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NEAR-INFRARED OBSERVATIONS OF THE $z \sim 2.3$ *IRAS* SOURCE FSC 10214+4724

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ABSTRACT

Near-infrared imaging and spectroscopy of the extremely luminous *IRAS* source FSC 10214+4724 have been obtained using the Cassegrain infrared camera on the 200 inch (5.08 m) Hale Telescope. A low-resolution spectrum ($\lambda/d\lambda \sim 100$) in the 2.0–2.4 μm atmospheric window shows a very strong Hα line at the optically determined redshift $z = 2.286$. The observed rest-frame equivalent width of Hα is 0.07 ± 0.02 μm, consistent with the largest values found in quasars. The images show an unresolved source, while the near-infrared colors are somewhat redder than the mean colors of quasars observed at the same redshift. The reddening inferred is $A_V \sim 1.5$ mag, with an upper limit of ~ 3.0 mag. The observations presented here cannot distinguish between starburst and quasar models for this source. Starburst models require $\sim 10^{12}$ $M_\odot$ of stars to have been formed over 10^7–10^8 yr. If FSC 10214+4724 is a quasar, the reddening-corrected bolometric luminosity is approximately equal to the observed infrared luminosity.

Subject headings: galaxies: formation — infrared: sources — infrared: spectra — quasars

1. INTRODUCTION

The *IRAS* source FSC 10214+4724 has been identified with an optical counterpart having a redshift of $z = 2.286$ (Rowan-Robinson et al. 1991, hereafter RR). The identification is strengthened by the coincidence of the optical object with a radio source having the nominal value of infrared to radio flux density as determined from nearby infrared bright galaxies (Helou, Soifer, & Rowan-Robinson 1985; Condon & Broderick 1991). If the identification is valid, this is one of the most luminous objects known in the universe (RR). Optical spectra (RR) show the source to have a high-excitation emission-line spectrum without evidence of broad recombination lines characteristic of quasar spectra. RR have suggested two possible models of this object: a massive "protogalaxy" undergoing its first burst of star formation, and a quasar heavily enshrouded in dust. In either case this is a fascinating source whose true nature is clearly of great interest. In this paper we assume the optical and the infrared source are the same.

2. OBSERVATIONS AND DATA REDUCTION

Near-infrared imaging and spectroscopic observations of FSC 10214+4724 have been obtained using the Cassegrain infrared camera (Carico et al. 1990) on the 200 inch (5.08 m) Hale Telescope. Images were obtained at J (1.27 μm), H (1.65 μm), K (2.2 μm), and L' (3.7 μm). Calibration of the imaging data was done using the standard star HD 84800 (Elias et al. 1982). The telescope pointing was verified by imaging the nearby field star A (RR, Fig. 1) on a frame with the target source.

Multiple frames were obtained at each wavelength, with the object moved about one-fourth of the camera field between images to allow for bad pixels in the array. The total observing time at each wavelength was ~ 6 minutes. Multiple frames at each wavelength were combined by first shifting the frames based on the accurate telescope offsets between frames, and then adding the frames. Photometry was done in a circular aperture of 3".8 diameter. Because the field of the camera is small (18" × 19"), no other stellar images appear on the frames in which FSC 10214+4724 is approximately centered. Thus determination of whether the source was resolved relied upon comparison with images of stars taken before and after the images of the source. The FWHM of the source is 1".0 at 2.2 μm, not significantly larger than the size of the images of the comparison standard star.

In addition to the imaging data, a spectrum of the source in the K-band atmospheric window was obtained using a GRISM capability incorporated into the camera. The spectra were obtained by placing a long slit in the (cold) telescope focal plane, and a transmission grating on a sapphire prism (GRISM) in the reimaged pupil plane of the camera. This configuration projects a long-slit (18") spectrum onto the infrared array. The spectral resolution with a slit width of 1" is $\lambda/d\lambda \sim 100$, and an entire atmospheric window can be observed in one instrument setting.

The spectrum of FSC 10214+4724 was obtained using a slit

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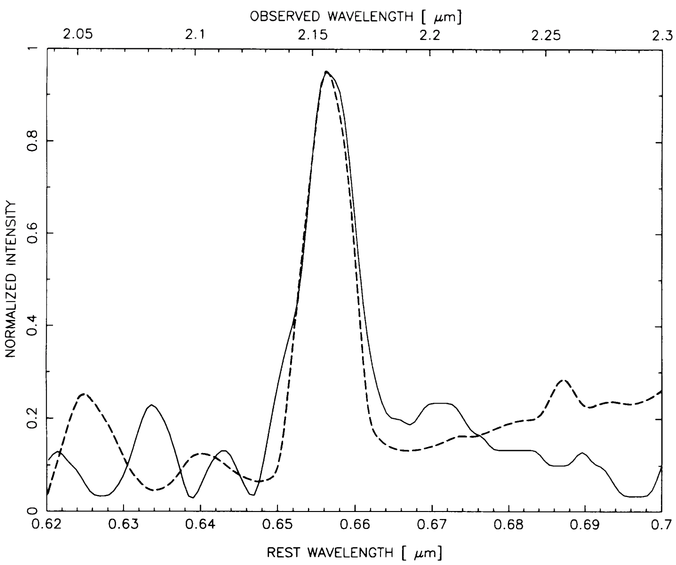

FIG. 1.—Spectrum of FSC 10214+4724 from 2.04 to 2.30 μm is shown (*solid line*) along with that of the planetary nebula BD +30°3639 (*dashed line*). The abscissa is given in the rest wavelength (*bottom scale*) of FSC 10214+4724 assuming a redshift of 2.286, and in observed wavelength (*upper scale*). The spectrum of BD +30°3639 has been shifted by 0.008 μm and normalized by subtracting a constant offset and adjusting the amplitude so that the Brγ line of BD +30°3639 can be compared directly with the Hα line in FSC 10214+4724.

width of 1″. Multiple spectra of the source were obtained by moving the source to various places along the slit, again to account for the various bad pixels on the array. Guiding for both imaging and the spectra was accomplished using an offset guider that ensures telescope tracking accurate to ∼0″.03 rms.

A total of 50 minutes of observing was spent on the K-band spectrum. The individual spectra were reduced to flattened two-dimensional spectra; then the spectra were shifted in the spatial dimension to co-add the spectra of the source. The spectrum of the source was determined from this combined spectrum by extracting the spectrum at the location of the source, and then subtracting the average of sky spectra extracted on both sides of the source location. The extracted spectrum is shown in Figure 1, along with a spectrum of the planetary nebula BD +30°3639 obtained with the same instrumental configuration. The latter has been shifted by 0.008 μm to make the Brγ line of BD +30°3639 appear to lie coincident with the Hα line.

3. RESULTS

The observed spectrum shows a strong line at 2.16 μm. At the optically determined redshift of FSC 10214+4724, Hα should appear at 2.156 μm. Thus we conclude that the observed line is Hα. At the resolution of the grism, Hα and the [N II] lines $\lambda\lambda$6548, 6584 are unresolved. The observed Hα line has a FWHM ∼3000 km s^{-1}, consistent with the instrumental FWHM as determined by observations of Brγ in the planetary nebula BD +30°3639. The planetary nebula filled the full slit widths, so the instrumental width is a maximum. There is a suggestion of broad-relatively symmetric wings in the Hα line (Fig. 1). The rest-frame equivalent width of the line is ∼0.07 ± 0.02 μm. The dominant uncertainty in the equivalent width is the continuum level. The equivalent width is only slightly larger than the largest equivalent widths of Hα in both low- and high-luminosity quasars (Soifer et al. 1981).

TABLE 1

BROAD-BAND MAGNITUDES OF FSC 10214+4724

Wavelength (μm)	Magnitude
1.27	18.65 ± 0.15
1.65	17.15 ± 0.10
2.20	16.37 ± 0.10
3.70	>10.66

The observed magnitudes of the source are given in Table 1. The 2.2 μm magnitude of the source is 0.4 mag brighter than the magnitude reported by RR. This disagreement could be intrinsic source variability or could be due, in part, to slightly different effective wavelengths of the filters used at Palomar and UKIRT. No detection was made at 3.7 μm, and the value in Table 1 is the 3 σ limit. The 3.7 μm limit does not significantly constrain any models of the source.

4. DISCUSSION

RR have suggested that FSC 10214+4724 is either a quasar or a "protogalaxy" heavily enshrouded in dust. The observed colors of this source are significantly redder than those expected of an unreddened quasar or a young galaxy at the observed redshift. Observations of quasars in the redshift range 1.9–2.7 (Soifer et al. 1983; G. Neugebauer & B. T. Soifer, unpublished) show colors of $J-K \sim 1.1 \pm 0.3$ mag and $H-K \sim 0.6 \pm 0.2$ mag, while a galaxy of A0 stars at a redshift of 2.286 would have colors of $J-K = 1.1$ mag and $H-K = 0.2$ mag. The observed $J-K$ color of 2.3 mag suggests $E(J-K) \sim 1.2$ mag, while the observed $H-K$ color of 0.8 mag suggests 0.2 mag $< E(H-K) <$ 0.6 mag. If the typical interstellar reddening curve (Cardelli, Clayton, & Mathis 1989; Mathis 1990) is assumed, the rest-frame extinction is $A_V = 1.5 \pm 0.5$ mag. RR have noted the lack of a 2200 Å extinction feature, which suggests that the reddening is not entirely like that in the interstellar medium of the Milky Way. An upper limit to the extinction can be inferred if the rest-frame optical/UV emission is the long-wavelength (Rayleigh-Jeans) limit of a hot blackbody ($T \gtrsim 40{,}000$ K). Then the intrinsic colors should be 0 mag, so the maximum reddening would be about twice that determined above.

The inferred extinction permits an estimate of the mass of gas, if a normal gas-to-dust ratio is assumed (Savage & Mathis 1979). If the extinction is uniformly spread over a sphere 10 kpc in radius (to maximize the required mass), the rest-frame extinction of $A_V \sim 1.5$ mag implies a gas mass of $10^8\ M_\odot$, at least three orders of magnitude less than inferred by RR from the dust emission. It is plausible that the gas-to-dust ratio is greater than that found in the Milky Way interstellar medium, but this is unlikely to be more than one order of magnitude, leading to a minimum of two orders of magnitude discrepancy between the dust mass derived from the thermal emission and from the extinction. While the dust-mass estimate assumes a spherically symmetric shell, effects of radiative transfer should not alter this result by orders of magnitude. A plausible explanation for this discrepancy is that the optical source is seen through a substantial hole in the dust shroud, or perhaps the source that powers the infrared luminosity is not detected. The latter interpretation is made more plausible by comparison with nearby ultraluminous infrared galaxies. For example, in Arp 220 it is clear that the source of the energy is optically invisible, and the visible source is on the outskirts of the ultimate power source of the infrared luminosity (Graham et al. 1990).

The observations presented here do not allow us to make a clear distinction between the alternative models proposed by RR for the origins of the luminosity in FSC 10214+4724, but they do provide constraints on these models. If the low signal-to-noise broad wing of the Hα line is confirmed, this would strongly argue that the source is indeed a dust-enshrouded quasar. Obviously, higher signal-to-noise, higher spectral resolution observations of this line are required to clarify this.

From the Hα equivalent width and K-magnitude, the observed flux in the Hα line is 1.8×10^{-17} W m^{-2}, corresponding to an Hα luminosity of 2×10^{38} W for $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. If the origin of the luminosity is a starburst, then it is likely that case B recombination describes the emitting region and the Hα luminosity corresponds to an ionizing flux of 1.5×10^{57} photons s^{-1}, uncorrected for extinction. This leads to a ratio of total luminosity to ionizing photon flux L/Q of 2×10^{-43} $L_\odot$ s, which is comparable to estimates from the starburst models of Scoville & Soifer (1991). If the source is indeed observed through a hole with $A_V \sim 1.5$ mag, then $A_{\mathrm{H}\alpha} \sim 1.1$ mag, so that the corrected L/Q is 0.7×10^{-43} $L_\odot$ s. This value is within the range of parameters for starbursts deduced by Scoville & Soifer if the age of the burst is in the range 10^7–10^8 yr, and the upper mass limit for the initial mass function of stars is 23–75 $M_\odot$. The total mass converted to stars in such models is $\sim 10^{12}$ $M_\odot$, nearly independent of the burst duration, so it is likely that more than 10^{11} $M_\odot$ of metal-rich gas is associated with the galaxy in such a model.

If, instead, the source is a dust-enshrouded quasar, it is not surprising that the Lyα line from the broad-line region was not seen by RR, since the Lyα extinction corresponding to $A_V \sim$ 1.5 mag is 4.5–6 mag (Cardelli et al. 1989; Mathis 1990). In this case none of the UV resonance lines would be coming from the broad-line region; rather, the lines would likely be coming from the circumnuclear environment. The observed equivalent width of the Hα line of ~ 0.07 μm implies a broad-line region, which is not unusual for quasars, i.e., the broad-line region would have a covering factor of roughly 0.2. If the infrared luminosity of the source is due to thermal reradiation by dust, the dust covering factor must be substantially greater, i.e., $\sim 98\%$, to account for the fraction of the total bolometric luminosity reradiated in dust. The dust responsible for this reradiation is not associated with the broad-line clouds, but rather is at a much greater distance from the central source. For a quasar of luminosity 3×10^{14} $L_\odot$, the broad-line region would be expected to be at a radius of ~ 3 pc, while the dust at a temperature of 500 K, the hottest inferred from the observed energy distribution (RR), would be at a distance of 300 pc for such a luminous quasar (Phinney 1989). Dust at 1500 K, barely able to survive against sublimation, would be ~ 10 pc from the power source in such a luminous quasar (Phinney).

From the observed magnitudes at 1.2 and 1.65 μm, the intrinsic blue luminosity, νL_ν (0.44 μm) is $\sim 1.0 \times 10^{13}$ $L_\odot$; the inferred extinction is 2.2 mag at 0.39 μm and 1.7 mag at 0.50 μm (for a typical extinction curve). Using the bolometric correction for quasars derived in Sanders et al. (1989), i.e., $L_{\mathrm{bol}}/\nu L_\nu(B) = 15$, we estimate the bolometric luminosity of this source to be 1.5×10^{14} $L_\odot$, quite consistent with the observed infrared luminosity from 6 to 36 μm of 3×10^{14} $L_\odot$. The existence of optically selected quasars with comparable luminosities (e.g., S5 0014+81; Véron-Cetty & Véron 1989) makes plausible the model of a dust-enshrouded object of this kind. RR estimate that the dust cloud required to produce the infrared luminosity in such a model is 4×10^8 $M_\odot$, or a total gas mass of $\sim 10^{11}$ $M_\odot$. This is only twice that found in the most molecular gas-rich galaxies known nearby (Sage & Solomon 1987; Sanders, Scoville, & Soifer 1988), while the distribution of the gas at 100–1000 pc from the power source, inferred from the observed range of dust temperatures of 150–500 K, is comparable to that seen in nearby, lower luminosity systems (Scoville & Soifer 1991).

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