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EXTINCTION VARIATIONS IN THE H II REGIONS SHARPLESS 156 AND 162

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SUMMARY

Accurate spectrophotometric observations of the nebulae Sh 156 and Sh 162 and of their exciting stars, combined with new high resolution radio maps by Israel, enable the derivation of A_V towards 15 points in these nebulae. These values are compared with other values of A_V for the entire nebulae and their exciting stars.

1. INTRODUCTION

Sharpless 156 (IC 1470) and Sharpless 162 (containing the Bubble Nebula NGC 7635) are two H II regions which have recently received considerable observational attention at optical, infrared and radio wavelengths. Sh 156 is a compact H II region embedded in an extensive cloud of gas and dust, as deduced from optical spectra (Glushkov & Karyagina 1972), infrared photometry (Cohen & Barlow 1973; hereafter Paper I) and radio interferometry (Israel, Habing & de Jong 1973). The exciting star is the northerly and brighter of two stars in the nebular core. Sh 162 by contrast is a large evolved H II region. The ring structure of NGC 7635 and the associated comet-like inclusions in the complex region surrounding the Of star BD +60° 2522 have been discussed by Johnson (1974), who details earlier work on this nebula.

In a previous paper (Barlow, Cohen & Gull 1974; hereafter Paper II), we established the presence of dust within both nebulae by means of optical spectrophotometry, which demonstrated the existence of a strong nebular continuum attributable to dust-scattered starlight. In the present paper we give our full spectrophotometric results and compare these with new high resolution radio interferometric data (Israel 1976) in order to derive the total visual extinction, A_V, towards several regions in each nebula. In addition, we present new narrow-bandpass filter photographs of the nebulae.

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2. THE MORPHOLOGY OF THE NEBULAE

2.1 *Sh* 156

Plate 1(a) shows a 30-min exposure of Sh 156 in the continuum at λ 6470 with a 90 Å bandpass, taken at the prime focus (f/2·7) of the Kitt Peak 4-m reflector. Plate 1(b) shows a 6-min exposure of this nebula in Hα+[N II], with a 90 Å bandpass, also taken with the 4-m reflector. Photographically the structure consists of a bright nebular core crossed by three dark lanes which radiate from the centre. There is, however, a close correspondence between the photographic isophotes and the isophotes in the 6-cm radio map of Israel (1976), indicating that the optical structure of Sh 156 is due to several bright condensations and not to dust lanes crossing a uniformly bright nebula.

2.2 *Sh* 162

Plates II(a), (b) and (c) show Carnegie two-stage image-tube photographs of Sh 162, taken with a 0·9-m reflector (f/7·5 and 13·5) at Kitt Peak, through narrow-bandpass filters isolating [O II] 3727 Å (30-min exposure), [O III] 5007 Å (15 min), and [N II] 6584 Å (40 min), respectively. Plate 2(d) is a 6-min exposure in Hα+[N II] taken with the 4-m telescope. The most obvious differences between these photographs are the dominant appearance of the cometary structure in [O II] and the overall diffuseness of [O III] emission. Again there is a close correspondence between the optical nebulosity and the high resolution radio data of Israel (1976) at 6 cm (for the ring and cometary structures) and of Israel *et al.* (1973) at 21 cm (for the outer condensations), indicating a lack of substantial variation in obscuration across Sh 162.

3. Hβ SPECTROPHOTOMETRY AND THE EXTINCTION TOWARDS THE NEBULAE

Spectrophotometric observations were carried out with the Wampler prime focus scanner on the 0·9-m Crossley reflector at Lick Observatory. To define the nebular continuum we observed in line-free regions on either side of the Hβ emission line, at wavelengths of 4828 and 4894 Å, with bandpasses of 48 Å, interpolating to obtain the effective continuum at 4861 Å. The Hβ line was observed with a 12·8 Å bandpass centred at 4861 Å. Absolute fluxes were obtained from observations of three Hayes (1970) standard stars, κ Aql, 58 Aql and ε Ori, in conjunction with the calibration for α Lyr of Oke & Schild (1971). Circular diaphragms were used throughout.

Table I presents our data for the following positions: the three regions in Sh 156 labelled '0', '1' and '2' on Plate I (b); two different diaphragm sizes centred on the bright northerly star in Sh 156, and the annular zone defined by these two diaphragms; and the eight regions in Sh 162 labelled in Plate II(d) following the nomenclature of Israel *et al.* (1973). For each position Table I gives the diaphragm size, f_{4861} the derived continuum flux at 4861 Å, $F(\mathrm{H}\beta)$ the Hβ flux corrected for continuum emission, $W(\mathrm{H}\beta)$ the equivalent width of the Hβ flux ($=F(\mathrm{H}\beta)/f_{4861}$), and the appropriate radio frequency and radio flux for each position and aperture. For positions A_2(W) and B in Sh 162, 1·415-GHz radio fluxes were derived from the 24×28 arcsec resolution map presented by Israel *et al.* (1973). For the other locations in both nebulae, radio fluxes were derived from 5-GHz Westerbork synthesis telescope maps which were kindly provided,

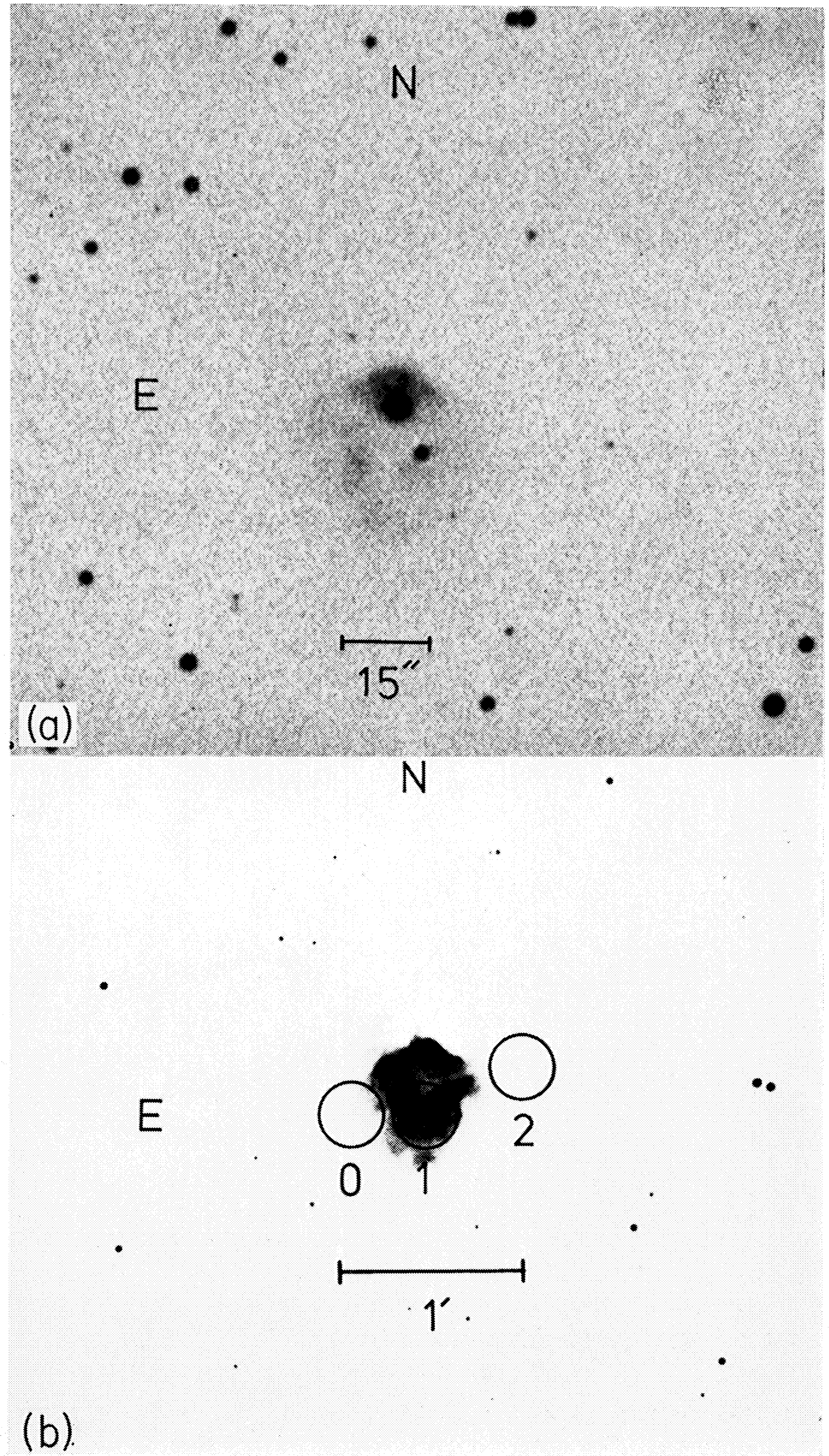
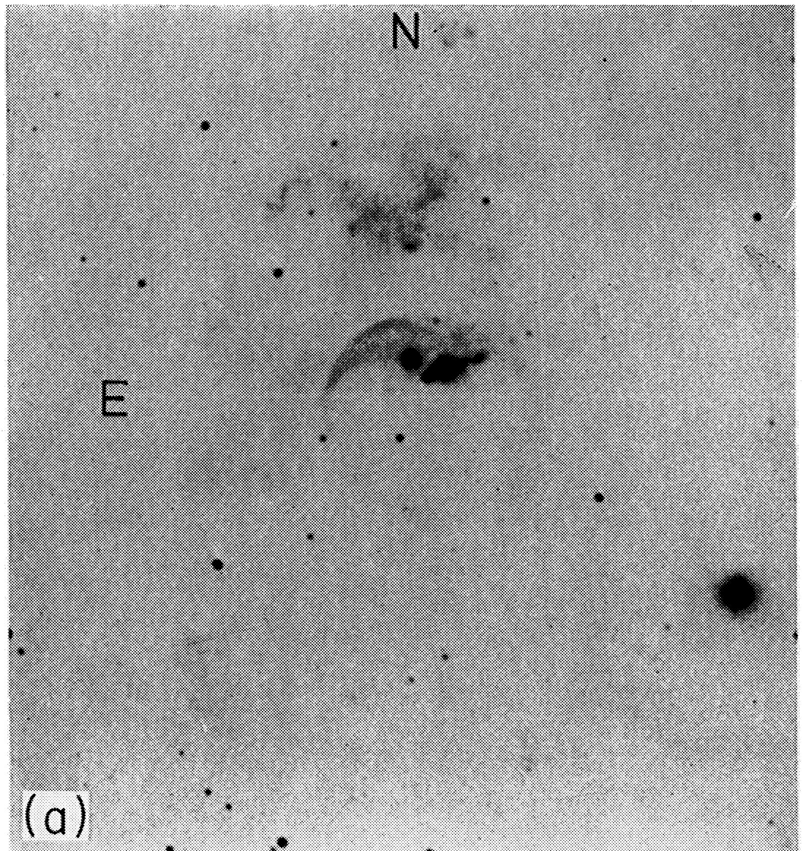


PLATE I. *Sh* 156. (*a*) λ 6470, *continuum;* (*b*) Hα + [*N* II]. *Details in text.*

[*facing page* 360]



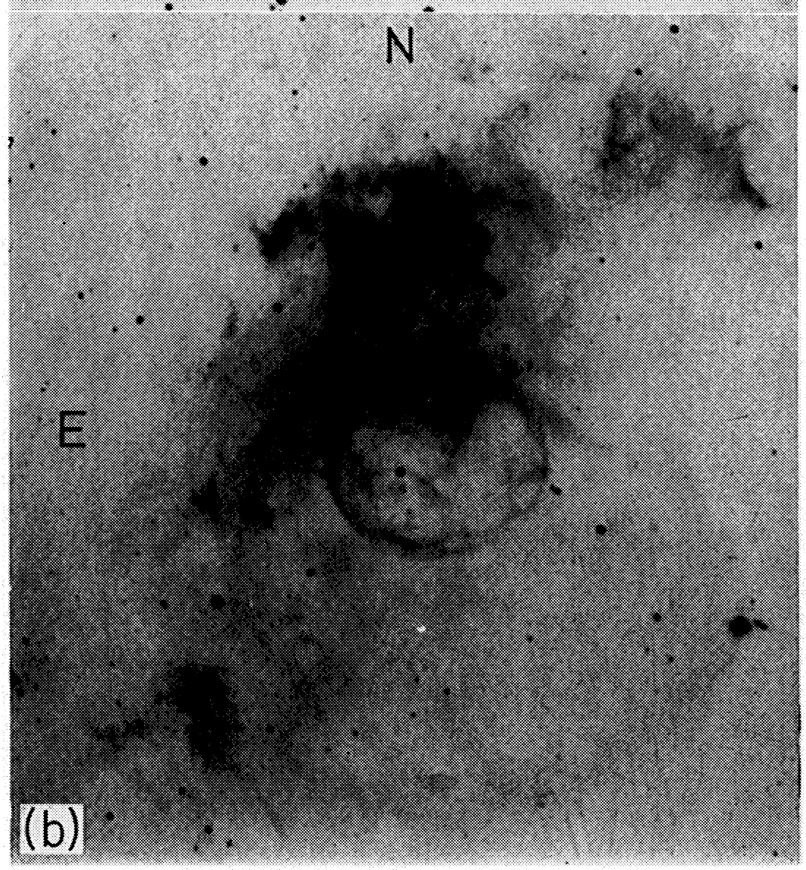
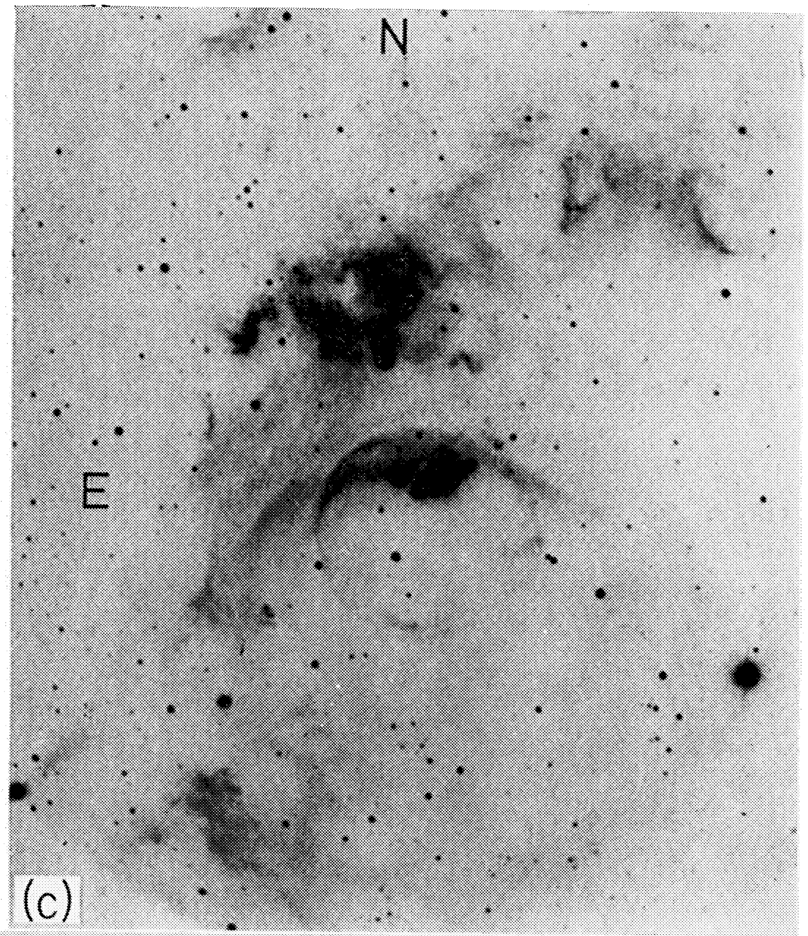


PLATE II a & b

PLATE II. *Sh* 162. (*a*) [*O* II] λ 3727; (*b*) [*O* III] λ 5007; (*c*) [*N* II] λ 6584; (*d*) *H*α + [*N* II]. *Details in text.*



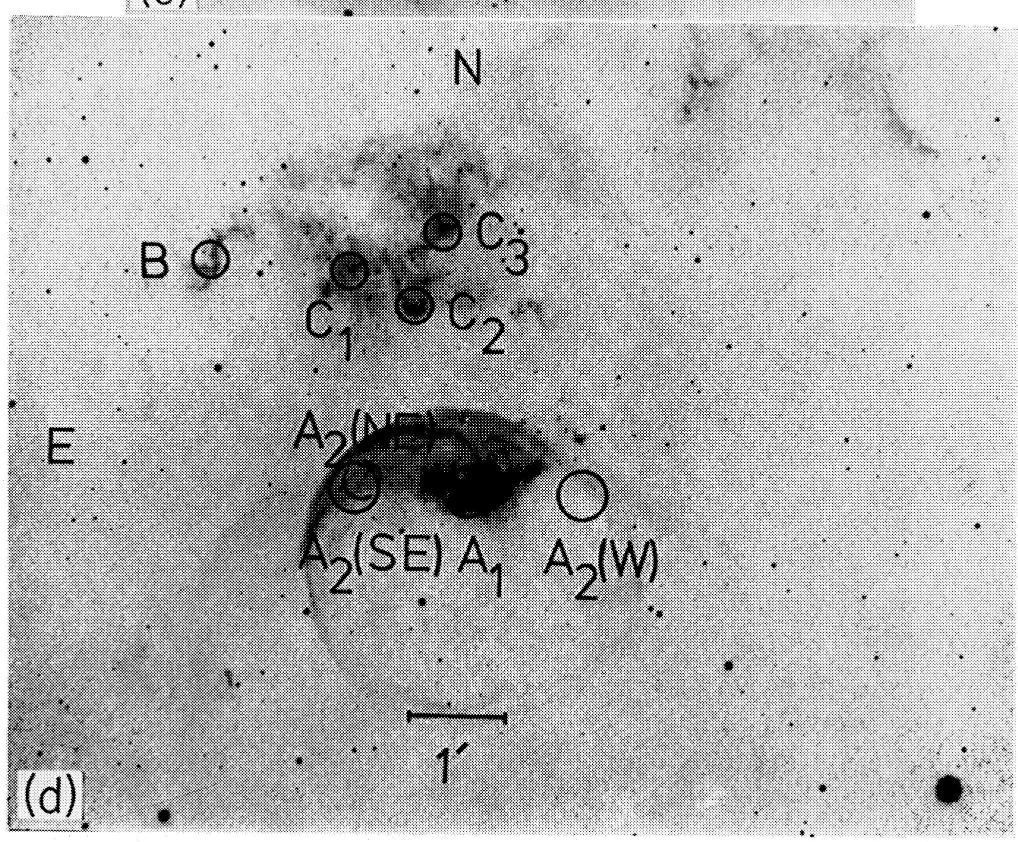


PLATE II c & d

TABLE I

Spectrophotometry and derived extinctions for the two nebulae

Position	Diaphragm diameter (arcsec)	f_{4861}*	$F(H\beta)$†	$W(H\beta)$ (Å)	Radio ν (GHz)	Radio S_ν (mJy)	$C(H\beta)$	A_V
Sh 156								
0	22	1·5 ± 0·5	4·6 ± 0·2	310^{+160}_{-90}	5	61	1·61	3·45
1	22	4·4 ± 0·7	26·2 ± 0·3	590^{+120}_{-90}	5	340	1·60	3·43
2	22	1·3 ± 0·5	1·4 ± 0·3	110^{+100}_{-40}	5	67	2·17	4·64
Centred on O7 star	22		28·0 ± 0·3		5	822	1·96	4·19
Centred on O7 star	10·5		11·4 ± 0·2		5	210	1·76	3·76
Annulus	outer–inner 22–10·5	4·6 ± 0·8	16·6 ± 0·4	360^{+180}_{-60}	5	612	2·06	4·40
Entire nebula			135‡		1·4	2300	1·66	3·56
Slit through nebula								3·51
O7 star, *UBV*								3·72
O7 star, slope of continuum								4·3
O7 star, λ 6284 feature								4·0
O7 star, D lines								3·1:
B5 star, slope of continuum								2·6
Nebula near B5 star								2·7
Sh 162								
A1	22	8·0 ± 1·1	22·7 ± 0·5	280^{+60}_{-40}				
A1	29	10·0 ± 0·8	26·9 ± 1·0	270 ± 30	5	314	1·56	3·34
A2(W)	29	1·4 ± 0·4	4·4 ± 0·1	320^{+130}_{-70}	1·4	13·4	0·92	1·97
A2(SE)	29	6·2 ± 1·0	11·3 ± 0·2	190 ± 30	5	42	1·06	2·27
A2(NE)	22	3·4 ± 0·8	6·7 ± 0·2	200^{+60}_{-40}				
B	22		3·2 ± 0·2	> 220	1·4	9	0·88	1·89
C1	22		4·5 ± 0·3	> 310	5	64	1·64	3·51
C2	22		6·2 ± 0·2	> 430	5	44	1·34	2·87
C3	22		3·9 ± 0·2	> 270	5	48	1·58	3·38
Entire nebula	1800		6030§		5	13700	0·85	1·81
Slit through nebula								2·67
BD +60° 2522								2·26

* Units 10^{-15} erg cm^{-2} s^{-1} Å^{-1}; † units 10^{-13} erg cm^{-2} s^{-1}; ‡ O'Dell (1963); § Gebel (1968).

convolved to a resolution of 15 arcsec, by F. P. Israel. Values of the correction parameter for space absorption, $C(H\beta)$, were derived from the observed radio and Hβ fluxes using the formula given by Higgs (1973), for an assumed nebular temperature of 10^4 K. Our narrow-bandpass photographs, showing variations in excitation to exist across Sh 162, indicate regional temperature variations. However, spectra taken by Doroshenko (1972) of seven different regions in Sh 162 yield a mean electron temperature of 9600 K, with little variation about this value. In any case, a variation of 50 per cent in the assumed electron temperature leads to a variation of only 6 per cent in the derived value of $C(\mathrm{H}\beta)$. The derived values of $C(\mathrm{H}\beta)$ were converted to equivalent values of A_V, the total visual extinction, using the interpolation formulae for the Whitford reddening law given by Miller & Mathews (1972). Implicit in the use of this reddening law is the assumption that $R\ (=A_V/E(B-V))$ is equal to 2·97. That a normal value of R exists towards Sh 162 can be shown directly using the colour difference method in conjunction with the optical and infrared photometry of BD +60° 2522 given in Paper I. A value of $R = 3{\cdot}1 \pm 0{\cdot}3$ is obtained (not $R = 3{\cdot}3 \pm 0{\cdot}3$ as stated in Paper II). The value of R towards Sh 156 can be determined by the method of Miller & Mathews (1972) from the observed ratio of two Balmer lines and knowledge of the expected flux in one of them. From their equation (A7) we have

$$R = [2{\cdot}5C(\mathrm{H}\beta) - 0{\cdot}425E(\mathrm{H}\alpha - \mathrm{H}\beta)]/0{\cdot}863E(\mathrm{H}\alpha - \mathrm{H}\beta),$$

where $C(\mathrm{H}\beta)$ and the colour excess $E(\mathrm{H}\alpha - \mathrm{H}\beta)$ and for the same nebular region. A slit spectrum passing through the central region of Sh 156, obtained by one of us (TRG) on a 0·9-m reflector at Kitt Peak, yielded a value of $E(\mathrm{H}\alpha - \mathrm{H}\beta) = 1{\cdot}366$, for an assumed nebular electron temperature of 10^4 K (the derived excess is insensitive to likely variations in the electron temperature). The total nebular Hβ and 1·415-GHz fluxes given in Table I, taken from O'Dell (1963) and Israel (1976) respectively, yield an overall value of $C(\mathrm{H}\beta) = 1{\cdot}664$ for Sh 156. Thus we obtain $R = 3{\cdot}04$ towards Sh 156. The assumption of a normal reddening law towards both nebulae is therefore justified.

Table I also includes the total nebular Hβ flux for Sh 162, from Gebel (1968), and the total 5-GHz flux for the same nebula, measured by us (Paper II). The value of $E(\mathrm{H}\alpha - \mathrm{H}\beta)$ for Sh 156 and the value similarly obtained for the central region of Sh 162 ($E(\mathrm{H}\alpha - \mathrm{H}\beta) = 1{\cdot}04$) have been converted into corresponding values of A_V using the Miller–Mathews (1972) relations. The derived values of A_V are also included in Table I. We have incorporated into Table I the values of A_V derived (assuming $R = 3{\cdot}1$) from the measured stellar colour excesses of $E(B-V) = 1{\cdot}2$ for the bright star in Sh 156 (Kostjakova *et al.* 1968) and $E(B-V) = 0{\cdot}73$ for BD +60° 2522 (Hiltner & Johnson 1956).

4. DISCUSSION

4.1 *Sh* 156

Good agreement is obtained between the values of A_V determined by three different methods ($C(\mathrm{H}\beta)$, $E(\mathrm{H}\alpha - \mathrm{H}\beta)$, $E(B-V)$). There would appear to be two distinct regions of extinction towards Sh 156, the first with A_V between 3·4 and 3·8, in the southern and eastern parts of the nebula, and towards the O star; and the second with A_V between 4·4 and 4·6, in the northern and western parts of the nebula. Good agreement is obtained between the value of A_V derived for the 10·5-arcsec diameter nebular disc surrounding the bright northerly star and the value of A_V derived from the colour excess of the star itself. The agreement between the extinction derived for this 10·5-arcsec aperture on the star and for position '1' to the south of the star, implies that the higher extinction found for the annulus must be due to greater extinction towards the bright nebular condensation north of the star. The highest extinction is found towards position '2', and correlates with the lowest value of $W(\mathrm{H}\beta)$ (i.e. the strongest scattered light continuum). This implies that the excess of extinction ($\Delta A_V \sim 1$) between the south-eastern and north-western parts of the nebula must be due to dust internal to the H II–H I complex.

Persson & Frogel (1974), from 1·65- and 2·2-μ photometry, derive $A_V = 8$ for an annulus with inner and outer diameters of 27 and 55 arcsec centred on the bright star, assuming that the intrinsic nebular spectrum is due to optically thin free–free emission. Our positions '0' and '2' significantly overlap this annulus, yet we find no evidence for such a large value of A_V. We note that Sh 156 shows excess 3·5-μ emission which must be attributed to dust (Persson & Frogel 1974, Paper I), and that the work of Persson & Frogel (1974) shows the 3·5-μ emission to increase with angular distance from the star. Consequently, it is possible that the 2·2-μ flux contains a contribution from thermal emission by dust grains which might significantly affect the value of A_V deduced by their method. (Persson & Frogel suggested that this was the case for two of the other nebulae which they observed.)

The spectral type of the exciting star of Sh 156 has sometimes been quoted as O7 (Becvar 1964; Glushkov & Karyagina 1972) but no reference to an original classification can be traced. Kazes, Le Squéren & Gadea (1975) quote Georgelin (1975) as having determined spectroscopically a spectral type of O7 V. For a kinematic distance of 4·3 kpc (Georgelin & Georgelin 1970) and a 1·4-GHz flux of 2·3 Jy (Israel 1976), an excitation parameter of $U = 47$ pc cm^{-2} is derived. From the *UBV* photometry of Kostjakova *et al.* (1968) and of Chopinet, Georgelin & Lortet-Zuckermann (1973), values of M_V for the star equal to $-4·2$ and $-4·6$ are obtained, respectively (for $R = 3$). This implies that the star lies on the main sequence. From Panagia (1973, Table II), a main sequence star with $U = 45$ pc cm^{-2} must have a spectral type earlier than O8. From Paper II the ratio of infrared luminosity to Lyman-α luminosity is $\geqslant 10·5$ for Sh 156. But any star earlier than O8, according to the results of Panagia (1973), cannot have a ratio of luminosity longward of 912 Å to that in Lyman-α greater than 4·0. The total infrared luminosity derived in Paper I for Sh 156 ($1·6 \times 10^5 L_\odot$) corresponds closely to the total luminosity of an O7 V star (Panagia 1973) and we have failed to locate any 10-μ source other than the O star in scans of the nebula. Since with an O7 exciting star the observed ratio of infrared to Lyman-α luminosity cannot be produced even with complete absorption by dust of all Lyman-α photons together with photons longward of the Lyman continuum, direct absorption of Lyman continuum photons by dust is implied. Such absorption increases the total infrared luminosity and reduces the ionizing flux absorbed by the gas (thus reducing the Lyman-α luminosity of the nebula) allowing a large ratio of infrared to Lyman-α luminosity to be attained.

We have recently (1976 January) obtained new spectrophotometry of both the bright and faint stars in Sh 156 (*cf.* Plate 1(a)) from 4300 to 6740 Å using the image-tube scanner at the Cassegrain focus of the Lick Observatory 3-m reflector. The spectrum of the bright star is unmistakably that of a very hot star but we are unable to sharpen the O7 classification. From the slope of the observed continuum which at these wavelengths should be in the Rayleigh–Jeans region for such a hot star, we deduce that the differential reddening corresponds to $A_V = 4·3$. The emission lines of He II at 4686 Å and of N III near 4640 Å are definitely not present, precluding the possible Of nature of this star. Several nebular emission lines appear against the stellar spectrum (Hα, [N II], [O III], and weak Hβ confused with stellar absorption) together with two strong absorption features at λ 6284 and at the D lines, apparently both interstellar in origin. From the investigation of interstellar absorption features by Bromage & Nandy (1973) we may convert absorption equivalent widths to values of $E(B-V)$. The λ 6284 feature has an equivalent width of $\sim$1500 mÅ (corrected for the instrumental resolution of 7 Å), corresponding to $E(B-V) = 1\cdot3$ and $A_V = 4\cdot0$. Similarly, the equivalent width of the two D lines together is $\sim$2000 mÅ, yielding an $E(B-V)$ of 1·0 and an A_V of 3·1. However, the relation between colour excess and equivalent width for the D lines is intrinsically much less well defined that that for the λ 6284 feature, and little weight should attach to the lower value of A_V.

The continuum of the faint star within Sh 156 is that of a B star but due to its faintness further precision in the classification is not directly possible. Certainly it is a hot star and its intrinsic continuum slope in the observed wavelength range should be that in the Rayleigh–Jeans domain. This argument leads to an A_V of 2·6. The same nebular emission lines appear in the spectrum of the faint star as in that of the bright star, but now Hα, Hβ and Hγ are all well defined. The observed ratios of line fluxes are Hα/Hβ = 8·8, Hβ/Hγ = 4·7 and this combination of values implies the presence of appreciable stellar absorption lines, particularly at Hγ. Such a conclusion is again consistent with a star of early spectral type. From our spectrum we can make an estimate of the strengths of the stellar Balmer absorption lines and can hence correct the nebular Balmer decrement. Such a correction indicates that Hα/Hβ = 7·6 and Hβ/Hγ = 2·8, from which we compute $A_V = 2\cdot7$, in excellent agreement with the value derived from the slope of the stellar continuum, although somewhat smaller than the extinction towards the bright star. We find $V = 15\cdot8$ for the faint star, whence $M_V = -0\cdot1$, using the distance of 4·3 kpc to Sh 156. This luminosity corresponds to a main sequence B5 star. Consequently, this star contributes very little to the excitation of the nebula, although there is a small radio peak near its position in the 6-cm map of Israel (1976).

Strong emission lines of He I $\lambda\lambda$ 5876, 6678 and of [S II] $\lambda\lambda$ 6717, 6731, together with a weak [N II] λ 5755 line, are also seen against the spectrum of the B5 star, which must arise in the nebular condensation on whose periphery the star appears to lie. The ratio of λ 6717:λ 6731 is $\sim$0·6 indicating $\log n_e \sim 3\cdot7$, almost independently of the value of electron temperature. The ratio of λ 5755:(λ 6548+ λ 6584) $\sim$ 0·03, yielding $\log n_e \sim 3\cdot6$ for $T_e = 15\,000$ K. We deduce that at the edge of this condensation $T_e \sim 10\,000$–$15\,000$ K and $n_e \sim 4000$ cm^{-3}. This result is in broad agreement with the conclusions of Glushkov & Karyagina (1972) and of Deharveng (1974) who found appreciably lower electron densities in this condensation than in that including the O7 star. One might speculate that the B5 star formed before the O7 star, on the basis of these different densities.

On the model of Mezger, Smith & Churchwell (1974), an abnormally low abundance of He II/H II is predicted for a nebula with the ratio of $L_{IR}/L_{L\alpha}$ that Sh 156 has, due to preferential absorption by dust of helium ionizing photons. Since their results are based upon radio recombination line data for H II regions which are mostly highly obscured or totally invisible optically, it would therefore seem important to establish whether Sh 156 has a low He II abundance by means of spectrophotometric observations of optical He I recombination lines emitted by this easily observable nebula. No nebular helium emission lines are visible against our spectrum of the O7 star so we cannot examine the helium abundance in the bright, high density condensation in Sh 156. For the lower density region where the B5 star is located we may apply the formula given by Miller (1974) for

$N(He^+)/N(H^+)$ by comparing the emission line fluxes of He I 5876 and Hβ, after correcting the observed fluxes for an $A_V = 2{\cdot}7$. Taking T_e as 10^4 K we find $N(He^+)/N(H^+) = 0{\cdot}12$ which value is not at all abnormal. However, it would still be valuable to investigate other regions in this nebula further from the exciting stars.

4.2 *Sh* 162

Inspection of the values of A_V in Table I, and comparison with Plate II, reveals that Sh 162 undergoes uniform extinction ($A_V \sim 1{\cdot}8$–$2{\cdot}2$) except in the directions of C_1, C_2, C_3 and A_1, where internal extinction within the condensations must be involved. These four condensations appear as bright radio knots in the maps of Israel *et al.* (1973) and Israel (1976) and it is clearly of interest to investigate the source of excitation of these objects. We have examined the brightest condensation, A_1, at 10 and 18 μ. Upper limits of 0·9 and 25 Jy were obtained at 10 and 18 μ, respectively, using an 11 arcsec beam with 15 arcsec throw, which place severe restraints on the presence of dust emission, particularly at 10 μ. Since an internal source of excitation in the object would be expected to lead to elevated dust temperatures and strong infrared emission, we therefore conclude that the cometary object A_1 is merely a dense globule ionized from without by BD +60° 2522, with no internal sources of excitation, as suggested by Israel *et al.* (1973).

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