy distributions of individual radio galaxies show a distinct rise up to the rest-frame optical from the rest-frame ultraviolet (which is sampled by optical observations at high redshift). This rise is thought to be caused by a dominant cool population of stars that, in conventional stellar population models (e.g., Bruzual 1983), must have a minimum age of order 10^9 yr (e.g. Lilly 1988). There is also a remarkably small dispersion ($\sigma \sim 0.4$ mag) in the infrared K-z Hubble relation for complete samples of radio galaxies with $z \leq 2$ (Lilly and Longair 1984; Lilly 1989*a*), despite the wide range of radio luminosities and optical-infrared colors and a bewildering diversity of optical morphologies exhibited by the objects concerned (see, e.g., McCarthy *et al.* 1987*b*; Chambers, Miley, and Joyce 1988; Le Fevre, Hammer, and Jones 1988). The uniformity of the K-z relation suggests that the observed infrared light in these systems is indeed dominated by rather uniform stellar populations, presumably with constant M/L from galaxy to galaxy. This supports the identification of the cool component in individual galaxies with a dominant "old" stellar population as opposed to more exotic interpretations and also argues in favor of a rather small dispersion in the ages of the radio galaxies (Lilly 1989*a*).

Evidence concerning the dynamical ages of these systems, as opposed to the ages of their constituent stellar populations, is much less direct. The small dispersion in the K-z relation and the continuity of this relation from lower redshifts suggests that the active nucleus "knows" what sort of galaxy it is in, and this may be an argument that the galaxies are not very young dynamically.

A major reason for regarding 3C 326.1 as a protogalaxy candidate (McCarthy *et al.* 1987*a*) was the absence of an obvious centrally condensed continuum object on their B, V, and R images. Such a component is seen in other radio galaxies at similar redshifts. In and around a Lyman-α cloud reported to be 10″ in diameter (of order 100 kpc for $H_0 = 50$ km s^{-1} Mpc^{-1}), however, several faint continuum objects were detected. Nevertheless, since the observed R band samples the far-ultraviolet waveband at 2500 Å, any truly old population of stars would be expected to be exceedingly faint at these wavelengths, even if of mass comparable to a present-day gE galaxy. Such a component will be most easily seen at infrared wavelengths. Unfortunately, no infrared data on 3C 326.1 (or on 3C 294) have been published. Such infrared data offer the best test of the idea that 3C 326.1 represents a new class of radio galaxy, i.e., one seen at a very early stage of evolution before it has formed a massive stellar population.

The purpose of this *Letter* is to report deep K-band (2.2 μm) infrared imaging observations of the 3C 326.1 field. These show that one of the faint continuum objects located on the periphery of the Lyman-α cloud and close to the center of the double radio source, has a K magnitude and $(R - K)$ colors that are similar to those of the other radio galaxies that have been observed at this redshift. Consequently, it is suggested that 3C 326.1 is, like them, a basically old system that is undergoing a burst of activity associated with the radio source. These data

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therefore substantially reduce the probability that 3C 326.1 is a prototype for a new class of radio protogalaxy.

II. OBSERVATIONS

The infrared K-band image of the field of 3C 326.1 was obtained on the nights of 1989 March 10–11 using the IRCAM camera (McLean 1987) on the 3.8 m United Kingdom Infrared Telescope (UKIRT). The camera employs an SBRC 58 × 62 InSb detector and was operated in a 0\".6 pixel^{-1} mode at a time when the image quality was about 1\".5 FWHM. A total of 7 hr integration was obtained in increments of 6 minutes.

Between individual exposures the telescope was moved slightly in R.A. and decl. to allow the construction of sky flats. Each image was flattened with a sky flat produced from the median average of the 10 temporally adjacent images. The technique produces flat-fielding to a few parts in 10^5. The known nonlinearity of the detector was removed through observations of a uniform source, and photometric calibration was achieved through the observation of standard stars from the list of Elias *et al.* (1982). Coregistration of the images was carried out to the nearest pixel, after which the images were temporally averaged, with a filter to remove cosmic-ray events. A 1 pixel FWHM smoothing was applied to the final image which is shown in Figure 1*a*. This has been truncated to that area which appeared on at least $\frac{2}{3}$ of the data frames (except for the area surrounding the bright object to the southeast which was included for astrometric purposes).

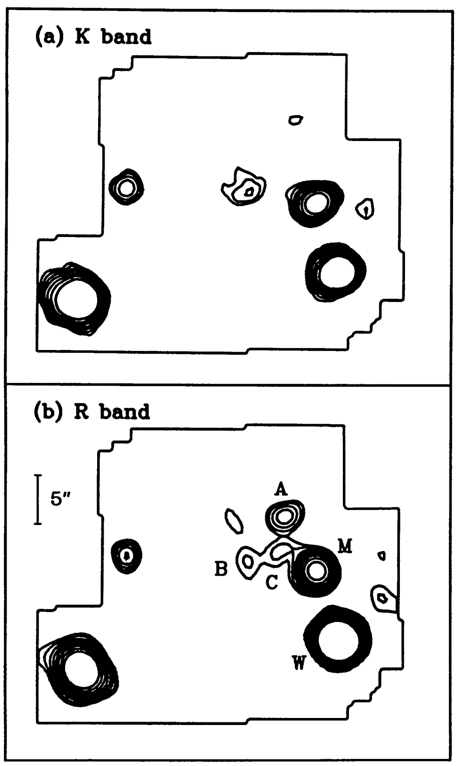

FIG. 1.—(*a*) Contour representation of the K-band image of the field of 3C 326.1. Base contour is at $\mu_K = 22.5$ mag arcsec^{-2}; successive contours are at 0.38 mag intervals. (*b*) Contour representation of the smoothed R-band image of this field, with individual components identified as by McCarthy *et al.* (1987*a*) and Le Fevre *et al.* (1988). Readers are also referred to the exquisite 0\".7 seeing image of Le Fevre *et al.* (1988). Contour interval is as in (*a*), with base level $\mu_R = 27.0$ mag arcsec^{-2}.

A new R-band image of this field was also obtained during the night of 1988 July 1 using the University of Hawaii wide-field grism spectrograph as a focal reducer on the 3.6 m Canada-France-Hawaii Telescope (CFHT). A TI 800 × 800 low-noise CCD camera was used at 0\".45 pixel^{-1} at a time when the image quality was 1\".0 FWHM. A total of 25 minutes exposure was obtained. CCD data reduction employed standard procedures. Photometric calibration (on the Cousins system with negligible color equation) was achieved through observations of Landolt (1983) equatorial standards. The R-band image, smoothed to the same resolution as the K-band image, is shown in Figure 1*b*. Readers are referred to Le Fevre, Hammer, and Jones (1988) for an exquisitely high-resolution R-band image of the field. The optical and infrared images were aligned using the three brightest objects on the K-band image, and the optical image has been clipped to the same area as the infrared image.

In describing our results, we will employ the nomenclature of McCarthy *et al.* (1987*a*) and Le Fevre, Hammer, and Jones (1988), which has been marked on Figure 1*b*. Note that 3C 326.1 has also been discussed by Strauss *et al.* (1987) and by Djorgovski (1988). Our K-band image (Fig. 1*b*), clearly shows a faint condensed source coincident with the optical object "B." This has $K = 19.25 \pm 0.20$ in a 5″ diameter aperture, and $K = 18.95$ in a 7″ diameter, though the latter measurement may be slightly contaminated by light from the nearby star "M." We determine an $(R - K)$ color for "B" of 4.6 ± 0.3 in the 5″ aperture.

While much fainter than the foreground objects "M" and "W," this component clearly dominates the field of 3C 326.1 at 2.2 μm, being much brighter than any component associated with either "A" or "C." Object "A" has $R \sim 23.4$ and $(R - K) \leq 2.4$, and "C" has $R \sim 23.8$ and $(R - K) \leq 3.8$, although photometry on the latter is difficult with our relatively poor image quality because of the close proximity of the other brighter objects.

The two foreground objects, Wyndham's (1966) galaxy "W" and the star "M" have $(R - K)$ colors of 3.4 and 4.3, respectively. Galaxy "W" is probably an early-type galaxy at $0.35 < z < 0.5$, while star "M," if truly "stellar," must be a very late M star.

III. DISCUSSION

The most interesting feature of the new observations is the identification of a dominant infrared component with object "B." This object is the closest to the center of the double radio source, although the astronomy of McCarthy *et al.* (1987*a*) places it about 2″ away from this point. It is therefore a plausible location for the central engine using the 0.2θ criterion of Laing, Riley, and Longair (1983). Our detection of the dominant infrared source in the system at the location of "B" makes this extremely likely.

To date, almost all the published infrared data on other high-redshift radio galaxies exist in the form of single-element measurements made through 8″ or larger apertures (Lilly and Longair 1984; Lilly, Longair, and Allington-Smith 1985; Eisenhardt and Lebofsky 1985; Lilly 1989*a*). In order to compare "B" with these other radio galaxies, we have estimated, based on the aperture measurements made from the K-band image described above, that an *uncontaminated* 8″ magnitude of "B" would be roughly $K = 19.0$. In Figure 2 we show this magnitude compared with the infrared K-z relation for all radio galaxies with spectroscopic redshift measurements

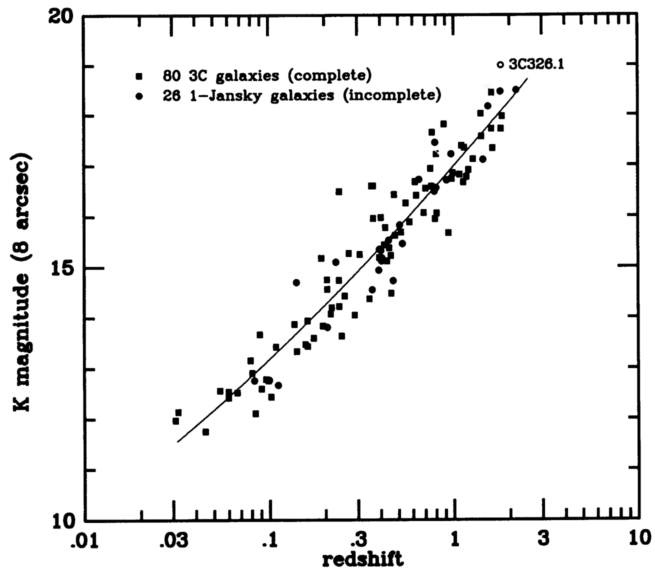

FIG. 2.—The infrared K-z relation for radio galaxies with spectroscopically determined $z < 2.5$. Squares represent a complete sample of 3C galaxies, circles represent an incomplete sample of "1 Jy" galaxies for which there may be some low-level selection biases (see Lilly 1989*a* for an unbiased version of this diagram). All magnitudes are as measured through a standard 8" aperture. The solid line is a low-order polynomial least squares fit of K on z (excluding 3C 326.1). Component "B" of 3C 326.1 is not anomalously faint within the large sample of high-z radio galaxies.

with $z < 2.5$ in the homogeneous set of infrared observations of Lilly and Longair (1984), Lilly, Longair, and Allington-Smith (1985), and Lilly (1989*a*). All the K magnitudes have been corrected to a standard 8" aperture as described by Lilly (1989*a*). On this diagram, it is clear that 3C 326.1 "B" is some 0.9 mag fainter than the median magnitude of radio galaxies at $z \sim 1.8$, but that this shortfall is only about twice the rms scatter within the population, which is $\sigma \sim 0.4$ mag. Within the context of the overall population of roughly 20 radio galaxies with $z > 1$, it is therefore not anomalous.

Similarly in Figure 3, we compare the optical-infrared color of 3C 326.1 "B" with those of other high-redshift radio galaxies, using the compilation of $(r - K)$ colors of Lilly and Longair (1984) and Lilly, Longair, and Allington-Smith (1985), and taking the $(r - K)$ color of 3C 326.1 "B" to be 5.0. Although many radio galaxies at $z \sim 1.8$ are substantially bluer (e.g., 3C 239 and 3C 256), the color of 3C 326.1 lies well within the envelope defined by the overall population. In terms of the conventional Bruzual (1983) models used elsewhere (see, e.g., Lilly 1988), this cool component has a minimum age of 10^9 yr (for a short "initial burst" of 10^8 yr) even if all the R-band light is assumed to come from this population.

The long-wavelength photometric properties of component "B" in 3C 326.1 are therefore not substantially different from those of the majority of radio galaxies at high redshift. We believe that it is an "old" (age $> 10^9$ yr) well-formed galaxy of similar mass to a present-day gE galaxy. At $z \sim 1.8$, it has absolute magnitude $-23 < M_V < -24$ for $0.5 > q_0 > 0.0$ and $H_0 = 50$ km s^{-1} Mpc^{-1}, assuming a rest-frame $(V - I) \sim 1.0$.

Clearly the relative faintness of this object compared with other radio galaxies, which we believe is probably a simple statistical effect within a basically homogeneous population, nevertheless contributed to its earlier interpretation as a protogalaxy candidate: If component "B" had been a magnitude brighter (so as to lie on the median K-z relation) and/or the $(r - K)$ color been a magnitude bluer (so as to resemble 3C 239, for instance), then the striking appearance of a "lack of a centrally concentrated nucleus" at optical wavelengths noted by McCarthy *et al.* (1987*a*) would have been substantially reduced.

If "B" is the true identification for the radio galaxy, then the "knots" of McCarthy *et al.* (1987*a*), "C," which lie at the center of the Lyman-α cloud close to the western radio lobe, may be seen as an example of the radio-optical alignment effect seen in many high-redshift radio galaxies (McCarthy *et al.* 1987*b*; Chambers, Miley, and van Breugel 1987). The aligned component may be produced by star formation triggered by the jet-medium interaction, although other possibilities should not be ruled out. An interesting feature of the 3C 326.1 system, in this interpretation, is that this activity peaks well away from the central galaxy (now identified as "B"), whereas in many of the other radio galaxies the activity appears to more diffusely spread out along the radio source axis. As noted by Le Fevre, Hammer, and Jones (1988), there is very little continuum emission between "B" and "C." The colors of this "lobe" component are thus relatively easily seen, although ideally infrared data of higher spatial resolution should be used. If it is a stellar component, then it is almost certainly young, and the colors of "C" are an important check on the assumption that red optical-infrared colors imply moderate to old ages. Our limit of $(R - K) \leq 3.8$ is consistent with the $(R - K) \sim 3.3$ expected for a "young" Irr galaxy at this redshift (based on the SED of Coleman, Wu, and Weedman 1980) and substantially bluer than that of the "old" host galaxy "B," which has $(R - K) \sim 4.6$.

Object "A," on the northern periphery of the cloud, is extremely blue with $(R - K) \leq 1.7$. We suspect that it is unrelated to 3C 326.1.

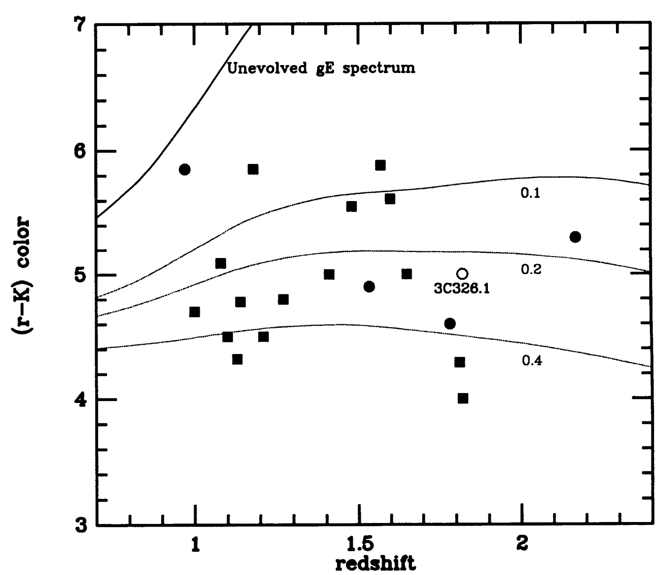

FIG. 3.—The optical-infrared $(r - K)$ colors of radio galaxies with $1 < z < 2.5$. Symbols are as in Fig. 2. The solid curve in the upper left-hand corner shows the expected colors of an unevolved gE galaxy, while the lighter curves marked 0.1, 0.2, and 0.4 indicate the colors of radio galaxies with roughly constant levels of ultraviolet activity, using the parameterization f_{5000} defined by Lilly (1989*a*), with f_{5000} as marked. Component "B" of 3C 326.1 has a typical color for radio galaxies at $z > 1$.

Even if it is unlikely to be a protogalaxy seen in the process of formation, there are still several interesting features of 3C 326.1. For instance, the equivalent width of Lyman-α is higher, and the ionization lower than in most other radio galaxies at high redshift, with C IV 1549 undetected (McCarthy *et al.* 1987*a*). If "B" is truly the host galaxy, then 3C 326.1 is also rather unusual in that the line emission is peaked in the direction of the farther of the two radio lobes, in contrast to other radio galaxies at similar redshifts (McCarthy and van Breugel 1988). It is potentially interesting that the large Lyman-α cloud reported by McCarthy *et al.* (1987*a*) to be 100 kpc in extent is apparently centered on one of the radio lobes rather than on the main galaxy "B," which presumably dominates the gravitational potential of the system. However, in this context it should be noted that a new medium-bandwidth (300 Å) image of 3C 326.1 centered on Lyman-α (see Lilly 1989*b*) suggests that the Lyman-α emission may be much more concentrated in the area of the hot spot "C" than has previously been thought, and that there is correspondingly very little Lyman-α emission from beyond the confines of the radio source.

IV. CONCLUSIONS

A deep K-band image of the field of the protogalaxy candidate 3C 326.1 at $z \sim 1.8$ has revealed a dominant infrared component associated with one of the faint optical continuum objects on the periphery of the Lyman-α cloud. This object has $K \sim 19.25$ in a 5″ aperture. While it is thus fainter than most other powerful radio galaxies at similar redshifts, the shortfall is only about twice the dispersion in absolute magnitude seen in the radio galaxy population and, within the context of the 20 or so radio galaxies known at $z > 1$, it is therefore not anomalous. The $(R - K)$ color of this object is also typical of other radio galaxies at similar redshifts and suggests a minimum age for the bulk of the stellar population in excess of 1 Gyr. While there are still several puzzling aspects to 3C 326.1, these new data substantially reduce the probability that 3C 326.1 is a genuine "protogalaxy" seen in the process of formation.

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