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G25.5+0.2: A RING NEBULA AROUND A LUMINOUS BLUE STAR

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ABSTRACT

We have obtained infrared images and infrared spectroscopy of the Galactic radio source G25.5+0.2, previously suggested to be a young supernova remnant. The 2.2 μm image exhibits a similar nebular structure to that seen in the radio. Spectroscopic measurements at 2.17 μm show a Brγ line that has the line-to-continuum ratio expected from ionized hydrogen at a temperature near 10,000 K. The line is resolved and has a total extent of 300 km s^{-1}. Ten micron photometry clearly establishes a physical connection between G25.5+0.2 and the *IRAS* source 18344−0632. Most important, the infrared image reveals a point source in the center of the nebula that has properties of a blue supergiant star that could excite an ionized ring nebula with the observed radio properties. G25.5+0.2 is almost certainly a ring nebula around a mass losing luminous blue star ~13.5 kpc distant and reddened by 20 mag of visual extinction.

Subject headings: ISM: individual (G25.5+0.2) — supergiants — supernova remnants

1. INTRODUCTION

Cowan et al. (1989) reported extensive observations of the Galactic radio source G25.5+0.2. These included radio continuum images at four frequencies, 21 cm absorption measurements, and a search for radio recombination line emission. Based primarily on the absence of the H76α recombination line, Cowan et al. concluded that G25.5+0.2 is a very young Galactic supernova remnant, perhaps only 25 years old. Based on 21 cm H I absorption lines, they give a minimum distance to G25.5+0.2 of 7.2 kpc. White & Becker (1990) and Green (1990) suggest that identification of G25.5+0.2 as a planetary nebula is more likely, based on the radio observations and *IRAS* fluxes. A third model, proposed by Zijlstra (1991), is that G25.5+0.2 belongs to a group of young outflow objects. We present infrared (1–2.5 μm) imaging and spectroscopy that demonstrates that G25.5+0.2 surely is not a very young supernova remnant, but is rather a ring nebula around a massive blue star that is in a mass loss stage. These results are in basic agreement with the new radio recombination line measurements of Subrahmanyan et al. (1993).

2. OBSERVATIONS

2.1. *Near-Infrared Imaging*

Infrared images of G25.5+0.2 were obtained at Mauna Kea Observatory in the photometric bands at *J* (1.25 μm), *H* (1.65 μm), and *K* (2.2 μm) using IRCAM on UKIRT (McLean 1987) in 1989 July. The images were bias-subtracted and flat-fielded using a median sky flat. Standard stars and faint white dwarfs of known magnitude were measured at *J*, *H*, and *K* to obtain the flux calibration. The overall uncertainty in the fluxes is estimated at 10%. Figure 1 is a contour plot of a 180 s *K* exposure taken with a 0″.62 $pixel^{-1}$ scale. The contours show extended emission on a scale of 5″–10″ FWHM, similar to the radio source size shown in Figures 1 and 2 of Cowan et al. (1989); the positional agreement (±2″) and the structural agreement assure physical association. At the very center of the extended 2.2 μm emission is a very red, unresolved source that we assume is a star. Photometry at *J*, *H*, and *K* of the star with the nebula subtracted is given in Table 1. Imaging of the central point source in 1993 June using the UCLA infrared camera KCAM (McLean et al. 1992) on the 3 m telescope at Lick Observatory produced a *K*′(2.1 μm) magnitude of 12.55.

2.2. *Infrared Spectroscopy*

Low-resolution spectra of G25.5+0.2 in portions of the atmospheric windows near 1.65 and 2.15 μm were obtained on the United Kingdom Infrared Telescope (UKIRT) on 1989 August 25 (UT) using a circular variable filter (CVF) with a resolving power (*R*) of ~100 and an aperture of diameter 12″ on the sky. The spectral regions covered contain an Fe II line at 1.64 μm, high *n* Brackett (Br) series lines between 1.60 and 1.70 μm, and the Brγ line at 2.17 μm. The spectra, along with one of the planetary nebula, NGC 6572, are shown in Figure 2. They were flux-calibrated using the bright star HR 6698. The prominent characteristics of the G25.5+0.2 spectrum are a strong Brγ line and a red continuum. The Fe II line is weak and apparently blended with the Br 12 line of roughly equal strength.

Moderate-resolution (R ~ 330) 2.04–2.44 μm spectra (not shown) were obtained of G25.5+0.2 on 1991 April 17 at UKIRT, using CGS 4. In addition to Brγ, these data reveal a strong He I 2.06 μm line, of equal strength to Brγ, both extending ~15″ along the NS slit. In the central part of the nebula a weak He I 4–3 blend is seen at 2.115 μm; its strength is ~1/15th that of Brγ. The He II 10–7 line at 2.191 μm was not detected and is less than 1/50th the strength of Brγ.

High-resolution spectra of the Brγ line were obtained using the echelle of CGS4 on 1991 September 12. For these data the width of the NS slit of the spectrograph subtended 2″.5 on the sky, and the dimensions of each pixel along the slit corresponded to 3″.8. As in the moderate-resolution data, Brγ emission was seen in a region ~15″ in declination, covering four rows of the array. The four spectra, smoothed to a resolution of

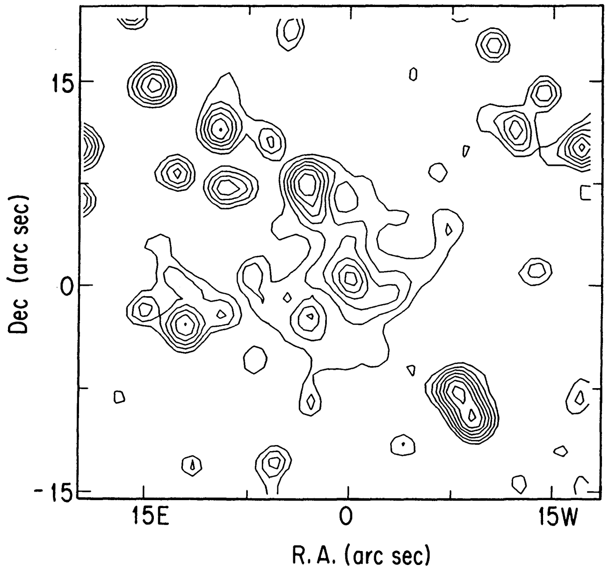

FIG. 1.—A 2.2 μm (K) contour plot centered on G25.5+0.2 obtained on the UKIRT with IRCAM. The contour intervals are 0.4 magnitudes (factor of 1.45). The lowest contour is $K = 16.0$ mag per square arcsec. The scale is 0″.62 pixel^{-1}, the InSb detector array had 58 × 62 pixels, and the integration time was 180 s. Similar images were taken at 1.65 (*H*) and 1.25 (*J*) microns. The reddest object is a point source in the center of the extended emission at position 0,0 on the map. The ~20 blue point sources across the field are probably foreground stars unrelated to G25.5+0.2. The position 0,0 corresponds to RA = $18^h34^m23^s.9 \pm 0^s.2$; Decl. = $-06°32'13'' \pm 2''$ (1950) as determined from offsetting the UKIRT telescope from nearby SAO stars.

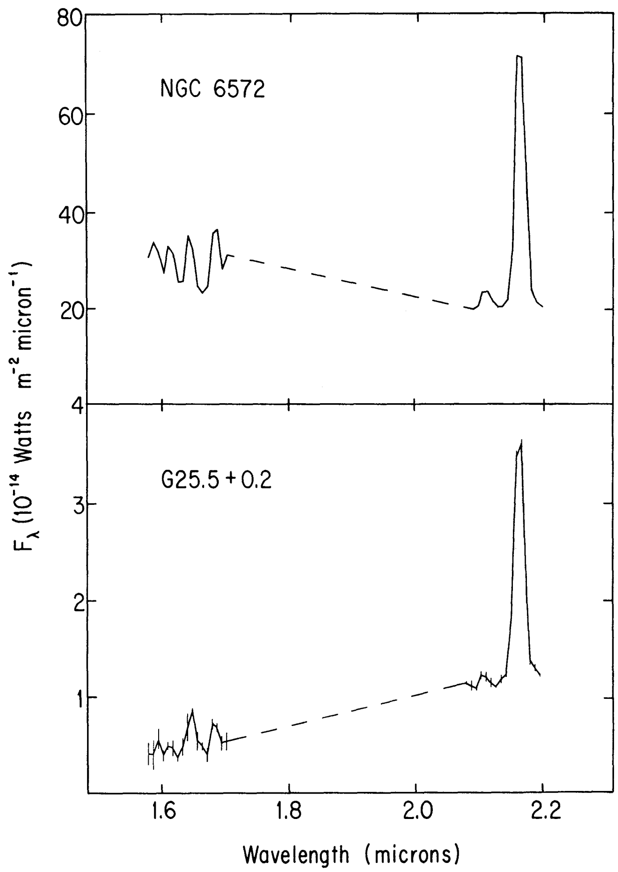

FIG. 2.—A CVF spectrum of G25.5+0.2 (*bottom*) obtained with UKT-9 on the UKIRT. The focal plane diaphragm had a 12″ diameter and the spectral resolution was $\Delta\lambda/\lambda = 0.01$. Also shown for comparison is the planetary nebula NGC 6572 (*top*). Brackett lines are seen at 2.17, 1.68, 1.64, 1.61, and 1.59 μm. Also at 1.64 μm is an Fe II line (which is found to be very strong in supernova remnants). The broken line connects the two spectral regions where measurements were obtained.

50 km s^{-1} are shown in Figure 3. The full width of the line in the central part of the nebula is ~300 km s^{-1}. The central LSR velocity is $+20 \pm 20$ km s^{-1}. A modest degree of bipolarity is evident in these spectra. The northern ionized gas contains a blueshifted component, whereas the southern gas is more redshifted. Several velocity peaks are seen, which may indicate discrete outflows, or shells. A better understanding of the bipolarity requires additional high-resolution spectra with higher spatial resolution and coverage of the entire nebula.

2.3. *10 Micron Photometry*

In 1989 August, the IRTF bolometer with a 7″.2 focal plane aperture centered on the radio source, was used to measure a 10 μm flux of 1.6 Jy through a broad-band *N* filter ($\Delta\lambda = 5$ μm). This places a firm lower limit to the 10 μm flux from G25.5+0.2. A five-point map on an 8″ grid showed that the 10 μm flux peaks on the center of the radio source.

2.4. CO (3–2) *Observations*

N. Evans and D. Jaffe very kindly obtained CO ($J = 3$–2) line observations of G25.5+0.2 with the 10 m CSO at Mauna Kea Observatory on 1989 November 4. A five-point map on a 30″ grid with a 20″ diameter beam showed a 2–4 K CO emission line at all five positions. The line has a width of ~15 km s^{-1} and a central LSR velocity of +106 km s^{-1}; the emission is therefore not associated with G25.5+0.2.

3. RESULTS

3.1. *Distance*

Cowan et al. (1989) give a minimum distance to G25.5+0.2 of 7.2 kpc based on H I absorption lines. This, together with the Brγ line velocity of 20 km s^{-1}, the Galactic rotation model in Figure 4 of Kerr & Westerhout (1965), and a Galactic center distance of 8.2 kpc implies a distance to G25.5+0.2 of 13.5 ± 1 kpc. We adopt this distance for the remainder of the paper.

3.2. *Reddening due to Interstellar Dust*

Before proceeding, it is necessary to determine the interstellar extinction toward G25.5+0.2. This can be estimated in several ways. First, we assume that the point source in the center of the nebula is associated with it and has the infrared colors of a star. Below we show that the point source is most likely to be an early supergiant star. Using the reddening law of Becklin et al. (1978) and the intrinsic colors for an early-type star given in Koornneef (1983) $H-K = -0.1$, $J-H = -0.1$, we find a moderately good fit to the observed colors with $A_K = 2.2$ mag or $A_V = 24$ mag. Second, we can assume that the 1.6–2.2 μm spectral shape of G25.5+0.2 and NGC 6572 are intrinsically the same because of the similarity in the line-to-continuum ratio (Fig. 2). The observed difference we ascribe to reddening; again using the Becklin et al. (1978) extinction curve, we derive $A_K = 1.8$ mag. Below, we assume that the extinction to G25.0+0.2 is $A_K = 2.2$ mag and that the extinction to the star is similar to that of the nebula. The uncertainty in the derived extinction at 2.2 μm is ~0.5 mag.

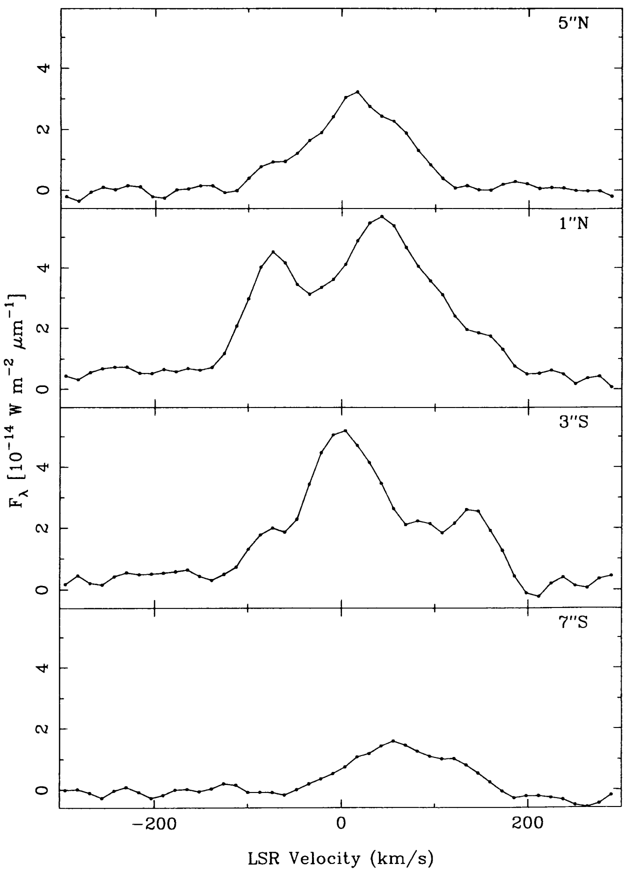

FIG. 3.—CGS4 spectra of Brγ at a resolution of 50 km s^{-1}. The slit, 2″.5 wide in right ascension, was placed near the center of G25.5+0.2. The long axis of the slit was north-south. Each spectrum corresponds to a region 3″.8 in declination. No emission was seen in the pixels north or south of those shown. Noise can be judged by the fluctuations in the baselines at the edge of the spectra. The positions listed are with respect to the central infrared point source and are accurate to $\pm 1''$.

3.3. *The Central Star*

To characterize the unresolved point source in the center of the nebula, we must correct the measured magnitudes (Table 1) for reddening. With an extinction of $A_K = 2.2$ mag and the reddening curve of Becklin et al. (1978), the apparent extinction-corrected magnitudes are given in column (4) of Table 1. At a distance of 13.5 kpc, the absolute K magnitude of the central star is $M_K = -5.3$.

3.4. *The Ionized Gas*

The spectrum in Figure 2 has a Brγ line-to-continuum ratio typical of those produced by regions of ionized gas (e.g., Wynn-Williams et al. 1978; Willner et al. 1979; and this paper). The measured line strength, corrected for $A_K = 2.2$ mag of reddening, can be converted to an expected free-free radio flux following Wynn-Williams et al. (1978) assuming $T_e = 10^4$ K. From Figure 2 we estimate a Brγ line strength of 5×10^{-16} W m^{-2} in a 12″ beam. Correcting for reddening of a factor of 7.6, and for flux outside the 12″ diameter beam, estimated from the radio map to be ∼20%, we derive a radio free-free flux of 0.5 Jy, which is similar to but slightly larger than the measured 6 cm radio flux of 0.34 Jy (Cowan et al. 1989). This implies that both the infrared flux and the radio flux are predominantly from ionized hydrogen free-free and bound-free radiation. The fact that the radio flux derived from the reddening corrected infrared flux is slightly higher than the measured radio flux is probably due to a combination of errors in the reddening curve and photometry, excess stellar, and dust emission in the K window and possibly more reddening to the star than to the nebula. Using formulae summarized in Genzel et al. (1982) we calculate the number of ionizing photons (N_L) and the luminosity of the Lyα line to be

$$\log N_L = 48.7\,, \quad L(\text{Ly}\alpha) = 2 \times 10^4\, L_\odot\,.$$

3.5. *Dust Emission from the Nebula*

The 10 μm flux of 1.6 Jy measured with a 7″.2 beam centered on the nebula demonstrates that thermal emission from dust originates in and around G25.5+0.2 since free-free and line emission would be less than 0.2 Jy (Willner, Becklin, & Visvanathan 1972). If the emission originates from a region that has the same shape as the radio and 2.2 μm sources, then the total 10 μm emission from the nebula is ∼4 Jy. This may be compared to the 6 Jy flux from the 12 μm *IRAS* source 18344−0632 in the ∼1′ *IRAS* beam. Considering the shape of the spectrum and likelihood of strong interstellar silicate absorption at 9.5 μm, the agreement of the two measurements establishes that the flux from IRAS 18344−0632 is associated with G25.5+0.2. Without the benefit of ground-based 10 μm measurements, White & Becker (1990), Green (1990), and Zijlstra (1991) independently deduced that IRAS 18344−0632 should be identified with G25.5+0.2, in spite of the 25″ discrepancy of the radio and *IRAS* position. Such a positional discrepancy when the quoted *IRAS* 95% confidence error in the cross-scan direction is 19″ is unlikely, but clearly possible.

The *IRAS* fluxes from G25.5+0.2 are given in Table 2. Column (2) gives results from the *IRAS* Point Source Catalog (PSC). Column (3) gives the *IRAS* flux from "Add Scans" obtained by Dr. G. Hawkins (1990, private communication) for the best-fit point source. The energy distribution is characteristic of a thermal source associated with ionized hydrogen (e.g., Wynn-Williams & Becklin 1974). Integration of the total *IRAS* flux gives $L_{\text{IR}} \sim 10^5\, L_\odot$.

TABLE 1

PHOTOMETRY OF CENTRAL STAR OF G25.5+0.2

Band (1)	λ (μm) (2)	Observed (mag) (3)	Reddening Corrected (mag) (4)
J.........	1.25	16.5	10.2
H.........	1.65	13.7	9.9
K.........	2.2	12.6	10.4

TABLE 2

IRAS FLUXES[a]

λ (μm) (1)	PSC (2)	Point Source Add Scans (3)
12	6	8
25	85	89
60	144	195
100	<466	270

[a] In janskys.

4. DISCUSSION

4.1. *Not a Supernova Remnant, Planetary Nebula, or Orion-like* H II *Region*

Our results, first discussed in Zuckerman (1993) and Becklin (1993), are consistent with the conclusions of Subrahmanyan et al. (1993) and of Zijlstra (1991) that G25.5+0.2 is neither a supernova remnant nor a planetary nebula. The infrared line and radio continuum emission are characteristic of an ionized region of temperature $\sim 10^4$ K and the line widths are too narrow to be the result of a supernova and too broad for a planetary nebula. The extended thermal continuum of G25.5+0.2 is considerably brighter than that expected from even a young SNR. Moreover, the central star is too bright for G25.5+0.2 to be either of the above objects. The large Brγ line width also rules out G25.5+0.2 being a young H II region like the Orion Nebula. The lack of strong molecular line emission from an associated cloud, and the *IRAS* colors of the source also argue against such an interpretation. Becklin (1993) argues, based on the number of ionizing photons and the absolute K magnitude, that the central star is a B0 to O9 supergiant.

4.2. *A Ring Nebula around a Massive Blue Supergiant Star*

Some Wolf-Rayet and emission-line O supergiant stars that have evolved from a massive main-sequence Population I star ($M \geq 40\ M_\odot$) are known to have associated ringlike nebulae of ionized gas (e.g., Chu 1982, 1991). The nebulae are thought to result from the interaction of a stellar wind ($V = 1400$ km s^{-1}) and the interstellar medium (Chu 1982; Tutukov 1982). The mass in the ionized ring results both from interstellar gas swept up by the wind and from mass loss from the massive star itself; the former material is thought to dominate (Tutukov 1982). Ring nebulae are much less common in the Galaxy than planetary nebulae. The ionization of the nebula comes from the ultraviolet radiation from the central star. Most known nebulae of this type are excited by Wolf-Rayet stars. Based on the strength of He I 4–3 relative to H I Brγ and the absence of He II 10–7, we judge that He/H is not far from normal in G25.5+0.2 and that the nebula likely is ionized by a B0 or O9 supergiant star.

Interpretation of G25.5+0.2 as a ring or bubble nebula explains naturally the broad recombination line seen in Brγ. The expansion velocity of ring nebulae is typically between 30 and 80 km s^{-1} (Georgelin & Monnet 1970; Lozinskaya & Esipov 1969; Pismis & Quintero 1982; Chu 1991). G25.5+0.2 is thus a rather extreme member of this class of objects because of the large expansion velocity. The ring nebula interpretation also explains the general morphology. The very symmetric-appearing emission in G25.5+0.2 is typical of many ring nebula, for example the ring nebula M1-67 (Felli & Perinotto 1979). The lack of CO emission at the kinematic velocity and the relatively large 25 to 60 μm flux ratio are also expected for a mass-loss–generated ionized nebula (White & Becker 1990). The physical diameter of the G25.5+0.2 ring is 1.0 pc, slightly smaller than any of the nebulae discussed by Tutukov (1982). The mass of the ionized gas is $\sim 15\ M_\odot$ based on equation (2) in Schneider et al. (1987). The infrared luminosity of $10^5\ L_\odot$ is $\sim 30\%$ of the total energy output of the central star. Other ring nebula such as M1-67 (*IRAS* Point Source Catalog; Joint *IRAS* Science Working Group 1988), S308, and NGC 6888 (Van Buren & McCray 1988) are strong *IRAS* sources but have a much lower fraction of the stellar luminosity emitted at infrared wavelengths.

We feel that an object that could be similar to G25.5+0.2 is the nebulosity pair NGC 6164-5, that surrounds the Of star HD 148937 (Bruhweiler et al. 1981; Dufour et al. 1988) and which originally was thought to be a planetary nebula. The radial velocities of the bright bipolar knots of NGC 6164-5 (see Fig. 1 in Dufour et al.) are only +21 and −43 km s^{-1}, but if its inclination is $\sim 10°$, which is plausible, then the true outflow velocities are comparable to those of G25.5+0.2. In other words, the primary outflow of G25.5+0.2. is nearly perpendicular to the plane of the sky whereas the outflow of NGC 6164-5 is nearly in the plane of the sky. The latter is suggested to be 1.3 kpc from Earth and, if so, then its linear size, a few parsecs, is similar to that of G25.5+0.2. Relative to H II regions, NGC 6164-5 has unusual elemental abundances, O is depleted and N and He are enriched. Dufour et al. remark that the star and nebula may be more akin to Eta Carinae and its condensations than to a Type I planetary nebula. Perhaps future IR spectroscopy of G25.5+0.2 will reveal abundances similar to those in NGC 6164-5.

Finally, most of the results and conclusions, given here are in agreement with those of Subrahmanyan et al. (1993) based on similar observations. Two primary differences exist. First we deduce an absolute *K* magnitude of $M_K = -5.3$ for the central object, while Subrahmanyan et al. deduce $M_K = -7$. David Allen (private communication) has pointed out that their color transformation from the *K* to *K′* filter is in error and their revised absolute magnitude is $M_K = -6.3$. Most of the difference between our value of $M_K = -5.3$ and their new value results from the *K* photometry which, when corrected for the different filters used, differs by 0.6 mag. Our most recent measurement mentioned in § 2.1 is intermediate between these two extremes and may indicate intrinsic variability of the central star.

A second difference between our results and those of Subrahmanyan et al. is that they conclude that the central object is on or near the main sequence with a spectral class hotter than O7. This is certainly incorrect since the absolute K magnitude of such a main-sequence star would be about $M_K = -4$ according to the models of Panagia (1973) and the colors in Koornneef (1983). In addition, David Allen (private communication) has pointed out an error in Figure 8 of Subrahmanyan et al. When this error is corrected, they would place the object above the main sequence by 2–3 mag. We thus believe that our interpretation of the object as an O9 to B0 supergiant is correct.

5. CONCLUSIONS

Based on infrared imaging, spectroscopy, and photometry, G25.5+0.2 is not a young supernova remnant. Based primarily on the discovery of a central point souce at 1.25, 1.65, and 2.2 μm, the near-infrared spectrum and the broad line width, we believe that G25.5+0.2 contains an O9 to B0 supergiant star which by vigorous mass loss has produced a ring nebula. It is interesting to note that this is not the first ring nebula that has been mis-identified as a supernova remnant. For example, NGC 6888 was thought by some authors to be a supernova remnant before analysis of radio and optical observations by Johnson (1973).

We thank A. J. Noymer for enthusiastic help with the imaging observations and early reduction of the data. N. Evans and D. Jaffe kindly made CO (3–2) observations, G. Hawkins provided us with *IRAS* add scan data, A. Tokunaga obtained early high-resolution Brγ observations, and T. Liu obtained and reduced the K' image in 1993 June. C. G. Wynn-Williams kindly pointed out to us the similarity of G25.5+0.2 and a Wolf-Rayet ring nebula. We thank R. Ekers for sending us their paper before publication. We especially thank D. Allen for a very special effort to communicate his most recent results just as he was to undergo major surgery. This research was supported in part by several NSF Grants to UCLA.

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Note added in proof.—Subrahmanyan et al. have submitted an erratum to MNRAS with a revised Figure 8. They now agree with us that the central star is off the main sequence. They suggest that the mass of the star may be as high as 100 $M_\odot$. Our absolute K magnitude of -5.3 is more consistent with a -50 $M_\odot$ supergiant, according to the models of Maeder & Meynert (A&A, 210, 155).