THE ASTROPHYSICAL JOURNAL, 420:L13–L16, 1994 January 1

NEAR-INFRARED IMAGING OF FSC 10214+4724 WITH THE W. M. KECK TELESCOPE[1]

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Received 1993 July 13; accepted 1993 October 12

ABSTRACT

Near-infrared observations of the $z = 2.286$ *IRAS* source FSC 10214+4724, made with the near-infrared camera on the W. M. Keck Telescope, are reported. Deep broad-band images at 2.15 and 1.27 μm, and narrow-band images at 2.165 and 2.125 μm with 0''.6 to 0''.9 seeing show that FSC 10214+4724 consists of at least three distinct components in a compact group of galaxies. The source of the infrared luminosity appears to be in a strongly interacting galaxy that has a luminosity $\sim$100 times that of a present-day L* galaxy. The interaction suggests an "age" of this galaxy of $\simeq 10^9$ yr. The Hα emission is resolved as a source of diameter $\simeq$5 kpc, suggesting that a starburst contributes to the observed Hα emission. There is an excess of objects in the FSC 10214+4724 field that could represent galaxies in an associated cluster.

Subject headings: galaxies: clustering — galaxies: individual (FSC 10214+4724) — galaxies: interactions — galaxies: peculiar — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

The *IRAS* source FSC 10214+4724 has come under intensive scrutiny over most of the electromagnetic spectrum since its identification by Rowan-Robinson et al. (1991) with a faint optical object of redshift 2.286. At this redshift, FSC 10214+4724 is the most luminous object known in the universe. The rest frame optical spectrum shows very strong Hα emission (Soifer et al. 1991; Elston et al. 1993) as well as strong lines of [N II] and [O III] (Elston et al. 1993). The optical spectrum is that of a Seyfert nucleus (Elston et al. 1993). The infrared spectral energy distribution shows that the interstellar medium of the host galaxy has a very gas rich galaxy's amount of dust ($>10^9\ M_\odot$; Rowan-Robinson et al. 1993; Downs et al. 1992), with temperature ranging from 50 to 150 K. Molecular observations (Brown & van den Bout 1992; Solomon, Radford, & Downs 1992) have shown the total gas content of this system to be $\sim 3 \times 10^{11}\ M_\odot$ of molecular gas.

Because of the interest in the origin of its luminosity and the possibility that FSC 10214+4724 represents a truly primeval galaxy, this source was a target during the science demonstration observations conducted with the near-infrared camera on the W. M. Keck Telescope. In this paper we report the results of these observations.

2. OBSERVATIONS AND DATA REDUCTION

The present observations were made on 1993 March 20–27 with the near-infrared camera (NIRC) on the 10 m W. M. Keck Telescope. The camera is described in detail elsewhere (Matthews & Soifer 1994), and only the essential elements are discussed here. It utilizes a 256 × 256 InSb array manufactured by the Santa Barbara Research Corporation with 0''.15 pixels to yield a field of view of 38'' × 38''. Wavelength determination is done by selecting filters housed in two filter wheels placed close to the image of the pupil.

The images reported here were obtained in the 1.11–1.40 μm (J), and 1.99–2.32 μm (K_s) broad-band filters, and in two 1% bandpass filters centered at 2.165 μm (rest frame 0.656 μm) and 2.125 μm (rest frame 0.64 μm). For each observation the total integration time was split into frames of shorter integration time to prevent saturation of the detector. The integration time per frame and total integration time were 21 and 1400 s at K_s, 40 and 1400 s at J, and 200 and 1800 s at 2.165 and 2.125 μm. The limiting magnitudes are 21.2 and 23.8 mag (5 σ detection in a 1 square arcsecond aperture) for the K_s and J images, respectively.

During an individual frame, an offset autoguider that viewed a field star $\sim$5'.5 off the telescope optical axis was used for guiding. After a frame was taken, the telescope was moved a few arcseconds to take into account possible bad pixels and to permit use of the observations themselves to provide a sky field for background subtraction.

The data were reduced by first subtracting a sky frame from the image frame, and then dividing by the flat field frame for the array. The sky frame was determined from the complete set of object frames. After sky subtraction and flat fielding, each object frame was shifted in location to place the nearby field star (star A in the nomenclature of Rowan-Robinson et al. 1991) in the same position in the final summation image.

3. RESULTS

The final co-added images of a 40'' × 40'' field centered on FSC 10214+4724 at K_s and J are shown in Figures 1*a* and 1*b* (Plate L8). The summed image at K_s has a measured full width at half-maximum (FWHM) for star A of 0''.6. The FWHM in the J image is 0''.8.

The highest signal-to-noise ratio was obtained at K_s, and the central 10'' × 10'' of this image is shown in Figure 1*c*. Figure 1*d* shows a Richardson-Lucy deconvolution of the

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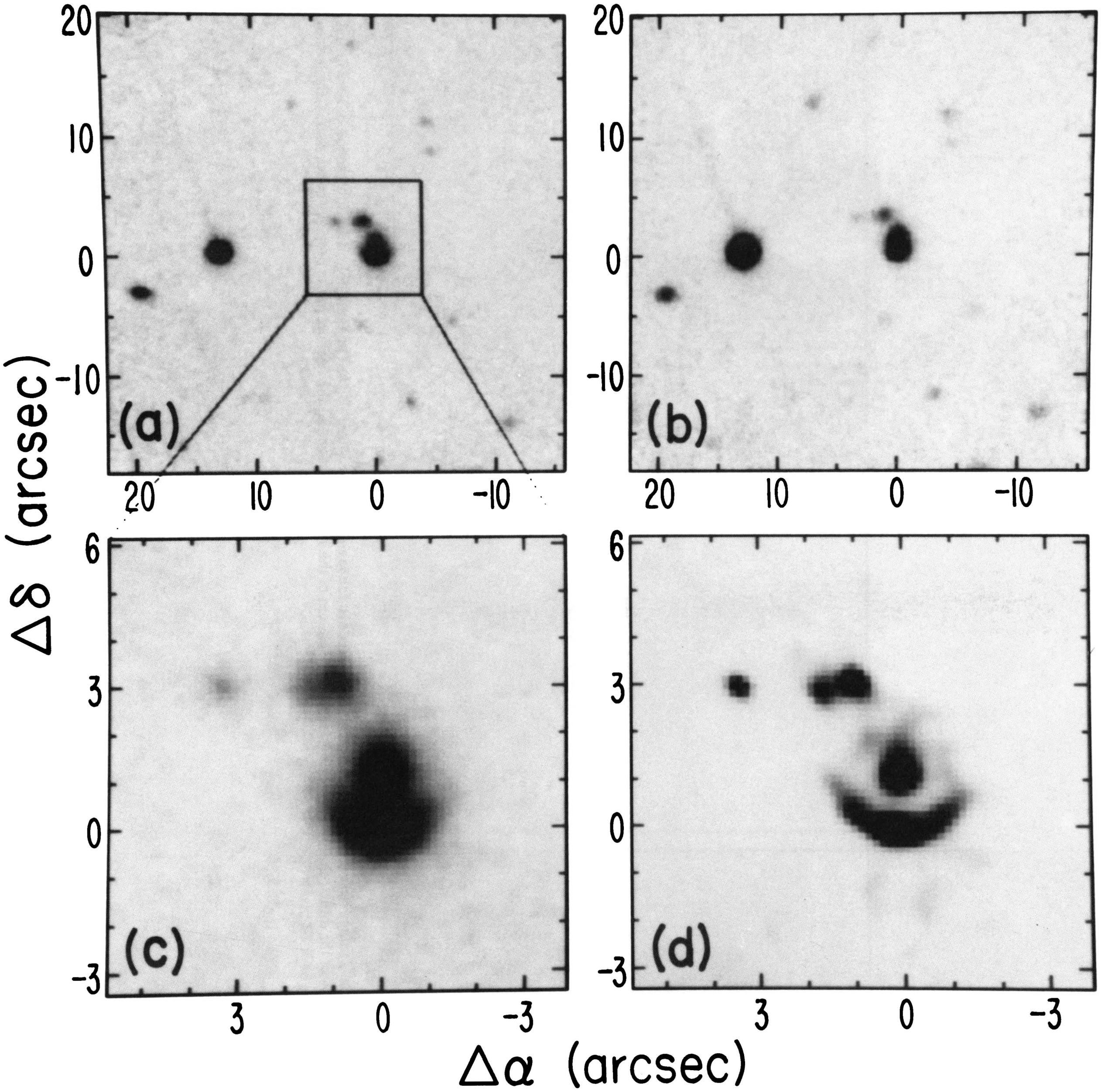

FIG. 1.—A mosaic of images of the field of FSC 10214+4724. North is up, and east is to the left in all the frames. Panel (*a*) is the image at K_s (1.99–2.32 μm) of a field 38″ × 38″, (*b*) is the same field at *J* (1.11–1.40 μm), (*c*) is the same image as panel (*a*) enlarged to show the central 10″ × 10″ around FSC 10214+4724, (*d*) is the same field as panel (*c*), where the Richardson-Lucy image restoration algorithm has been used to enhance low-level features.

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central 10″ × 10″ portion of the K_s image after 30 iterations. This shows fainter components more plainly. Figure 1*d* shows low surface brightness arcs emerging from the southern (brightest) of the components of FSC 10214+4724 and extending to the east and west to form a rough semicircle.

Since Hα and [N II] 6548+6584 at a redshift of 2.286 falls in the bandpass of the 2.165 μm filter and the 2.125 μm filter corresponds to a continuum free of lines at 0.64 μm at this redshift, the difference between these images should represent the distribution of the Hα + [N II] emission in the FSC 10214+4724 environment. The only source detected in this difference image to a limiting (3 σ) flux of $4 \times 10^{-20} W$ m^{-2} coincides to within 0″.05 with the peak brightness of FSC 10214+4724 in the *J* and K_s images. The Hα + [N II] emission has a total flux of 6×10^{-18} W m^{-2}.

The flux in Hα + [N II] is a factor of 3 smaller than that stated by Soifer et al. (1991). The origin of this discrepancy is that the original flux estimate by Soifer et al. measured the equivalent width in the spectrum with a 1″.5 slit length, and assumed all the flux in both the continuum and line was contained in this size beam. The current data clearly show the continuum to be extended on the scale of several seconds of arc, which invalidates the assumption of the previous calculation of the Hα flux.

In the brightest 1″ × 1″ part of FSC 10214+4724, the Hα+[N II] line flux accounts for 50% of the total flux in the K_s filter. The size of the Hα+[N II] image is significantly larger than that of a point source. Figure 2 shows the radial intensity profiles for the Hα+[N II] source and star A in the image formed from the sum of the images at 2.165 and 2.125 μm. The featureless spectrum of star A (Rowan-Robinson et al. 1991; Rowan-Robinson, private communication) makes its identification secure as a galactic field star. The FWHM of a circular Gaussian fitted to the Hα+[N II] radial profile is 1″.03, while that of one fitted to star A is 0″.88. This leads to an inferred size of the Hα+[N II] source of 0″.5. Contour plots of the Hα+[N II] image show the source to be slightly elongated in the east-west direction. Although obtained with an entirely different camera and filter system, the Hα+[N II] data presented here are consistent with the Hα+[N II] image presented in Soifer et al. (1992). However, these results are inconsistent with the size of 1″.8 in the north-south direction recently reported by Clements et al. (1993); the reason for this inconsistency is unknown.

4. DISCUSSION

The K_s image (rest frame 0.65 μm) shows an impressive variety of structures associated with FSC 10214+4724. The brightest source, the source which contains the Hα+[N II] emission and which is associated with the radio source (Soifer et al. 1992), is clearly elongated in the east-west direction, similar to the orientation of the Hα+[N II] source and the radio source (Lawrence et al. 1993). Hereafter we refer to this as source 1.

To the north of source 1 there are three other condensations. The source closest to the southern brightness peak (hereafter source 2) was previously reported by Soifer et al. (1992), while the source, slightly to the northeast (source 3) can be seen in the H+K image of FSC 10214+4724 presented by Lawrence et al. (1993). The faintest of the three condensations (source 4) is separated from the closest of the other sources by ~2″. While there are no measured redshifts to demonstrate that these sources are physically associated with FSC 10214+4724, because of their small angular separation we will assume that they are associated. At a redshift of 2.286, 1″ corresponds to ~10 kpc, so the total structure of FSC 10214+4724 extends over ~50 kpc; we adopt $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

Because of the very high signal-to-noise ratio of star A in the K_s image, the point spread function of star A allows the sizes of the sources associated with FSC 10214+4724 to be accurately assessed. Source 1 has a deconvolved FWHM of 0″.7 × 0″.5 with the major axis in the east-west direction, while source 3 is extended ≃0″.6 in the east-west direction. Sources 2 and 4 are not extended compared to the measured size of star A of 0″.6. This places an upper limit on the sizes of the unresolved sources of 0″.3 or ≃3 kpc, comparable to the diameter of galactic bulges.

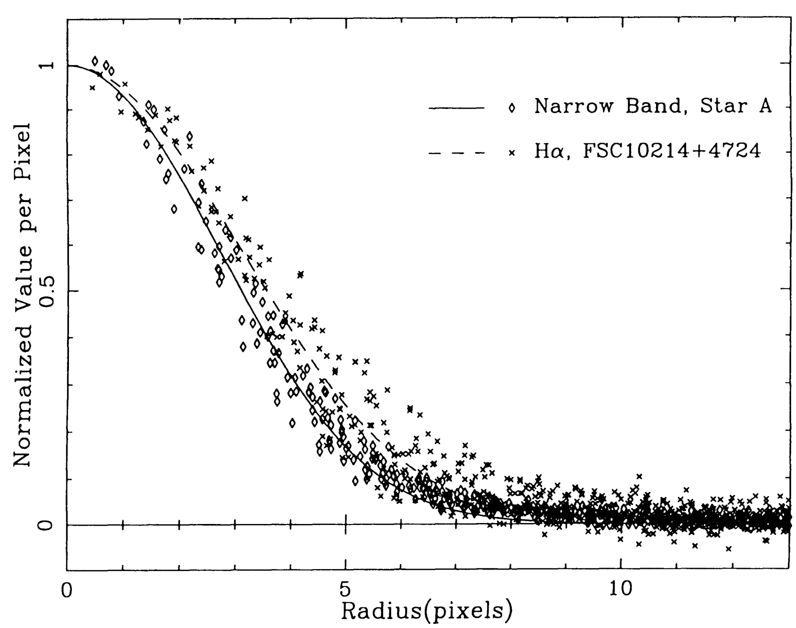

FIG. 2.—Radial profiles of the Hα+[N II] image of FSC 10214+4724 and the point spread function of star A from the same frames. The measured FWHM of the circular Gaussian fitted to the Hα+[N II] image is 1″.03, while that fitted to star A is 0″.88.

TABLE 1

PARAMETERS OF SOURCES ASSOCIATED WITH FSC 10214+4724

Source	K_s(mag)[a]	νL_ν(0.65 μm)	M_R(mag)
1.........	17.6[b]	$7.5 \times 10^{11}\ L_\odot$	−25.8
2.........	17.6	$7.5 \times 10^{11}\ L_\odot$	−25.7
3.........	18.5	$3.3 \times 10^{11}\ L_\odot$	−25.2
4.........	20.0	$8.3 \times 10^{10}\ L_\odot$	−23.0

[a] Apertures were selected to include all of the flux from each source and to isolate the sources.

[b] Corrected for Hα in the K_s bandpass.

Sources 1–4 are suggestive of a very compact group of galaxies. If these sources are at $z = 2.3$, their luminosities are quite large. Table 1 lists the observed K_s magnitudes of sources 1–4, and the corresponding luminosities (νL_ν at 0.65 μm) and M_R. (The values of the luminosities derived from the assumed H_0 and q_0 are quite similar to the values derived for $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 1$). All these systems are more luminous than L* galaxies (Schechter 1976) in nearby clusters. Lugger (1986) has found that in the red (i.e., the rest frame wavelength of the K_s observations for galaxies at the redshift of FSC 10214+4724) L* galaxies in nearby clusters have $M_R = -21.8$ mag to -22.3 mag for $H_0 = 75$ km s^{-1} Mpc^{-1}. Source 1 represents a galaxy nearly 100 times more luminous than a nearby L* galaxy, even when the strong Hα emission is accounted for. The faintest of these systems, source 4, is $\sim$1 brighter than a present-day L* galaxy.

The arms emanating from source 1, seen in Figure 1*d*, are suggestive of interacting galaxies as exemplified by the nearby interacting system Arp 148 (Arp 1966). Possibly this interaction has triggered the incredibly luminous core as part of the merger process. If the arcs are indeed tidal tails, this implies an age of at least an orbital time of two galaxies at a distance of $\sim$50 kpc (the diameter of the arcs) or at least 5×10^8 yr. Another argument suggestive of the presence of older stars is that the color of the tails is $J - K_s = 2$ mag, while the body of the galaxy (source 1) shows $J - K_s = 1.3$ mag (when corrected for the Hα emission in the filter). This argues for a population of stars in the tails of at least 10^9 yr, based on stellar population models of Bruzual (1985) and suggests that FSC 10214+4724 is not a galaxy undergoing its first significant episode of star formation, but must have stars at least 10^9 yr old. This is consistent with the interstellar medium of the galaxy having a significant abundance of heavy elements. We conclude that FSC 10214+4724 is a system that has formed stars for $\sim 10^9$ yr and is therefore not a truly "primeval" galaxy.

The arcs visible in Figure 1*d* are also suggestive of the arcs produced by gravitational lensing, and it is impossible to rule out that the arcs are due to such a lens. We do not believe, however, that the arcs are the result of lensing. The image morphology is not achromatic; the significant change between the images at 2.12 and 2.16 μm is an example. It is possible, of course, that the image seen is a reflection of structure in the lensed source. If this is a gravitational lens, the symmetry suggests that source 2 is the lens. A direct measurement of the redshift of source 2 would distinguish these possibilities.

Figure 2 shows the Hα + [N II] source to be extended by 0".5 or $\sim$5 kpc and slightly elongated east-west. This is comparable to the size and position angle of the 8 GHz source (Lawrence et al. 1993) and is substantially larger than the size expected for the narrow-line regions of quasars ($\sim$1 kpc; Osterbrock 1989). The size of the Hα source suggests that star formation is occurring over much of the disk of source 1. This is not surprising, considering that this is an extremely gas rich galaxy. Such a disk-wide starburst is the probable origin of the excitation of the gas that makes this system an H_2O maser source (Encrenaz et al. 1993).

The observed Hα flux, correcting for the strong [N II] emission found by Elston et al. (1993), is 2.4×10^{-18} W m^{-2}. This leads to an observed ratio of the bolometric flux to ionizing photon flux $L/Q = 6 \times 10^{-16} J$. This ratio must be corrected for the extinction through which the Hα flux is observed. A lower limit is derived as the reddening required to make the Hα corrected $J - K_s$ color of source 1 consistent with a rapidly star-forming galaxy, i.e., a flat spectrum source. An upper limit is the reddening required to make the (Hα corrected) $J - K_s$ color of source 1 that of a Rayleigh-Jeans continuum. These two limits give $A_{H\alpha}$ values between 0.4 and 1.8 mag. This then leads to a reddening corrected L/Q of $4 \times 10^{-16} J$ to $1 \times 10^{-16} J$. By comparison, models of starburst systems predict $L/Q \lesssim 5 \times 10^{-17} J$ (Scoville & Soifer 1991). This suggests that a starburst that produces the observed extended Hα flux in FSC 10214+4724 can account for between $\frac{1}{8}$ and half of the bolometric flux from this system. Based on the upper limits to the Hα flux for sources 2 and 3, these cannot be extreme star-forming galaxies like source 1.

The very deep images obtained of this field suggest the possible presence of a cluster of galaxies at $z = 2.3$. Five other fields were observed to comparable sensitivity by the NIRC in the commissioning run. The mean number of sources observed per field ($\sim$0.4 arcmin^{-2}) in the brightness range $K_s = 20$–21 mag was 6 ± 1, which is consistent with the counts presented by Cowie et al. (1993). The observed number of nine sources in the FSC 10214+4724 field (excluding sources 1–4) is a 3 σ excess over the expected number, which suggests that some of these sources could be galaxies at the same redshift. The limits on the Hα fluxes in the field do not place significant limits on star formation in these systems if they are at the same redshift as FSC 10214+4724. The observed $J - K$ colors of all the objects in the field are shown in Figure 3. The $J - K_s$ colors of the field galaxies range from 0.6 to 2.0 mag. Most of the field

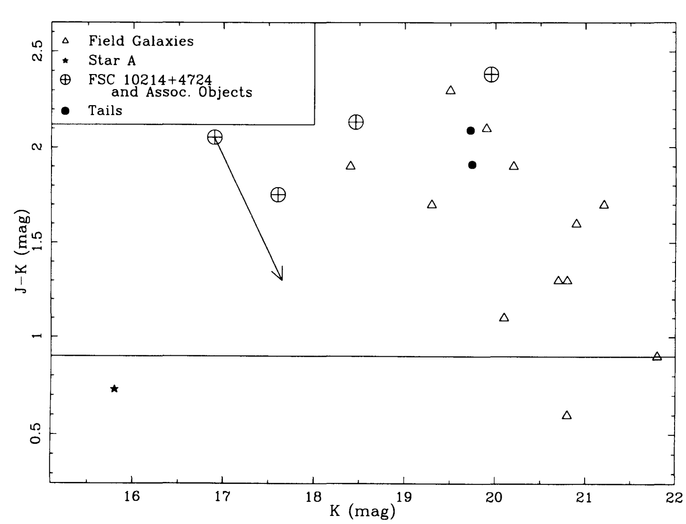

FIG. 3.—Plot of the $J - K_s$ color vs. K_s magnitude for all the objects in Fig. 1*a*. For the field galaxies, the measurement aperture was 1" diameter (except for the tails to source 1, where the aperture was 2" × 2". The arrow indicates the change in color and magnitude for source 1 to subtract the contribution to the K_s flux due to Hα flux.

galaxies have colors in the range of colors of sources 1–4, and so are consistent with being galaxies at the same redshift. Such galaxies would have a rest frame $M_R = -22.5$ to -23.5 mag. As mentioned above this is between 0.7 and 1.7 mag brighter than a local cluster L* galaxy (Lugger 1986), and so is not unreasonable for galaxies at that redshift.

The W. M. Keck Observatory is operated as a scientific partnership between the California Institute of Technology and the University of California. It was made possible by the generous gift of the W. M. Keck foundation, and the support of its president, Howard Keck. We are most grateful for their visionary endowment that has made possible the first of the next generation of telescopes.

It is a pleasure to thank E. Stone, W. Frazier, W. Sargent, S. Faber, E. Romano, and W. Lupton and all of the many devoted people whose unflagging efforts have made possible the success of the W. M. Keck Observatory. We thank R. Blandford and S. Phinney for discussions and P. Eisenhardt for providing data in advance of publication.

Infrared astronomy at Caltech is supported in part by grants from the NSF and NASA.

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