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G25.5 + 0.2: a new luminous blue variable in the Galaxy?

Ravi Subrahmanyan,[1]* R. D. Ekers,[1] W. E. Wilson,[1] W. M. Goss[2] and David A. Allen[3]

[1] *Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia*
[2] *National Radio Astronomy Observatory, PO Box 0, Socorro, NM 87801, USA*
[3] *Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia*

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ABSTRACT

Using the Australia Telescope, the Galactic source G25.5 + 0.2 has been detected in broad H105α and H106α radio recombination lines. Subsequent observations with the Very Large Array detected the H92α transition. The width of the recombination line is about 200 km s^{-1}, attributed to large-scale velocity structure. Infrared imaging and spectroscopy with the Anglo-Australian Telescope reveals a luminous central star with an absolute magnitude of $M_K \sim -7$ that is at least as hot as an O7 main-sequence star. The object is not a supernova remnant as was previously suggested. We interpret G25.5 + 0.2 as an unusually energetic ejection associated with a post-main-sequence star of very high mass. The exceptional thermal bremsstrahlung emission from the nebula is due to photoionization by the high Lyman continuum flux of the central star.

Key words: stars: variables: other – H II regions – ISM: individual: G25.5 + 0.2 – ISM: jets and outflows – radio lines: ISM.

1 INTRODUCTION

A Very Large Array (VLA) survey of 290 small-diameter (< 2 arcmin) objects in the Galactic Plane (Sramek et al. 1992) identified only one source, G25.5 + 0.2, as a candidate young supernova remnant. The radio structure was observed to be bipolar or of shell type, and the integrated radio spectrum was unpolarized and flat with a low-frequency turnover at about 1 GHz (Cowan et al. 1989). Although these radio properties are consistent with a thermal interpretation for the emission nebula, no radio recombination lines were detected with the VLA, suggesting that the source is not a conventional H II region. Primarily for this reason, G25.5 + 0.2 was proposed as a young supernova remnant with an age of between 25 and 100 yr.

An *IRAS* source, 18344 – 0632, has a positional error box that barely includes G25.5 + 0.2. The unusual nature of G25.5 + 0.2 and its close proximity to this *IRAS* source suggest that they could be the same object. The *IRAS* colours and the radio-to-infrared flux density ratio led Helfand et al. (1989) to interpret G25.5 + 0.2 as an H II region. White & Becker (1990) suggested that it was more likely to be a planetary nebula. The *IRAS* low-resolution spectrum also resembles that of a compact H II region or planetary nebula (Green 1990). Since the non-detection of radio recombination lines could be due to large-scale velocity structure in the thermally emitting gas, Zijlstra (1991) proposed that the source is a young outflow object.

The ambiguity caused by the uncertainty in the identification of the *IRAS* object with G25.5 + 0.2 was partially resolved by *K*-band imaging of the field by Becklin et al. (in preparation), which showed a red object with extended nebulosity at the position of the radio source. Infrared spectroscopy revealed Brackett γ emission with a width (FWHM) of ≈ 230 km s^{-1}, and these observations are consistent with a thermal stellar outflow.

We report here our detection of broad radio recombination lines from G25.5 + 0.2 with the wide bandwidths available in the spectral-line system of the Australia Telescope (AT). In addition, the H92α transition has now been detected with the VLA using higher sensitivity and spectral resolution. Infrared imaging and spectroscopic observations were made using the Anglo-Australian Telescope. The implications of these observations for the nature of G25.5 + 0.2 are discussed in Section 5.

2 OBSERVATIONS OF H105α AND H106α RECOMBINATION LINES

We observed G25.5 + 0.2 with the AT on 1992 March 7 to search for unusually broad radio recombination lines that

*On leave from the Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India.

might have eluded detection with the VLA. Five antennas of the AT compact array were used in a 750-m configuration. Simultaneous observations were made of the H 105α and H 106α transitions using two bands of 64 MHz centred close to the rest frequencies (5600.567 and 5444.273 MHz, respectively). The observations were made in a pair of orthogonal linear polarizations in both bands. Spectra were obtained in 64 frequency channels at each transition, with channel separations of 53.5 and 55.1 km s^{-1} respectively. The bands individually spanned a velocity range of about ± 1400 km s^{-1} with respect to the local standard of rest (LSR).

G25.5 + 0.2 was observed for a total of about five hours, and the 1-MHz resolution spectra at each of the two frequencies were expected to have an rms noise of ≈ 1 mJy. Temporal changes in instrument complex gain as well as the frequency variations of this gain were calibrated by repeated observations of the unresolved source PKS 1830 − 210. The flux-density scale was set by an observation of PKS 1934 − 638, whose flux density was assumed to be 5.32 Jy at 5444 MHz and 5.12 Jy at 5600 MHz. A set of continuum visibility data was constructed by averaging channel data in LSR velocity ranges −1400 to −400 km s^{-1} and 400 to 1400 km s^{-1}. The continuum was subtracted by removing linear spectral baselines fitted to the channel visibilities in these velocity ranges (Cornwell, Uson & Haddad 1992) and spectral-line visibility data were obtained. Continuum and spectral-line images were made using visibilities that were tapered (assuming a uniform line-to-continuum ratio over the source) to produce optimum signal-to-noise ratio spectra towards G25.5 + 0.2. The Hanning-smoothed spectra of the H 105α and H 106α transitions, with a velocity resolution of 107 and 110 km s^{-1}, are shown in Figs 1 and 2 respectively. The beam corresponding to these spectra has a size of 3.6×0.2 $arcmin^2$ FWHM and a position angle of 0°. The amplitude spectra obtained towards the continuum peak have been normalized by the continuum flux densities towards the peak; the values of the continuum flux density are 352 ± 3 and 335 ± 3 mJy $beam^{-1}$ respectively (errors refer to rms noise in the images). The rms noise in the two spectra is 2×10^{-3} in units of line-to-continuum ratio.

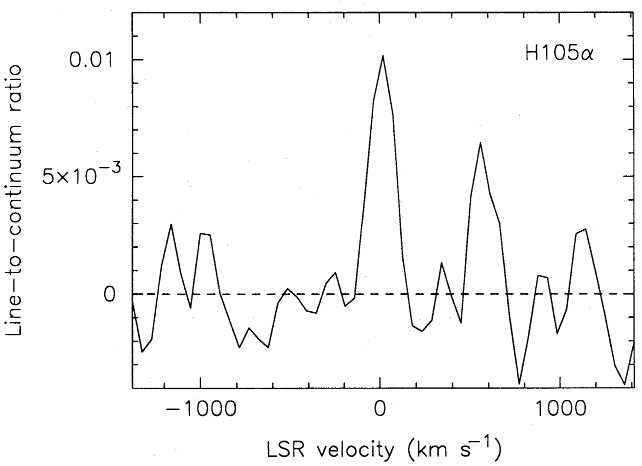


Figure 1. Spectrum of the H 105α radio recombination line towards G25.5 + 0.2 made with the Australia Telescope. The spectral resolution is 107 km s^{-1}. The spectrum is plotted as line-to-continuum ratio against LSR velocity.

Radio recombination lines have been detected in both the transitions with peak flux densities in the lines that are a factor 5 above the rms noise in the spectra.

3 OBSERVATIONS OF THE H 92α RECOMBINATION LINE

G25.5 + 0.2 was observed in the C- and D-array configurations of the VLA in spectral-line mode encompassing the H 92α recombination line (rest frequency 8309.402 MHz). 16 independent frequency channels spanned a bandwidth of 25 MHz, giving useful coverage of the LSR velocity range −345 to +388 km s^{-1} with a velocity resolution of 56.4 km s^{-1}. Spectra were obtained in a single circular polarization.

The observations were made on 1992 May 15 (C array) and 1992 July 26 (D array) and a useful integration time of about 75 min was obtained in each of the array configurations. The unresolved source 1730 − 130 was observed periodically to calibrate the antenna complex gains and their spectral responses. The absolute flux-density scale was also set using the observations of 1730 − 130, whose flux density was adopted to be 5.08 Jy. A set of continuum visibility data was contructed by averaging channel data in the LSR velocity ranges −374 to −204 and +247 to +417 km s^{-1}. The continuum subtraction was performed by fitting and subtracting linear spectral baselines from the complex visibility data. The fits were performed to the channel data in the above LSR ranges alone, but the subtraction was done from all channel data to yield spectral visibilities. The AT observations described above, made with a much wider bandwidth, show that no significant line emission is present at velocities deviating by more than 150 km s^{-1} from the mean LSR velocity of the line emission (14 km s^{-1}). Therefore the determinations of spectral baselines from fits in the above LSR velocity ranges will not bias the derivation of the properties of the line emission from the spectral-line visibilities.

A contour representation of the continuum image of G25.5 + 0.2 at 8310 MHz is shown in Fig. 3. In this 3-arcsec resolution image, the source is resolved into north-east and south-west emission peaks that appear to be part of a shell-type structure of about 15 arcsec extent. The total con-

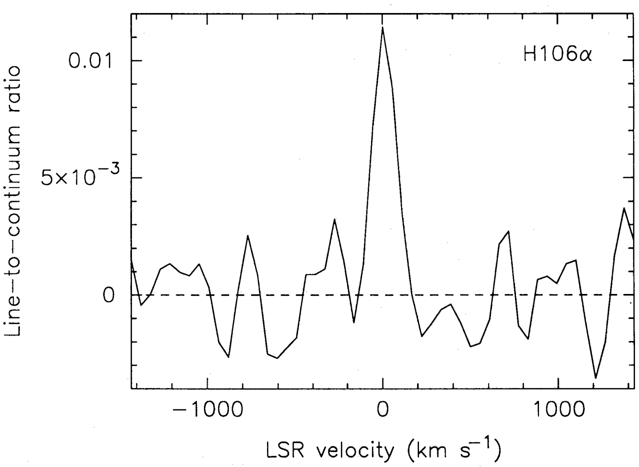


Figure 2. As Fig. 1, but for H 106α. The spectral resolution is 110 km s^{-1}.

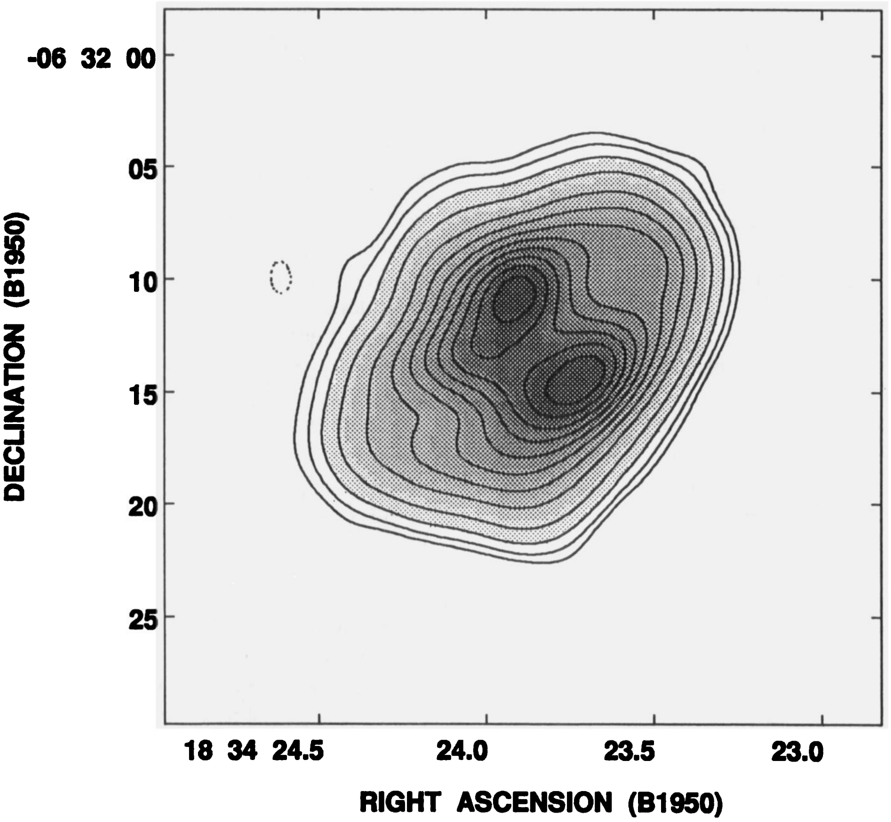


Figure 3. Contour and grey-scale representations of the 8310-MHz continuum image (VLA) of G25.5 + 0.2 made with a Gaussian beam of 3.2×2.8 arcsec^2 at a position angle of 6°.5. The peak flux density is 40 mJy beam^{-1}, and contours are at -0.5, 0.5, 1, 2, 4, 8, 12, 16, 20, 24, 28, 32 and 36 mJy beam^{-1}.

tinuum flux density at this frequency is 330 mJy. The structure and flux density are consistent with the continuum observations reported by Cowan et al. (1989).

A spectrum of the H 92α recombination line with high signal-to-noise ratio was obtained by imaging the spectral visibilities using an optimal taper. A continuum image created in similar fashion has a peak intensity of 240 mJy beam^{-1}, and the spectrum towards the continuum peak is shown in Fig. 4. The rms noise in the spectrum is 0.2 mJy beam^{-1} or about 0.1 per cent of the continuum flux density, and the peak value of the observed line is a factor of 20 above this rms noise. The beam corresponding to this spectrum has a size of 14×12 arcsec^2 FWHM.

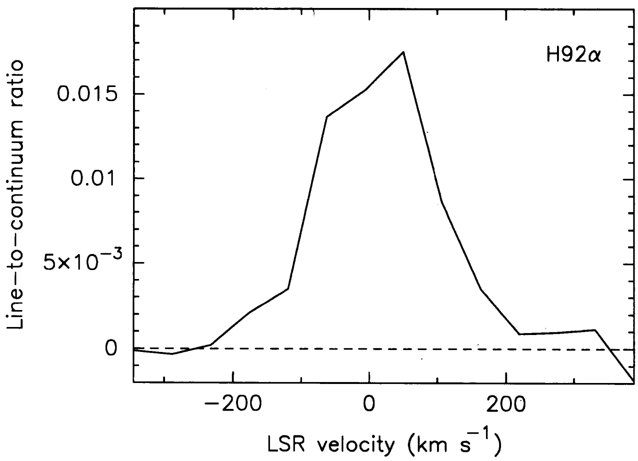


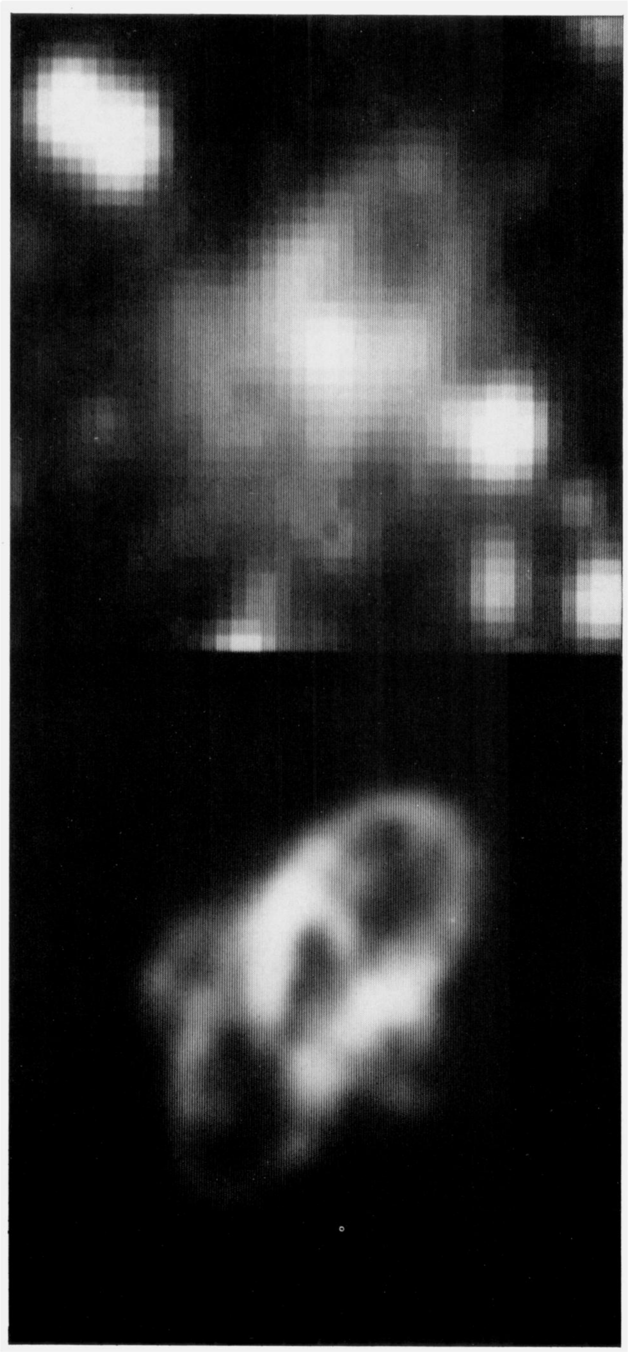
Figure 4. VLA spectrum of the H 92α transition towards the continuum flux-density peak of G25.5 + 0.2 made with a velocity resolution of 56.4 km s^{-1}. The line-to-continuum ratio is shown plotted against LSR velocity, and the rms noise in the spectrum (0.2 mJy beam^{-1}) is about 0.1 per cent of the continuum flux density.

4 INFRARED IMAGING AND SPECTROSCOPY

Infrared observations of G25.5 + 0.2 were made using IRIS (Allen 1992) on the Anglo-Australian Telescope. IRIS combines imaging and low-resolution spectroscopy, and uses a 128×128 format HgCdTe array manufactured by Rockwell International. All observations were made in service time on 1992 October 3 (imaging and spectroscopy) and 10 (imaging and photometry).

The infrared counterpart to G25.5 + 0.2 comprises a very red star enveloped in an elongated emission nebula. Fig. 5(b) (opposite p. 870) shows an image made through an interference filter selecting the Brackett γ (7–4) line of hydrogen. The nebula corresponds closely to the 5-GHz radio image in Cowan et al. (1989), shown in Fig. 5(a).

A spectrum was obtained using an E–W slit across the nebula and central star. We used the cross-dispersed echelle mode in IRIS to cover the wavelength range 1.5 to 2.5 μm. The spectrum was summed along the slit to produce Fig. 6. Since



(a) (b)

Figure 5. Grey-scale images of G25.5 + 0.2, (a) from the 5-GHz radio image in Cowan et al. (1989) and (b) made through a 1 per cent bandpass filter selecting the 2.16-μm line of Brackett γ.

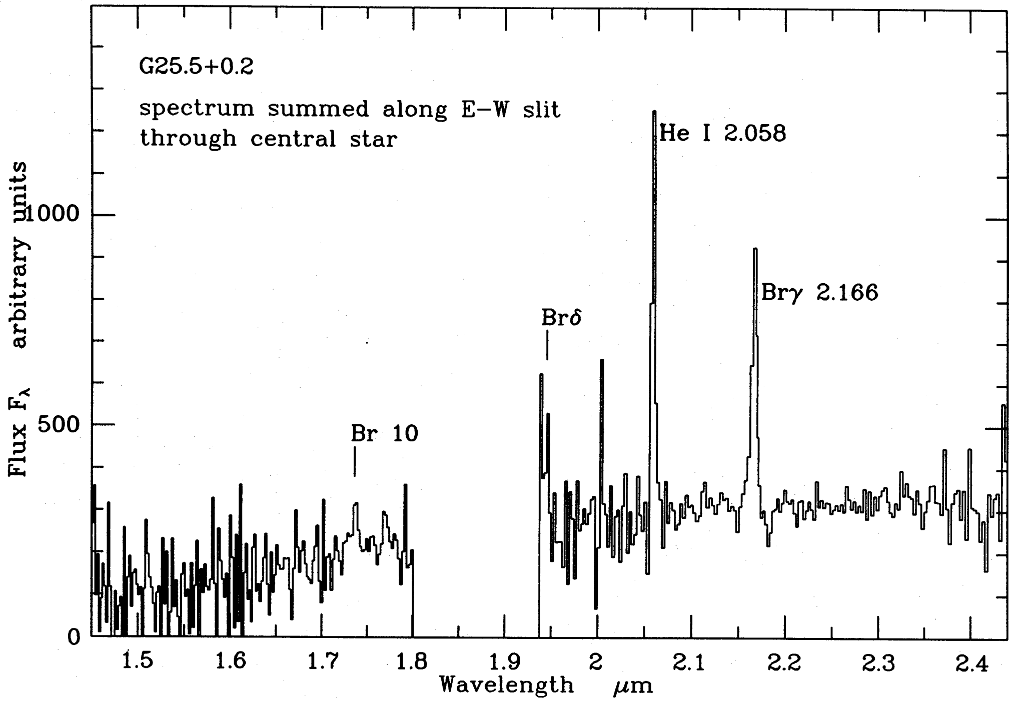


Figure 6. Infrared spectrum of G25.5 + 0.2 obtained through an E–W slit across the nebula and central star. The plot shows a summation of the spectrum over the slit approximately scaled to units of F_λ.

this observation was taken through cloud, no absolute calibration is given. However, correction for atmospheric absorption has been made using a standard star at similar air mass, and the ordinate was then adjusted to be in F_λ. Since cloud extinction is neutral, line ratios are expected to be reliable. Several emission lines are recorded, but intensities can be derived for three only: Brγ, Br10 and He I (2.058 μm). The emission lines of H I, Brγ and Br10, have a ratio of about 7:1.

4.1 Extinction towards G25.5 + 0.2

Two alternative estimates of the extinction can be made. First, from the Brγ image we estimate an integrated line intensity of $0.7 \pm 0.2 \times 10^{-12}$ erg cm^{-2} s^{-1}. The predicted intensity, given the 5-GHz flux density of 0.34 Jy, is 3.3×10^{-2} erg cm^{-2} s^{-1} (cf. Wynn-Williams 1982). Thus the extinction at 2.16 μm (very similar to that at K) is 1.7 ± 0.3 mag. Secondly, our spectrum shows the ratio between the two emission lines of H I, Brγ and Br10, to be 7:1, whereas we would expect a ratio of 3.0:1 (Giles 1977). This is a small baseline over which to determine extinction, but it yields $A_K = 1.6 \pm 0.7$ towards the diffuse nebula.

We derive photometry for the central star from images taken in J, H and K' (1.25, 1.65, 2.12 μm) filters. We find $J = 16.83 \pm 0.08$ (the uncertainty being dominated by confusion), $H = 13.72 \pm 0.02$ and $K' = 12.32 \pm 0.04$. Using the transformation between K (2.2 μm) and K' given by Wainscoat & Cowie (1992) we infer that $K = 11.44 \pm 0.06$. The IRIS J filter has slightly longer effective wavelength than the standard J. The colour indices are close to those of a blackbody at a temperature of 850 K. They are also quite compatible with a hot star extinguished by interstellar material with $A_K \sim 2.7$ mag ($A_V \sim 30$).

If the extinctions towards star and nebula were the same, then the dereddened colours of the star would correspond to 1600 K, which is unrealistically hot for dust. We conclude that extinction towards the star exceeds that towards the nebula, and the near-infrared colours of the star are dominated by extinction rather than by thermal emission from dust.

5 DISCUSSION

5.1 Distance

The H I emission spectrum towards G25.5 + 0.2 shows gas over the entire LSR velocity range −40 to +115 km s^{-1} (Weaver & Williams 1974), whereas the H I absorption spectrum obtained with the VLA (Cowan et al. 1989) shows absorption features only at positive LSR velocities up to +115 km s^{-1}. On the assumption of a simple axisymmetric velocity field for the interstellar matter in the Galaxy and a distance of 8.5 kpc to the Galactic Centre, these indicate that G25.5 + 0.2 is located beyond 7.5 kpc and within 15.5 kpc of the Sun (see, for example, Burton 1988). The average LSR velocities of the radio recombination lines observed at the AT and VLA are 12–14 km s^{-1}. Together, these imply a distance of 14.5 ± 1 kpc from the Sun. The error includes an uncertainty of ± 10 km s^{-1} assumed for possible peculiar motion from the mean Galactic velocity field. The extinction derived towards G25.5 + 0.2 in the preceding section is consistent with a distance beyond the Galactic Centre.

5.2 Thermal gaseous nebula

Since polarized radio emission is not detected from the nebula, we may assume that the entire continuum emission is thermal bremsstrahlung from H II gas. The integral flux in the lines indicates an LTE electron temperature of 5800 ± 200 K (the error quoted is a 1-σ value), which is typical of photoionized H II regions. The radio emission appears to originate in a photoionized thermal plasma with physical properties and radio luminosity similar to a low-density H II region like M42 (Orion A).

The implied linear diameter is ≈ 1.4 pc. If we model the object as a simple spherical H II region with a uniform density distribution, the central density would be about $1.5 \times 10^3 f^{-0.5}$ cm^{-3} and the total mass of thermally emitting gas would then be about $12 f^{0.5}$ M$_\odot$, where f is the volume filling factor. If the H II region is photoionized, an excitation parameter of 55 pc cm^{-2} is required to maintain ionization equilibrium, implying that the central star would have to emit about 8×10^{48} Lyman continuum photon s^{-1}. It follows that any central source of photoionizing radiation would have to be at least as luminous in the Lyman continuum as an O7 main-sequence star. The emission measure is approximately 10^6 pc cm^{-6}.

The source structure in both the radio continuum and Brγ, shown in Fig. 5, suggests a bipolar form, with axis NW–SE, originating from the central star. There is no reason to doubt the association of the star with the nebula. In common with many bipolar nebulae, the lobes are more clearly seen along their peripheries, and thus appear to be hollow. The solid angle covering factor is probably less than unity, in which case the emission measure of the nebula provides a lower limit to the Lyman continuum flux of the central star. We have no firm grounds for choosing a value for the value filling factor, but consider 10^{-1} or 10^{-2} to be compatible with the VLA image, in which case the nebular mass is, at most, a few solar masses.

The infrared emission lines appear weaker at the position of the star than in the nebula to either side. We thus infer that, currently, little mass loss is occurring, and suggest that the nebula was ejected in a brief episode. This is an added reason for believing that warm dust is unlikely to be present and to contribute to the near-infared colours.

The *IRAS* flux density is well determined at 12 and 25 μm, but confusion influences the 60-μm figure, and the 100-μm value is only an upper limit. The 12-, 25- and 60-μm values fit quite well a blackbody at about 120 K. The luminosity of such a blackbody, at a distance of 14.5 kpc, is very close to 10^5 L$_\odot$. This is the main-sequence luminosity of a fairly late O star.

5.3 Velocity structure

The new VLA observations of the H 92α transition have a velocity resolution of 56.4 km s^{-1} and well resolve the recombination line. Its FWHM is 195 km s^{-1}. Radio recombination lines from conventional H II regions have widths of 20–30 km s^{-1} (Caswell & Haynes 1987). Except for the width of the recombination lines, the radio observations are consistent with G25.5 + 0.2 as an H II region with a moderate emission measure. The peak line-to-continuum ratio is observed to be about 1–2 per cent towards G25.5 + 0.2, whereas conventional H II regions have values of about 10 per cent at centimetre wavelengths. The anomalous width is most likely due to Doppler broadening. The nebula is clearly composed of thermal plasma, but with a velocity structure unusual in H II regions.

The H 92α transition appears broader than either H 105α or H 106α (compare Figs 4, 1 and 2). Continuum images at 1.5 and 8.3 GHz, both being able to resolve the north-east and south-west components, show no significant differences. In addition, the radio continuum image at 1.5 GHz has a peak brightness of 2000 K, which is well below the electron temperature of the nebula. Therefore the object is optically thin above 1.5 GHz, and any changes in emission-line widths are probably not due to optical depth effects. Since the AT is an east–west array and G25.5 + 0.2 has a low declination, the synthesized beam for the H 105α and H 106α observations is more elongated north–south than the VLA synthesized beam. The difference in the observed line widths therefore suggests velocity structure across the source.

The widths of the radio recombination lines exceed those observed in any other Galactic object. We constructed spectral-line image cubes in the H 92α transition to examine the distribution of velocity over the source. Separate spectra along lines of sight towards the north-east and south-west peaks are shown in Fig. 7. The width towards the north-east peak is about 70 per cent greater than that towards the south-west peak, and structure is evident in the velocity distribution over the source. However, we find no evidence for any linear velocity gradient as expected in a one-dimensional bipolar flow. The velocity field is also inconsistent with a homogeneous rotating system. The velocity structure is complex and contains non-aligned components with velocities of about 100 km s^{-1}.

5.4 The nature of the central star

We adopt an extinction $A_K \sim 2.5$ mag. A distance of 14.5 kpc therefore leads to an unreddened $M_K \sim -7$. For a main-

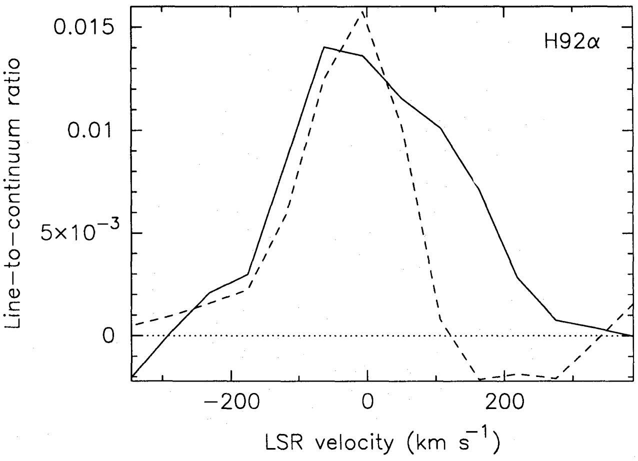


Figure 7. Separate spectra of the H 92α recombination line obtained towards the NE (solid line) and SW (dashed line) peaks in the radio continuum image of G25.5 + 0.2. The line-to-continuum ratio is plotted versus LSR velocity with a spectral resolution of 113 km s^{-1}. The rms noise in the spectrum is 0.15 mJy beam^{-1}, and the corresponding rms noise in the line-to-continuum ratio is about 0.35 per cent.

sequence star the required spectral type would be early O. Our spectrum shows no CO absorption beyond 2.29 μm, and so an M giant or supergiant, which would have comparable M_K, is precluded. Since no spectral features appear intimately associated with the central star, we cannot say whether it lies on the main sequence or has evolved off it.

The most striking feature of the infrared spectrum is the intensity of He I λ2.058. The line appears narrower than Brγ, but this may be an effect of the telluric absorption that overlies it and was possibly not fully corrected (the observation was made at high zenith angle). Taken at face value, the He I and Brγ lines have the same intensity, but we may have slightly underestimated the former.

A recent analysis of this line pair has been presented by Doyon, Puxley & Joseph (1992). They predict a He I/Brγ ratio that increases with the temperature of the exciting star until it reaches a plateau value of 0.8 when the stellar temperature exceeds about 35 000 K. The plateau value is sensitive to abundance; Doyon et al. assumed solar values. We therefore infer that the central star is no cooler than O7, and find some evidence for enhanced helium abundance in G25.5 + 0.2.

To clarify the nature of the central star, we present, in Fig. 8, the relevant portion of an HR diagram. On this we place limits derived from the He I/Brγ ratio and the Lyman continuum flux. The *IRAS* flux is also a lower limit, according to the covering factor and optical depth of the dust. Only the absolute *K*-magnitude provides a locus of possible values. It is clear that the object lies on or near the main sequence at a mass of 40–60 $M_\odot$.

5.5 G25.5 + 0.2: a rare outflow phenomenon

The inferred mass of ionized gas and the bulk velocity in G25.5 + 0.2 would imply mass ejection at a mean rate of about 10^{-4} $M_\odot$ yr^{-1} over an age no greater than 10^4 yr. Since the ejection appears to have been episodic, the mass-loss rate must have been much higher.

Planetary nebulae typically have LTE electron temperatures of about 12 000 K, and their recombination lines have velocity widths in the range 20–70 km s^{-1} (Terzian 1990). The ejected masses of the radio emitting shell of planetary nebulae are in the range 0.1–0.5 $M_\odot$ (Barlow 1989). An interpretation of G25.5 + 0.2 as a planetary nebula is precluded by the luminosity, velocity width, electron temperature and the likely nebular mass.

Bipolar outflows from young pre-main-sequence stars produce jets and Herbig–Haro objects with velocities of 200–400 km s^{-1}. However, the mass-loss rates inferred for the bipolar outflows (Mundt 1988) are several orders of magnitude smaller than that of G25.5 + 0.2. The typical radio luminosities of these outflows are also several orders of magnitude smaller.

The presence of a central star clearly precludes G25.5 + 0.2 from being a supernova. On the other hand, Fig. 8 shows it to be a very massive star. We consider the most credible interpretation to be that the object is a luminous blue variable (LBV; Humphreys & Davidson 1979; Davidson, Moffat & Lamers 1989) that has undergone a major mass-loss episode, probably following its first attempt to evolve rightward from the upper main sequence. The high

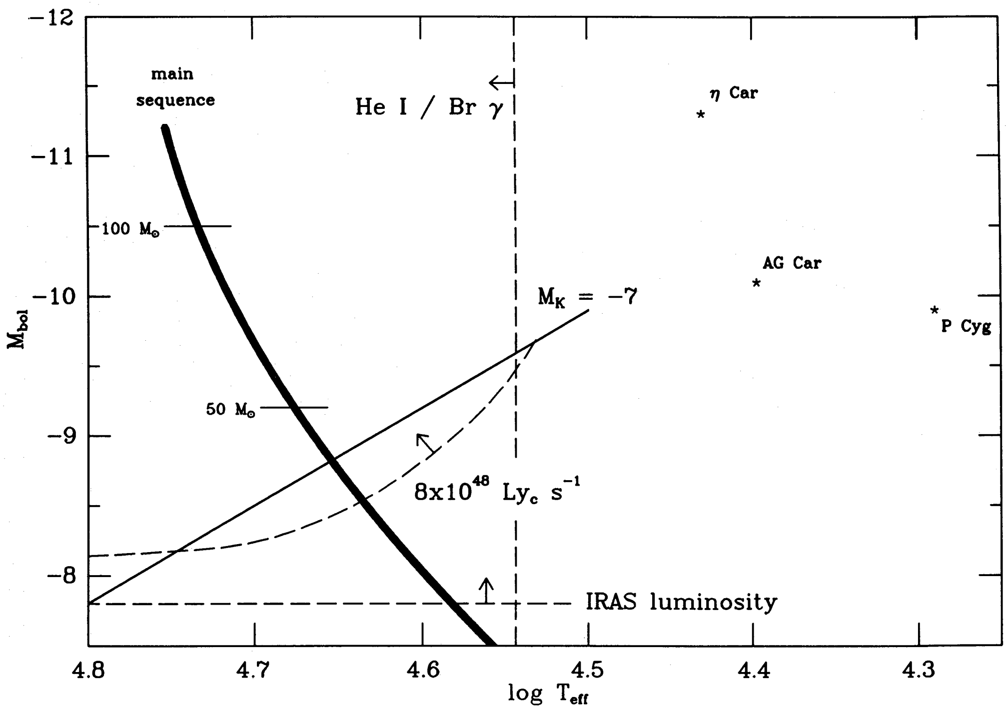


Figure 8. The upper portion of the HR diagram showing constraints on the central star in G25.5 + 0.2. The star lies on or near the line marked $M_K = -7$, probably between the main sequence and the vertical limit. The location of three luminous blue variables is shown (after Humphreys 1989).

ionization state indicates that at present the central star lies close to the main sequence, which is presumably why we see little contemporary evidence for mass loss. On Fig. 8 we have marked three LBVs in our Galaxy that have evolved to the right of the main sequence, and probably encountered the Humphreys–Davison (1979) instability line.

It is tempting to make comparisons with η Carinae, the most massive known LBV. The Homunculus nebula that surrounds η Car contains 0.03 $M_\odot$ of dust (Mitchell & Robinson 1978), implying a gas mass of a few $M_\odot$. It shows morphological similarities to G25.5 + 0.2, which is about five times larger in linear extent. We speculate that the two owe their existences to similar outbursts of massive stars encountering the Humphreys–Davison (1979) instability.

If this speculation is correct, and in the absence of evidence for expansion velocities higher than in η Car, then G25.5 + 0.2 must be an older example. G25.5 + 0.2 is a much more luminous radio source. Hence more Lyman continuum emitted by the star is absorbed by the nebula. The absence of He II emission in η Car (Hillier & Allen 1992) indicates that that star is cooler than a main-sequence object of its luminosity. By contrast, the central star in G25.5 + 0.2 may lie quite close to the main sequence. Evolution back towards the main sequence following a shell ejection is predicted for LBVs in the models of Maeder (1989), but no example has previously been found. Thus G25.5 + 0.2 may represent a particularly interesting phase in the evolution of a massive star.

The VLA survey of 290 small-diameter sources in the Galactic Plane (Sramek et al. 1992) detected only one object with the properties of G25.5 + 0.2. Considering the Galactic disc to have a radius of 12 kpc, the flux-density limit of the search and the sky coverge of the sample imply that only one object with the properties of G25.5 + 0.2 exists in about 20 per cent of the area of the Galactic disc. The search volume includes the Galactic Centre region, and therefore G25.5 + 0.2 probably represents an extremely rare outflow phenomenon. If we correctly interpret G25.5 + 0.2 as a massive LBV, 10^{3-4} yr after a major outburst, then it would very likely be unique in the entire Galaxy.

6 CONCLUSIONS

We have shown that G25.5 + 0.2 is an ionized, filamentary nebula surrounding a very hot, massive and luminous star that probably ejected the nebula $\sim 10^4$ yr ago and now photoionizes it. We conclude that G25.5 + 0.2 is not a young supernova remnant, but a stellar outflow of thermal plasma with an unusually high bremsstrahlung luminosity. We believe it to resemble η Carinae, but at a slightly more advanced phase of its evolution.

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