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Two-micron line emission from the H II region G333.6 − 0.2

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Summary. Spectrophotometry of the H II region G333.6 − 0.2 with $\lambda/\Delta\lambda \simeq 100$ shows strong emission lines of hydrogen and helium superimposed on a continuum. Spatial variations in the equivalent widths of the lines suggest the presence of very hot (⩾ 600 K) dust grains within the region. The shape of this very powerful H II region indicates that its dense ionized core is being continuously replenished from a reservoir of neutral gas.

1 Introduction

At infrared wavelengths G333.6 − 0.2 is one of the most powerful H II regions known (Becklin *et al.* 1973, hereafter BFNPW). It lies about 4 kpc from the Sun and is associated with a faint visible nebulosity (Churms *et al.* 1974) and an 84-Jy radio source (Shaver & Goss 1970). The 12.8 μm emission line of ionized neon was found by Aitken & Jones (1974) and further studied by Wollman *et al.* (1975) and Aitken, Griffiths & Jones (1977), hereafter AGJ. Maps of the source by the latter authors show that the distributions of both the warm dust and the ionized neon have a simple, compact and nearly symmetric structure with a core diameter of about 7 arcsec.

In this paper we describe spectrophotometry of G333.6 − 0.2 in the 2.2 μm window, with a resolution of $\lambda/\Delta\lambda \simeq 100$. The main features under study were the 2.17 μm Brackett γ line of hydrogen (n = 7–4), and the 2.06 μm line of neutral helium ($2\,^1P$–$2\,^1S$). Of particular

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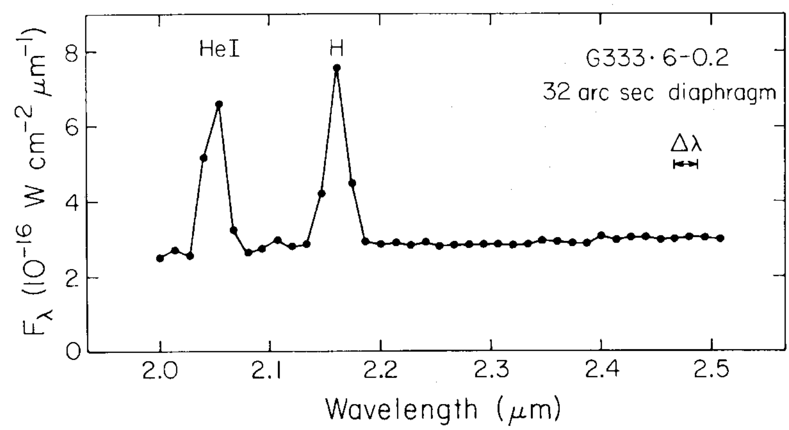

Figure 1. Spectrum of G333.6 – 0.2 from 2.0 to 2.5 μm made with a resolution of 0.021 μm.

interest were the spatial variation of the line-to-continuum ratios and the properties of the outer lower density regions of the source.

2 Observations

The observations for this paper were made on the CTIO 4-m telescope on 1976 July 18 and on the CTIO 0.9-m telescope on 1976 July 10 and 11. A continuously variable interference-filter wheel was used in conjunction with an indium antimonide photovoltaic detector. The focal-plane diaphragm on the 0.9-m telescope was 2 mm in diameter, corresponding to 32 arcsec; on the 4-m telescope it was either 0.5, 1.0 or 2.0 mm, corresponding to 3.3, 6.6 and 13 arcsec. In all cases the seeing disk was small compared with the diaphragm size. The spectral resolution of the filter wheel depends on the diaphragm diameter and source geometry. For the 0.5 and 1.0 mm diaphragms and for sources which are compact enough to form images less than 1 mm in diameter, the resolution was 21 nm at 2.1 μm; observations of an extended source with a diaphragm of diameter 2 mm, however, degraded the resolution to 30 nm.

The number of spectral elements measured at each point varied. A 39-element spectrum covering the whole 2.0–2.5 μm window was obtained with the 32 arcsec diaphragm on the 0.9-m telescope (Fig. 1), but most observations involved measurements only at the 2.17 μm hydrogen line, the 2.06 μm helium line, and of three continuum points at 2.03, 2.11 and 2.21 μm. The spectra were normalized by comparing the measured flux densities with those

Table 1.

Position	Diaphragm (arcsec)	Equivalent width Brackett γ (nm)	He/H	$S_{2.2}$ (mJy)	[1.65]–[2.2] (magnitudes)
Centre	3.3	23 ± 3	0.80 ± 0.04	780 ± 60	2.09 ± 0.08
	6.5	26 ± 3	0.73 ± 0.04	2080 ± 160	1.90 ± 0.08
	13	30 ± 3	0.76 ± 0.10	3700 ± 300	1.79 ± 0.08
	32	37 ± 4	0.75 ± 0.03	5200 ± 300	1.66 ± 0.07
13″ E	13	41 ± 8	–	49 ± 4	–
13″ W	13	40 ± 8	0.66 ± 0.13	97 ± 9	1.59 ± 0.10
13″ N	13	40 ± 8	0.76 ± 0.08	75 ± 6	1.63 ± 0.18
13″ S	13	47 ± 8	0.64 ± 0.06	270 ± 20	1.66 ± 0.12

from an early-type star that was assumed to have a Rayleigh–Jeans spectrum. The hydrogen and helium line-strengths were calculated by subtracting a mean continuum based on the flux densities on each side of the line. These line strengths are shown in Table 1 as the equivalent width of the hydrogen line and the ratio of the helium to hydrogen line-strengths. For the locations where only five spectral points were measured, the equivalent width was estimated using line-widths equal to the spectral resolution. Over most of the 2.0–2.5 μm window corrections for atmospheric extinction of 0.05 mag per air mass were applied, but at 2.03 and 2.06 μm the presence of CO_2 absorption features necessitated larger corrections of 0.20 and 0.30 mag per air mass respectively. The errors in fluxes due to uncertainties in the atmospheric extinction are only important for the helium data.

Broad-band 2.2 and 1.65 μm measurements were also made at each point where a spectrum was measured. Since it is the variation in the infrared colour and not its absolute value that is the more interesting parameter, the errors assigned to the infrared colour in Table 1 represent statistical and guiding uncertainties only, and do not include any calibration error.

In addition to the spectral measurements through variously sized diaphragms, spatial scans were also made on the 4-m telescope with a 3.3 arcsec diaphragm at wavelengths of 2.06 μm (the helium line), 2.17 μm (the hydrogen line) and 2.11 μm (continuum). Comparison scans were also made of the nearby star γ^2 Norma in order to determine the instrumental profile.

3 Results

Fig. 1 shows the spectrum of G333.6 – 0.2 from 2.0 to 2.5 μm as measured with a 32 arcsec diaphragm. The spectrum is dominated by the 2.06 μm singlet helium line and the 2.17 μm hydrogen Brackett γ line.

Table 1 shows the spectrophotometric results for the central parts of the source. It may be seen from the table that there are systematic trends both in the line-to-continuum ratios and the infrared colours. The sense of these trends is that, near the centre, the continuum emission is redder and relatively stronger with respect to the line emission. On the other hand the helium to hydrogen line ratio remains constant within the uncertainties of the measurements over a range of flux density of a factor of 100. The variation with diaphragm size of the 2.2 μm broad-band flux density agrees with that given by BFNPW. The scans through the source with a small diaphragm confirm the structure of G333.6 – 0.2 as shown by AGJ, in that the main peak is broader in declination than in right ascension, and that there are extended wings to the east and west of the source. Comparison of the line and continuum scans indicates that these wings are relatively stronger in line than in continuum emission. This effect corresponds to the increase in equivalent width with increasing radius indicated in Table 1.

The strength of the hydrogen line as a function of position is shown in Fig. 2. The numbers represent the mean emission measure (in units of 10^6 pc cm^{-6}) corresponding to the appropriate diaphragm size and location, assuming a temperature of 10^4 K, and an extinction at 2.2 μm, derived from BFNPW's estimate of $A_V = 15$ mag, of 1.5 mag. The relation between line strength and emission measure is discussed in the Appendix. The observations located at distances of 32 arcsec from the centre were made on the 0.9-m telescope with a 96 arcsec north–south chopper spacing. Because of a low signal-to-noise ratio and because of the likelihood that the continuum emission at these points includes a contribution from field stars, the corresponding equivalent widths and infrared colours are considered too unreliable to be included in Table 1.

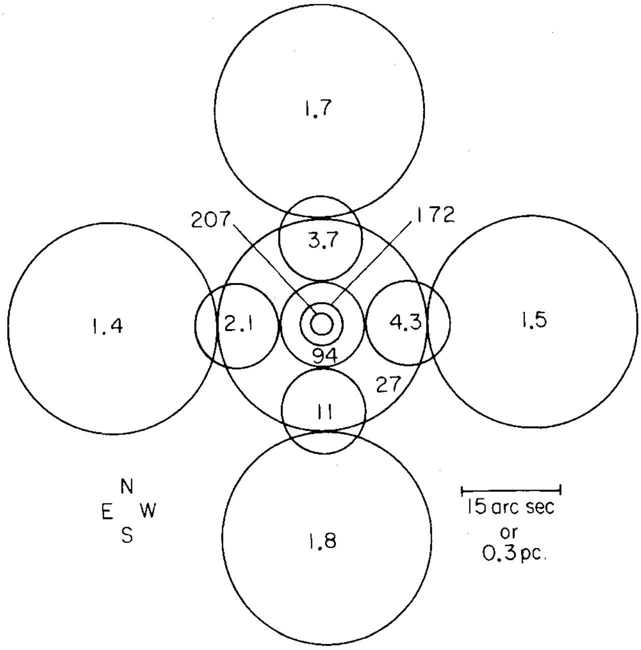

Figure 2. The emission measure as a function of position and diaphragm diameter in G333.6 − 0.2. The units are 10^6 pc cm^{-6}.

4 Discussion

4.1 HYDROGEN LINE AND CONTINUUM EMISSION

At 2 μm the continuum emission from a plasma at 10 000 K arises in approximately equal parts from free–free and free–bound transitions (Willner, Becklin & Visvanathan 1972). Since the line and the continuum emission depend on density in the same way, the equivalent width of the hydrogen emission line depends almost solely on the electron temperature. The equivalent width of the Brackett γ line is given for several electron temperatures in the Appendix.

The observations listed in Table 1 show that the equivalent width of the Brackett γ line at all points in the source is less than the predicted width for a 10^4 K plasma by a factor of between 1.3 and 2.6. If the weakness of the line were to be explained purely in terms of atomic processes, the electron temperature in the central region would have to be in excess of 2×10^4 K, which is much larger than is found in any other H II region (Seaton 1974), or else the abundance of ionized helium, He^{++}, would have to be much larger than the cosmological helium abundance (see Appendix). There thus appears to be an extra component to the 2.2 μm continuum, this emission being relatively strongest near the centre of the object. The extra continuum appears to be redder than the normal free–free continuum, but its intrinsic colour is hard to estimate because of the uncertainties in the reddening correction.

An apparently plausible cause of this emission is dust grains. Although it is now generally accepted that dust grains lead to strong infrared emission at wavelengths longward of 3 μm, there has, up until now, been little evidence that the process is important in H II regions at wavelengths as short as 2 μm. A lower limit to the temperature of the dust may be obtained by ensuring that the 3.5 μm emission from these grains does not exceed what is observed from the source. On the assumptions that the extinction at 2.2 μm is 1.5 mag (BFNPW), that the extinction at 3.5 μm is therefore 0.9 mag (Becklin *et al.* 1978), that half of the 2.2 μm continuum is from hot dust and that the 3.5 μm flux density is as given by BFNPW, it may be deduced that the colour temperature of the grains causing the 2.2 μm emission is at least 600 K. Although grains at such a temperature are frequently found near cool stars, the present results are significant in that these hot grains are seen at so large a distance ($\geqslant 3 \times 10^{17}$ cm) from the central star. The environment of these grains is different from that surrounding cool stars in that, for H II regions, the radiation field heating the grains is a mixture of Lyman α and ultraviolet stellar continuum rather than visible light. If these hot grains exist they are probably very small refractory particles of some sort. Since, however, the continuum emission at 2.2 μm is much less than that at longer wavelengths, these small particles probably comprise only a small minority of the grains in G333.6 – 0.2.

4.2 THE HELIUM LINE

The λ 20581 line is the only helium line observed in G333.6–0.2 up until now, apart from the He 109α radio recombination line (Mezger *et al.* 1970). The transition is the singlet ($2\,^1P$–$2\,^1S$) equivalent to the triplet λ 10830 line; its intensity is strongly dependent on the optical depth of the principal ($n\,^1P$–$1\,^1S$) lines in the nebula (Robbins & Bernat 1974). The theoretical strength of the line relative to the Brackett γ line may be estimated from the relation

$$\frac{I_{20581}}{I_{\mathrm{B}\gamma}} = \frac{I_{20581}}{I_{4471}} \times \frac{I_{\mathrm{H}\beta}}{I_{\mathrm{B}\gamma}} \times \frac{I_{4471}}{I_{\mathrm{H}\beta}}.$$

Treffers *et al.* (1976), in their paper on NGC 7027, discussed the λ 20581 transition and showed that, if the nebula were optically thick in the λ 584 ($2\,^1P$–$1\,^1S$) transition, then the ratio I_{20581}/I_{4471} should be equal to 0.65. The second term in the equation may be calculated from hydrogen recombination theory (e.g. Osterbrock 1975) and for a plasma at 10 000 K is equal to 36. For the third term we use the empirical value of 0.04, which is typical for optically visible H II regions (Peimbert & Torres-Peimbert 1971). The predicted value for the ratio of λ 20581/Bγ is therefore 0.9, as compared with the measured value of 0.7. Considering the assumptions made, the agreement between observation and theory is good. The fact that the helium to hydrogen ratio is apparently unchanged over the face of the H II region is compatible with the assumption that the principal series are still being resonantly scattered at a distance of at least 13 arcsec from the centre of the nebula.

4.3 THE SHAPE OF THE H II REGION

In Fig. 3 the Brackett γ flux density is plotted against diaphragm diameter, and is compared with the distribution of the 12.5 μm continuum radiation as given by AGJ. The figure emphasizes the importance of the outer parts of the source, in that at least 25 per cent of the flux density of the source comes from outside a diameter of 30 arcsec. It also suggests that the ratio of Brackett γ emission to 12.5 μm continuum emission decreases towards the central parts of the source. This effect is in the same sense as that found in this paper for the ratio of Brackett γ to 2 μm continuum, and by AGJ for the ratio of the neon line strength to 12.5 μm continuum; it is doubtlessly related to the detailed mechanism by which the variously sized grains are heated by stellar and nebular photons.

The values derived in Fig. 2 for the emission measure as a function of radius are fairly close to those predicted by AGJ's simplified model for the source, which has a core of diameter 0.16 pc and electron density $3 \times 10^4\,\mathrm{cm}^{-3}$ surrounded by a region of diameter 1.1 pc and electron density $4 \times 10^3\,\mathrm{cm}^{-3}$; our data could equally well be fitted by models with a more gradual gradient of electron density, however. This agreement provides support for AGJ's

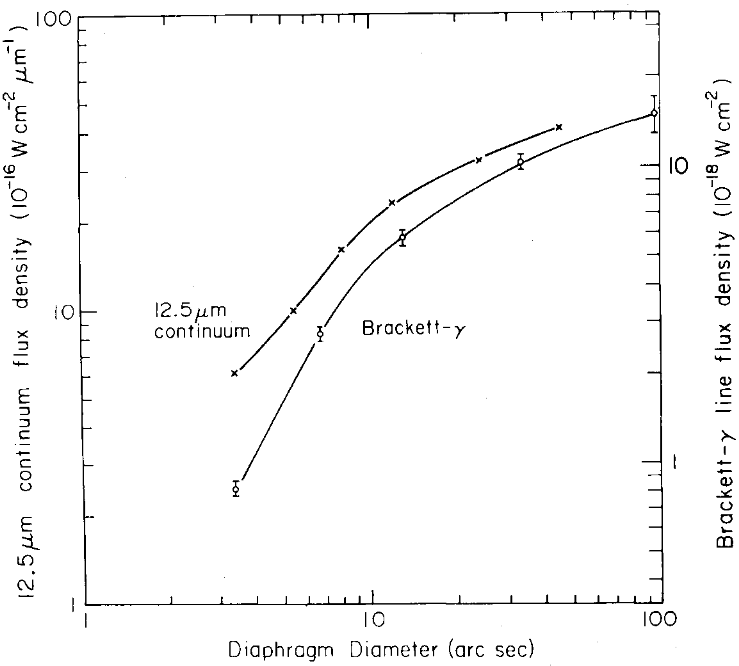

Figure 3. Variation of the measured Brackett γ line intensity as a function of diaphragm diameter, as compared with the 12.5 μm continuum emission. The Brackett γ flux for a 96 arcsec diaphragm is an extrapolation based on the distribution indicated in Fig. 2. The 12.5 μm continuum data are from AGJ. The maximum errors in the diaphragm diameter are about 1 arcsec.

assumption that the neon abundance in G333.6 – 0.2 is normal. Shaver & Goss (1970) measured a free–free flux density of 84 Jy within a 4 arcmin beam at 5 GHz. We can compare this value with the Brackett γ flux density by using the relationship given in the Appendix. On the assumption that the 2.2 μm extinction is 1.5 mag and that the electron temperature is 10^4 K, the infrared data predict a 5-GHz flux density of 69 Jy within a 96 arcsec diameter. Given the uncertainties in the extinction to the source, the possibility that the outer envelope may extend to even larger radii, and the fact that those regions of the source with an emission measure greater than about $10^8 \, pc \, cm^{-6}$ will be self-absorbed at 5 GHz, the agreement between these flux densities is good.

The phenomenon which Figs 2 and 3 emphasize is the degree to which G333.6 – 0.2 is centrally condensed around what is presumably a single star or a very compact cluster of stars. In this respect it is a contrast to, for example, W3(A) (Harris & Wynn-Williams 1976), which has a shell shape rather than a central condensation, and which is one of a group of H II regions rather than an isolated entity. The emission measure in the centre of G333.6 – 0.2 is nearly as high as that of very compact H II regions such as W3(OH) (e.g. Harten 1976); the crucial difference between these objects, however, is that the ionization rate is some 100 times greater in G333.6 – 0.2 than in W3(OH).

The fact that G333.6 – 0.2 has such a compact core suggests that its central region is being continuously regenerated by ionization of dense neutral gas. The source for this neutral gas is probably the molecular cloud which has been found in the vicinity of G333.6 – 0.2 by Gillespie *et al.* (1977). The existence of the low-density wings, on the other hand, implies that the H II region is not ionization-bounded in all directions. A simple geometrical configuration for the object would be for the H II region to lie on the edge of a molecular cloud, a configuration which seems to apply to some other H II regions (Israel 1977). Alternatively, the neutral material could be contained in a number of small globules within the H II region, as suggested by Dopita, Dyson & Meaburn (1974). These conjectures could be tested by making more detailed studies of the molecular clouds in the vicinity of G333.6 – 0.2.

5 Conclusions

(1) The 2.2 μm line spectrum of G333.6 – 0.2 is dominated by the 2.06 μm line of helium and the 2.17 μm hydrogen Brackett γ line.

(2) The equivalent widths of the lines increase outwards from the centre of the source, while the colour of the continuum radiation becomes less red. We attribute these effects to the existence of an extra, red continuum source which is strongest at the centre, and probably comprises small dust grains at a temperature in excess of 600 K.

(3) The helium to hydrogen line ratio does not vary over the face of the source. The strength of the helium line is compatible with the assumption that the nebula is optically thick in the principal UV series of helium lines.

(4) The wide range in emission measure and the symmetric structure of this very powerful H II region is probably an indication that its dense ionized core is being continuously replenished from a reservoir of un-ionized gas.

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Appendix: theoretical strength of the Brackett γ line

	5000 K	10 000 K	20 000 K
Emission coefficient γ_{74} (10^{-27} erg cm^3/s)	7.13	3.39	1.53
Equivalent width (nm)	87	59	34
$S_{5\,\mathrm{GHz}}/S_{\mathrm{B}\gamma}$ (10^{-12}/Hz)	0.68	1.14	1.99

The intensity I_{74} (erg cm^{-2}/s/sr) of the Brackett γ line can be calculated from the emission coefficient γ_{74} by the formula

$$I_{74} = \frac{\gamma_{74}}{4\pi} \times (3 \times 10^{18}\,\mathrm{EM}),$$

where EM is the emission measure in units of pc cm^{-6}. The emission coefficient and equivalent width of the Brackett γ line were calculated from standard recombination theory on the assumption that 90 per cent of the ions are H^+, 10 per cent are He^+ and none are He^{++}. The bound–free and free–free Gaunt factors were estimated from the figures in the paper of Karzas & Latter (1961), while the Gaunt factor of the line itself was calculated from the formula given by Burgess (1958). Following Hilgeman (1970), the effective b_n factors were calculated by taking a suitable mean of Clarke's (1965) b_{nl} values, weighted according to the relative probabilities of the permitted $nl \rightarrow n'l'$ transitions, as described by Burgess (1958). No contribution to the 2 μm continuum was included for the two-photon decay of the $2\,^2S$ level of hydrogen, since this process is suppressed at densities above about 10^4 cm^{-3}. At worst, however, this process could increase the continuum flux (and hence decrease the equivalent width) by about 4 per cent. To calculate the ratio between the 5-GHz free–free emission and the Brackett γ line emission, the formula of Scheuer (1960) was used. The calculation of line strength was made under Menzel & Baker's (1938) case B assumptions; the line strengths are about 10 per cent weaker if case A conditions are assumed. Collisions of electrons with He^{++} ions produce about four times more 2 μm emission than the same number of collisions between electrons and H^+ or He^+ ions. If the plasma contained 10 per cent of He^{++} instead of 10 per cent of He^+, therefore, the continuum emission would be about 30 per cent stronger.