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ON THE SUPERNOVA REMNANT S8, AND OTHER GASEOUS NEBULAE, IN IC 1613

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RESUMEN

Se presenta espectrofotometría fotoeléctrica de líneas de emisión en el intervalo comprendido entre λλ3400 y 7400 A para el remanente de supernova S8 y para la nebulosa gaseosa S11 en la galaxia IC 1613 del grupo local. Se encuentra que S8 fue producido por una explosión de supernova de tipo II, con una energía total de 2×10^{51} erg. Se determinaron las condiciones físicas antes y después de la onda de choque; de estas condiciones se sigue que para una misma densidad del medio interestelar, el campo magnético de IC 1613 sería menor que el de la vecindad solar. A partir de las observaciones de S8 y de modelos para remanentes de supernova, se determinaron las abundancias relativas de H, He, N, O, Ne y S. Estas abundancias corresponden a Z = 0.0014 e Y = 0.230. Se dan argumentos que indican que estas abundancias son representativas de las del medio interestelar y, consecuentemente, que la abundancia del helio pregaláctico Y_p está dada por 0.227±0.025. También se discuten brevemente las condiciones físicas de S3, S11, A10 y A17, otras nebulosas en IC 1613.

ABSTRACT

Photoelectric spectrophotometry of emission lines in the λλ3400–7400 A region is presented for the supernova remnant S8 and for the gaseous nebula S11 in IC 1613. It is found that S8 was produced by a type II supernova event, with a total energy of 2×10^{51} erg. The physical conditions before and after the shock were obtained; from these conditions it follows that for the same density of the interstellar medium, the magnetic field in IC 1613 would be smaller than that in the solar vicinity. From the observations of S8 and models for supernova remnants, the relative abundances of H, He, N, O, Ne and S were determined. These abundances imply that Z = 0.0014 and Y = 0.230. It is argued that these abundances are representative of the interstellar medium and therefore that the pregalactic helium abundance, Y_p, is given by 0.227±0.025. A brief discussion on S3, S11, A10 and A17, other gaseous nebulae in IC 1613, is given.

Key words: ABUNDANCES – GALACTIC EVOLUTION – IRREGULAR GALAXIES – NEBULAE- H II REGIONS – SUPERNOVA REMNANTS

I. INTRODUCTION

IC 1613 is a low mass irregular galaxy of the local group. Some of its general characteristics are given in Table 1. Its large hydrogen to total mass ratio makes it a good object for the study of the early stages of galactic chemical evolution and the determination of the pregalactic helium abundance. Moreover, due to its low mass, it provides a good test for the relation found by Lequeux *et al.* (1979) and Talent (1980), in the sense that the higher the mass of the galaxy, the higher its heavy element content. To compare with a better known irregular galaxy, the general properties of the SMC are also shown in Table 1.

There are in the literature several papers devoted to the analysis of emission line objects in IC 1613 (e.g. Smith 1975; Talent 1980; Davidson and Kinman 1982; D'Odorico and Rosa 1982; D'Odorico and Dopita 1983; Hunter and Gallagher 1985). These objects are very faint, and the number of observed line intensity ratios available to determine their physical conditions is small; moreover, the accuracy of the observations is low. We decided to make new observations of Sandage 8 and Sandage 11 (Sandage 1971), hereafter S8 and S11, and to rediscuss previous observations of S8, S3, A10 and A17. S8 has been positively identified as a supernova remnant (D'Odorico, Dopita and Benvenuti 1980), SNR, S3 as an H II region with an embedded Wolf-Rayet star (Smith 1975; Davidson and Kinman 1982), whereas the nature of the other objects is still controversial. In the absence of radio data, SNR identifications are based on optical line ratios such as I(Ca II)/I(Hβ), I([S II])/(Hβ) and I(4363)/I(5007) of [O III]. For some objects these ratios are not available, and therefore their classification is uncertain.

1. Visiting Astronomer, KPNO National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

GENERAL PROPERTIES OF IC 1613 AND THE SMC

		IC 1613	SMC
Distance	(kpc)	640[a], 690[b], 770[c]	70[d]
Diameter	(kpc)	4.6[b]	6.5[e]
M_{TOT}	(10^8 $M_\odot$)	2.6[b], 3.9[f]	18[d], 9[f]
M(H I)/M_{TOT}		0.22[b]	0.28[d], 0.27[g]
M(H I)/L_{pg}	($\odot$ units)	0.74[b]	1.02[h]
σ (H I)	(10^{-3} g cm^{-2})	0.7[b]	3.0[d]
⟨N(H I)⟩	(cm^{-3})	0.03[b]	0.10[d]

References: (a) de Vaucouleurs 1978, (b) Epstein (1964), (c) Sandage 1971, (d) Lequeux 1984, (e) Allen 1973, (f) Humphreys 1980, (g) Dopita *et al.* 1985, (h) for $L_{pg} = 4.9 \times 10^8$ $L_\odot$ from Epstein 1964.

II. OBSERVATIONS

The observations were carried out in 1978–1981 during three observing seasons with the 2.1-m telescope at Kitt Peak National Observatory and the Intensified Image Dissector Scanner (IIDS). The observational procedure was described by Torres-Peimbert and Peimbert (1977). The dual entrance slits used correspond to 3.8×12.4 arcsec on the plane of the sky; the slits were oriented east-west, and the separation between the centers of both slits was 99 arcsec. Several gratings were used covering the following wavelength ranges: λλ3400–5200, 4800-6600 and 5600–7400. Each spectrum was recorded into 1024 channels. The FWHM resolution was 3.8 channels.

The data were reduced to absolute fluxes via standard stars of Oke (1974) and Stone (1977), and considering that the actual flux, F, is related to the instrumental signal by the relation

$$S \propto F^{1+\beta} \quad , \qquad (1)$$

with $\beta = 0.07$ (Peimbert and Torres-Peimbert 1987).

In Figure 1 we show typical spectra of one observing season. In Table 2 we present the intrinsic line intensities given by

$$\log[I(\lambda)/I(H\beta)] = \log[F(\lambda)/F(H\beta)] + C(H\beta)\, f(\lambda) \quad , \qquad (2)$$

where F(λ) is the observed flux corrected for atmospheric extinction and C(Hβ) is the logarithmic reddening correction at Hβ presented in Table 2. The I(Hβ) flux in Table 2 is given in erg cm^{-2} s^{-1}, and corresponds to the region observed through the slit and not necessarily to the whole object. The reddening function, f(λ), normalized at Hβ was derived from the normal extinction law (Whitford 1958) and is listed in Table 2. The C(Hβ) value for S8 presented in Table 2 was determined by fitting the I(Hα)/I(Hβ) ratio to that predicted by the H shock wave model of Raymond (1979), since the velocity of this model is close to the one expected in S8 (see §§ III.b and III.a), and it is equal to 0.05±0.10. It is also possible to determine C(Hβ) by fitting the observed Balmer decrement to the one computed by Hummer and Storey (1987) for case B, $T_e = 10000$ K and $N_e = 10000$ cm^{-3}. In this case C(Hβ) is equal to 0.10, in excellent agreement with the previous value.

From results of different nights we estimate that the standard deviation, σ, is of 0.02 dex for Balmer line intensities relative to Hβ, and $\sigma < 0.04$ dex for all other line intensities relative to Hβ, with the exception of those marked with a colon where $\sigma < 0.08$ dex. The standard deviation of the absolute flux at Hβ for S8 is 0.06 dex, while for S11 it is 0.10 dex. We subtracted the contribution of [Ca II] 7323 from I(7320+7323+7330) under the assumption that I(7323) = 0.67 I(7291).

In Table 2 we also present the line intensities of D'Odorico and Dopita (1983), hereafter DD, for region S8. Their line ratios of lines of similar intensities and close in wavelength, such as I(6717)/I(6731), are similar to ours. However, DD systematically underestimate the fainter lines relative to the brighter ones. This effect is present, for example, in the very large differences between the I(4363)/I(5007) line ratios and the C(Hβ) values. Due to this systematic difference, which is larger than our observational errors, in what follows, we will treat independently both sets of data.

In Table 2 we present the observations of Smith (1975). In general his observations are closer to ours than to those of DD, but he also obtains a larger C(Hβ) value than the one derived by us. Due to the low spectral resolution of Smith's observations, his I([N II])/(Hα) and I(6731)/I(6717) line ratios are not reliable. Our low

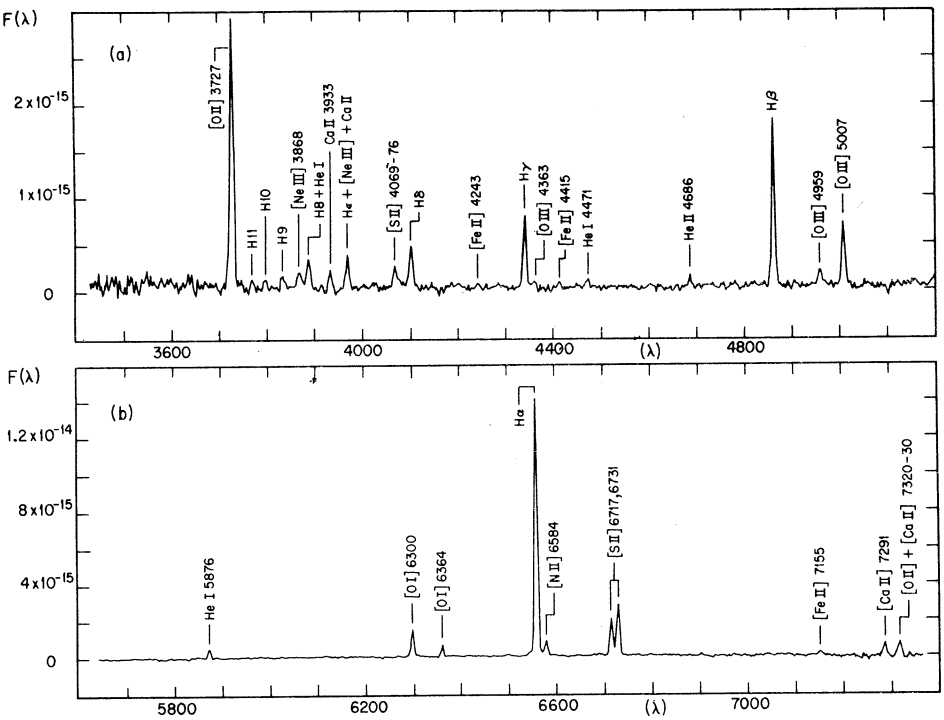

Fig. 1. a) Blue spectrogram of S8, b) Red spectrogram of S8.

TABLE 2

LINE INTENSITIES IN IC 1613[a]

λ	ID	f(λ)	S8 (a)	S8 (b)	S8 (c)	S11 (a)
3727 + 3729	[O II]	+0.315	+0.15	+0.22	. .	+0.30:
3835	H9	+0.280	-1.13:	...	...	...
3869	[Ne III]	+0.270	-1.09	...	...	...
3889	He I + H8	+0.265	-0.73	...	...	...
3933	Ca II	+0.250	-1.00	...	...	...
3967 + 3968 + 3970	[Ne III] + Ca II + H7	+0.235	-0.61	...	...	...
4068 + 4076	[S II]	+0.210	-0.75	-0.70	...	...
4102	Hδ	+0.200	-0.60	-0.62	...	...
4340	Hγ	+0.135	-0.34	-0.37	...	...
4363	[O III]	+0.130	-1.38	-1.59	...	...
4415	[Fe II]	+0.120	...	-1.47	...	...
4471	He I	+0.105	-1.43:	...	...	...
4686	He II	+0.045	-1.26	-1.44	...	...
4861	Hβ	+0.000	0.00	0.00	0.00	0.00
4959	[O III]	-0.020	-0.91	-0.92	...	...
5007	[O III]	-0.030	-0.43	-0.47	-0.39	-0.57:
5158	[Fe II]	-0.060	-1.15	-1.26	...	...
5199 + 5200	[N I]	-0.075	...	-1.70	...	...
5876	He I	-0.210	-0.99	-1.10	-1.01	...
6300	[O I]	-0.285	-0.47	-0.52	...	...
6364	[O I]	-0.300	-1.03	...	...	...
6563	Hα	-0.335	+0.47	+0.42	+0.45	...
6583	[N II]	-0.340	-0.67	-0.70	-0.38	...
6717	[S II]	-0.370	-0.29	-0.44	-0.34	...
6731	[S II]	-0.370	-0.19	-0.35	-0.17	...
7155	[Fe II]	-0.415	-1.25	-1.52	...	...
7291	[Ca II]	-0.430	-0.72	-0.92	...	...
7320 + 7323 + 7330	[O II] + [Ca II]	-0.435	-0.67	-1.05	...	...
7320 + 7330	[O II]	-0.435	-1.06	-2.07	...	...
C(Hβ)			+0.05	+0.60	+0.50	+0.05:
log I(Hβ)			-13.40	...	...	-14.02

a. Given in log I(λ)/I(Hβ). References: (1) This work, (2) D'Odorico and Dopita 1983, (3) Smith 1975.

C(Hβ) value is consistent with the very high latitude of IC 1613, its very low heavy element content (see Table 5), and the determinations of E(*B*− *V*) values of supergiant stars (Sandage 1971; Humphreys 1980).

Also in Table 2 we include observations of S11 which were obtained with the set-up mentioned above; S11 was observed on two different nights but only in the 3400 to 5200 A region. The C(Hβ) value for S11 was not determined, so we adopted the one derived by us for S8.

III. SANDAGE 8

a) *Densities and Temperatures*

The relevant references to the atomic parameters used to derive electron temperatures, electron densities and chemical abundances are from the compilation by Mendoza (1983).

We present the derived densities and temperatures in Table 3. From the I(6717)/I(6731) ratio given in Table 2, which has an error of 0.02 dex, we obtain that x = 0.13±0.02, where $x = 10^{-2} N_e T_e^{-1/2}$. Combining this value with the observed I(6717 + 6731)/I(4068+4076) ratio, which has an error of 0.04 dex, we find T_e = 13500±1000 K and N_e = 1510±230 cm^{-3}. From the I(7320+7330)/I(3726+3729) ratio, and adopting the same value of x, we find T_e = 13650 K, in excellent agreement with the S^+ temperature. This result indicates that the S^+ and O^+ lines originate in the same region. From the I(4959+5007)/I(4363) ratio, and an error of 0.04 dex, a T_e = 80000±15000 K is derived. For comparison, the [O III] temperature in different regions in the Cygnus Loop is between 25000 and 45000 K (Miller 1973; Raymond *et al.* 1988). Thus, the high [O III] temperature observed in S8 not only confirms it as a SNR, but also that the cooling region is underabundant in heavy elements (Raymond 1979).

In Table 3 we also present the temperatures derived from the DD data, which lead to $T(S^+) > T(O^+)$, in disagreement with all theoretical models. This discrepancy is probably due to the systematic effect present in the DD data mentioned in § II.

b) *Shock Velocity*

The presence of the [O III] emission lines in the spectrum of S8 indicates that the shock velocity, V_s, is larger than about 100 km s^{-1} (Shull and McKee 1979; Dopita *et al.* 1984), otherwise there would not be enough energy to ionize oxygen twice. The line intensity ratio I(5876)/I(Hβ) provides another clue to the possible range of values of the shock velocity. According to Raymond (1979), V_s is between 80 and 120 km s^{-1} if this ratio is larger than 0.13 and N(He)/N(H) = 0.085. For an extreme case of N(He)/N(H) = 0.075, the lower limit of the line ratio would be 0.11. The spectrum of S8 shows that I(5876)/I(Hβ) = 0.1, which combined with the presence of the [O III] lines, leads to $V_s > 120$ km s^{-1}. A large shock velocity is also expected when there is a small difference between the S^+ and O^+ regions (Raymond 1979). In § III.a we showed that this is indeed the case. A more precise estimate of the shock velocity can be obtained from a plot of I(5876)/I(Hβ) vs. I(4686)/I(5876). In Figure 2 we present the observed and theoretical values of these line ratios, the latter taken from models E, F, G, H and I of Raymond (1979), which are identical except for the shock velocity. The observed ratios indicate that the shock velocity should be close to 160 km s^{-1}. It cannot be much larger than this, since the cooling time would be very long, specially in a medium of low heavy element abundance. Thus, we take 160 km s^{-1} as the most probable value for the shock velocity. The I(4686)/I(5876) match between models and observations is not very good. We consider that new models are needed to obtain a better fit; similar differences in the oxygen lines have been reported earlier in other objects (e.g. Blair, Kirshner and Chevalier 1982).

c) *Pre-shock Density and Magnetic Field*

The pre-shock density, N_0, is usually determined from the electron density in the recombination region, this being equal to the one derived from the [S II] lines. From the momentum and mass conservation equations,

TABLE 3

DENSITIES AND TEMPERATURES FOR S8

Line ratio	This paper	(a)
I (6717)/I(6731)	x = 0.13 ± 0.02	x = 0.12
I (6724)/I(4073)	T_e = 13500 ± 1000	T_e = 26000
I (7235)/I(3727)	T_e = 13650	T_e = 5000
[S II]	N_e = 1510 ± 230	N_e = 1930
I(4959 + 5007)/I(4363)	T_e = 80000 ± 15000	T_e = 40000[b]

(a) Observations by D'Odorico and Dopita 1983, densities and temperatures recomputed in this paper.
(b) These are upper limits due to the possible contribution of λλ 4358.37 and 4359.34 of [Fe II] to λ4363 of [O III].

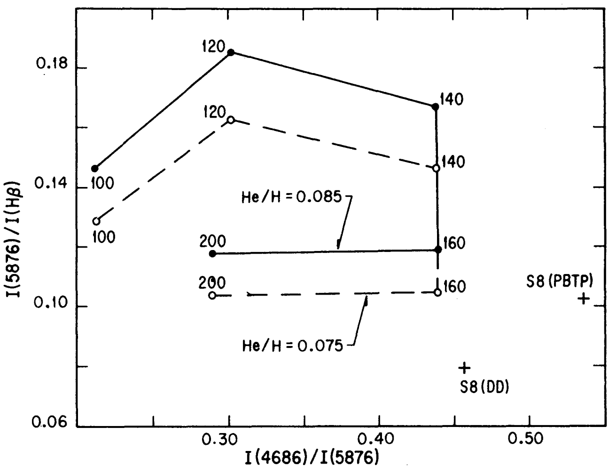

Fig. 2. I(He I, 5876)/I(Hβ) vs. I(He II, 4686)/I(He I, 5876) diagram. The solid lines connect models E. F, G, H, and I by Raymond (1979) for N(He)/N(H) = 0.85, the numbers denote shock velocity in km s^{-1}. The broken lines connect scaled models from those by Raymond for N(He)/N(H) = 0.075. The crosses denote the observations of S8 by D'Odorico and Dopita (1983) and this paper (PBTP).

and with the condition of a frozen-in magnetic field, Bohigas *et al.* (1983) showed that,

$$(\rho_1/\rho_0)^2 V_{0a}^2 + (\rho_1/\rho_0)(V_{0a}^2 + C_0^2) - V_s^2 = 0 \quad (3)$$

where ρ_1 and ρ_0 are the downstream and upstream mass densities, V_{0a} is the upstream Alfvén speed defined as $(B_0^2/8\pi\rho_0)^{1/2}$, with B_0 being the interstellar magnetic field, and C_0 the upstream sound speed. If there is no magnetic field we obtain a pre-shock density of 5.9 cm^{-3} with C_0 = 10 km s^{-1}, N_e = 1510 cm^{-3} and V_s = 160 km s^{-1}. This is a minimum value since magnetic pressure inhibits compression. On the other hand, we have no information regarding the magnitude of magnetic fields in irregular galaxies, and it is not clear which value of B_0 should be taken in order to obtain a better estimate of the pre-shock density. Consequently, we will consider another method to calculate these quantities.

Most shock wave models for a plane parallel shock wave predict that the Hβ intensity, i_{pp}(Hβ), is proportional to $N_0 V_s^2$ (Raymond 1979; Shull and McKee 1979), though recent calculations of Hartigan, Raymond and Hartmann (1987) lead to $i_{pp} \propto N_0 V_s^{1.7}$. Since the difference between these models is relatively minor, we will use Raymond's (1979) models, which lead to

$$i_{pp}(\mathrm{H}\beta) \approx 5.4 \times 10^{-21} \; N_0 V_s^2 \; \mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}} \; . \quad (4)$$

His models indicate that the chemical composition and the pre-shock magnetic field have a minor effect on this quantity. Since we are not dealing with a plane parallel shock wave, equation (4) has to be modified to take into account the real structure of the object being considered. In the simplest case we can assume that the SNR is a perfectly spherical shell. If its thickness is at most 10% of its radius, the expected Hβ intensity is 3 times larger than what is given in equation (4). Equating the observed flux to the one expected for this structure, and taking into account that the angular diameter of S8 is 5.4″ (Sandage 1971) and that the slit size is 3.8″x 12.4″, we find $N_0 V_s^2$ = 51x10^{14} cm^{-1} s^{-2}. For V_s = 160 km s^{-1} we obtain N_0 = 20 cm^{-3}. Applying equation (3) we now find that B_0 = 5.6 μG with a mean mass per particle of 2x10^{-24} gr.

The values just estimated for N_0 and B_0 are probably larger than the real ones, since the remnant is surely more complex, and the area projected by the shock larger than the one projected by a sphere. Thus, the two methods used here have probably yielded lower and upper bounds for N_0 and consequently for B_0. We consider that the estimates based on the assumed geometry are more accurate than the ones based on a null magnetic field. Therefore, we present the former ones in Table 4.

d) *Energy, Age and Swept-up Mass*

The distance to IC 1613 is between 640 and 770 kpc (Table 1). Adopting a distance of 700 kpc, and for an angular diameter of 5.4″, the linear diameter of the optical remnant is 18.3 pc. Assuming that this corresponds to the total size of the remnant, and with V_s = 160 km s^{-1}, the energy involved in the supernova explosion is at least 5.9x10^{50} ergs (for N_0 = 5.9 cm^{-3}) but not larger than 2x10^{51} erg (for N_0 = 20 cm^{-3}), as long as S8 is in the adiabatic or radiative expansion phase (Sedov 1959; Chevalier 1974). This energy suggests that S8 was produced by a type II supernova event (Chevalier 1977). Considering that it is located in a region characterized by vigorous star formation, revealed by the presence of several giant loops and a strong concentration of Population I stars (Sandage 1971; Sandage and Katem 1976; Humphreys 1980), this is not surprising. Of course, such an association does not exclude the possibility that S8 was produced by a type Ib supernova event (Wheeler and Levreault 1985). On the other hand, the size of the real

TABLE 4

S8 PROPERTIES

Diameter•	(arc sec)	5.4
Diameter	(pc)	18.3
Shock velocity	(km s^{-1})	160
Age	(year)	22500
N_0	(cm^{-3})	20
B_0	(μG)	5.6
Swept-up mass	($M_{\odot}$)	1900
Energy	(10^{51} erg)	2.0

remnant must be comparable to its optical size, otherwise the energy associated to S8 would be atypically large.

Under the assumption that the expansion velocity of the remnant is equal to the one revealed by the spectral properties of its optical emission (160 km s^{-1}), the age of S8 is 22500 years if it is in the adiabatic or radiative expansion phase (Sedov 1959; Chevalier 1974). On the other hand, assuming that the object expanded in a uniform density medium, this being equal to the present one, the swept-up mass is about 1900 $M_{\odot}$ (for N_0 = 20 cm^{-3}). These estimates rely heavily on the assumption that the overall properties of S8 are identical to those found in the optical region. But if the optical emission is localized in regions where the main shock has encountered zones of enhanced density, as in the scenario proposed by McKee and Cowie (1975), then the mean expansion velocity would be larger and the mean particle density smaller than the derived values. In such a case both the age and the swept-up mass are smaller than the values given above. This does not modify the value estimated for the energy, since ram pressure is approximately uniform along the shock wave.

e) *Heavy Element Abundances*

At present, the models of Dopita *et al.* (1984) provide the most extended grid in order to enquire into the chemical composition of SNR's. They find that for shock velocities larger than 100 km s^{-1}, the emergent spectrum depends only slightly on pre-ionization and that the ratios of most forbidden lines with respect to Hβ are relatively insensitive to shock velocity. Thus, the emergent spectrum is essentially a function of the chemical composition as long as $V_s > 100$ km s^{-1}, as found here. The oxygen to hydrogen abundance was determined from their Figure 7, which plots I(4959+5007)/I(Hβ) vs. I(3726+3729)/I(Hβ), and is found to be O/H = 6.7× 10^{-5}, our result being mainly based on the [O III]/Hβ ratio. From a plot of I(6548+6584)/I(Hα) vs. I(4959+5007)/I(Hβ) (their Figure 10), we obtain O/N = 14 and O/H = 6.7× 10^{-5}, consistent with the previous estimate. Finally, we find O/S = 34 and, once again, O/H = 6.7× 10^{-5}, from their Figure 11, a plot of I(4959+5007)/I(Hβ) vs. I(6731)/I(Hα). Furthermore, from Raymond's (1979) work we obtain Ne/O = 0.30±0.04, the uncertainty arising from his models. Finally, according to this work, the presence of the calcium lines in our spectrum probably indicates either an undepleted pre-shock gas by dust formation or that the shock wave was responsible for partial grain destruction.

The abundances derived here, as well as those obtained by DD, are presented in Table 5. The lower value found by them for O/H probably comes from the I(3726+3729)/I(Hβ) ratio, which is density sensitive for $N_e \geqslant 10^3$ cm^{-3}, yielding O/H ratios that are smaller than the real ones. Therefore we give preference to our result, since it is mainly based on the I(4959+5007)/I(Hβ) ratio.

By assuming that Hβ is emitted from a shell with T_e = 13500 K and N_e = 1510 cm^{-3}, from the computations by Hummer and Storey (1987) and the Hβ flux given in Table 2, it is found that the volume, thickness and mass of this shell are about 10^{55} cm^3, 10^{15} cm and 15 $M_{\odot}$ respectively. This shell mass is considerably smaller than the 1900 $M_{\odot}$ estimated for the swept-up mass. Therefore, most of the mass in the remnant is closer to the center as a neutral shell of high density material, as found in shock wave models (e.g. Raymond 1979).

According to several authors, the enriched material ejected by the supernova explosion is prevented by a reverse shock wave to be mixed throughout the remnant (Gull 1973; McKee 1974; Chevalier 1975). Chevalier (1979) finds that the mixing timescale is very long and that, for a SNR which is 10^4 to 10^5 years old, the heavy elements ejected by the explosion are likely

TABLE 5

TOTAL ABUNDANCES

	S8		S3		A17	NGC 2363	SMC	Orion	Sun
	(a)	(b)	(c)	(d)	(a)	(e)	(e), (f)	(g)	(h)
He/H	0.075 ± 0.01	0.08	0.091 ± 0.02	0.073 ± 0.009	...	0.077	0.078	0.102	...
C	...	7.04:	...	...	...	7.39	...	8.57	8.67
N	6.68	6.70	⩽ 6.65	6.88:	...	6.44	6.41	7.68	7.99
O	7.83	7.60	7.86 ± 0.15	7.87	7.80:	7.92	7.89	8.65	8.92
Ne	7.31	...	7.33 ± 0.15	7.30	...	7.18	7.03	7.80	...
S	6.30	6.04	...	...	...	6.32	...	7.10	7.23
Y	0.230 ± 0.025	0.242	0.267 ± 0.04	0.226 ± 0.02	...	0.235	0.237	0.280	...
Z	0.0014	0.00082	0.0014	0.0015	0.0013	0.0017	0.0016	0.013	...

He/H by number, Y and Z by mass, C, N, O, Ne, and S in 12 + log N(X)/N(H). References: (a) This work, (b) D'Odorico and Dopita 1983. (c) Talent 1980, (d) Davidson and Kinman 1982 (e) Peimbert *et al.* 1986, (f) Peimbert and Torres-Peimbert 1976, Lequeux *et al.* 1979, (g) Peimbert and Torres-Peimbert 1977, Torres-Peimbert *et al.* 1980, (h) Lambert 1978, Lambert and Luck 1978.

to be in a hot, low density phase, interior to the neutral shell. Soft X-ray observations of the Cygnus Loop (Rappaport *et al.* 1979) have not revealed the presence of a hot interior region where heavy elements are overabundant, as predicted by Chevalier (1979). If no mixing has occurred, then the chemical abundances of the shell given in Table 5 correspond to those of the interstellar medium. By assuming that the interstellar medium has a $Z = 0.0007$, to be able to reproduce the observed $Z = 0.0014$ in S8 we require 1.3 $M_\odot$ of heavy elements ejected by the supernova explosion if the remnant is well mixed. Since the abundances of S8 are in excellent agreement with those derived for S3 and A17 (see § IV), we conclude that mixing has not modified appreciably the abundances in the outer shell of the SNR.

The Z values for the IC 1613 nebulae, given in Table 5, were derived under the assumption that oxygen makes up 60% of the total heavy element content (Peimbert, Peña and Torres-Peimbert 1986).

f) *Helium Abundance*

From the O, S and He line intensities we concluded that the shock velocity is close to 160 km s^{-1}. In Figure 2, the models closer to the observed I(4686)/I(5876) ratio are those with shock velocities of 140 and 160 km s^{-1}. For shock velocities between 100 and 140 km s^{-1}, the average helium atom is singly ionized more often than the average hydrogen atom. For velocities between 160 and 200 km s^{-1}, the hydrogen and helium atoms show a similar ionization pattern, and I(5876)/I(Hβ) reaches a constant value (see Figure 2).

It is possible to derive the He/H ratio by comparing the observations with the models, and by considering that the I(5876)/I(Hβ) ratio is proportional to He/H. From our I(5876)/I(Hβ) ratio and the models by Raymond (1979) for shock velocities between 160 and 200 km s^{-1}, we obtain He/H = 0.075±0.01, where the estimated uncertainty is mainly due to the comparison with models and not to the accuracy of the line intensity ratio. For shocks in the 100 to 140 km s^{-1} range, we would have obtained a smaller He/H value. Similar results are obtained by comparing the I(5876)/I(Hβ) *and* the I(4686)/I(Hβ) ratios with models. To obtain a more precise He/H abundance ratio, a grid of models with lower heavy element abundances should be constructed, to match the line intensities and test the uniqueness of the solution.

IV. OTHER GASEOUS NEBULAE IN IC 1613

a) *Sandage 11*

This region has an angular diameter of 2″ which, at a distance of 700 kpc, implies a linear diameter of 6.8 pc. The only spectral information we have on this region is I(3727)/I(Hβ) = 2, I(5007)/I(Hβ) = 0.27 and an Hβ flux of 9.55×10^{-15} erg cm^{-2} s^{-1}. If S11 is a SNR, the Hβ flux leads to a kinetic energy of 3.35×10^{49} erg for the case of a spherical shell. This is the total energy if S11 is in the free expansion phase. If it is in the adiabatic expansion phase, the total energy would be 1.2×10^{50} erg. Considering the physical diameter of S11, the most probable situation is that this object is in the transition between the free expansion and adiabatic phases, so that its energy is between 3.35 and 12×10^{49} erg. This range of energies is typical of type I supernovae (e.g. Bohigas 1984), as found in RCW 86, SN 1006, Tycho and Kepler. Thus, if S11 is a SNR, it was produced by a type I supernova explosion.

Our spectral information is limited to the oxygen lines, which lead to a O/H ratio of 5×10^{-5} when we use the above mentioned line ratios in combination with Figure 7 of Dopita *et al.* (1984). This ratio is 0.13 dex smaller than the O/H ratio found by us for S8, but 0.10 dex higher than the value derived by DD. The small difference, if real, could be due to incomplete mixing in the interstellar medium of IC 1613. On the other hand, S11 may be an H II region and not a SNR, in which case the oxygen abundance cannot be determined from shock wave models.

By assuming that S11 is an H II region, it is possible to derive the root mean square density, N_e(rms), the ionized mass of the H II region, M(rms), and the total number of Lyman continuum photons, N(Lyc), produced by the ionizing stars. For a homogeneous sphere of radius r and at a distance d, the N_e(rms) value is given by

$$N_e^2(\mathrm{rms}) = \frac{3\,d^2\;I(H\beta)\;[1 + N(He^+)/N(H^+)]}{r^3\;a(H\beta)\;h\nu(H\beta)} \quad , \qquad (5)$$

where a(Hβ) is the effective recombination coefficient. From the a(Hβ) value given by Hummer and Storey (1987) for T_e = 14000 K, and assuming that 50% of He is He^+ and the rest He^0, we obtain N_e(rms) = 36 cm^{-3} and M(rms) = 180 $M_\odot$. The total flux at Hβ, L(Hβ) is 5.6×10^{35} erg s^{-1} and N(Lyc) = 1.2×10^{48} s^{-1}. From the relatively low degree of ionization, it follows that the radiation field is softer than the one produced by an O8 star. Moreover, from the N(Lyc) value and the tabulation by Cruz-González *et al.* (1974), the ionizing stellar flux is intermediate between an O8 V star, with N(Lyc) = 1.8×10^{48} s^{-1}, and an O9 V star, with N(Lyc) = 10^{48} s^{-1}.

There is a faint underlying continuum in our observations of S11, with $m_v \approx 17.0$ that corresponds to $M_v \approx -7.4$. This continuum could be due to a cluster of OB stars, with the earliest one being O9 V with $T_e \approx 30000$ K, $N_H \approx 10^{48}$ s^{-1} and $M_v \approx -4.3$ (Cruz-González *et al.* 1974). This continuum favors the idea that S11 is an H II region.

There is no appropriate grid of models to determine accurately the O/H ratio for H II regions of such low degree of ionization.

b) *Sandage 3*

Talent (1980) and Davidson and Kinman (1982) have determined the abundances of S3 from a direct measurement of the T_e(O III), and these are presented in Table 5. The ionizing star is a Wolf-Rayet (D'Odorico and Rosa 1982; Davidson and Kinman 1982; Armandroff and Massey 1985). It is possible that mass loss from the WR star has been responsible for contamination of the H II region with N and He, as detected in the galactic ring nebulae NGC 2359 and NGC 6888 (Parker 1978; Peimbert 1979; Talent and Dufour 1979; Kwitter 1981).

c) *A10 and A17*

Hunter and Gallagher (1985) observed two emission regions in IC 1613 located in the A10 and A17 associations defined by Hodge (1978); A10 includes S12 and A17 corresponds to the S10 and S13 emission nebulae defined by Sandage (1971). From the line intensity ratios presented, it is not possible to ascertain whether A10 and A17 are H II regions or shock excited nebulae. In what follows we will assume that they are H II regions.

The only data available are the I(3727)/I(Hβ) and the I(4959+5007)/I(Hβ) ratios. To determine the O/H ratio we also need the electron temperature, which is not known. To estimate this ratio we have to rely on an empirical relation between the nebular line intensities and the abundance ratio. The calibration of this relationship is based on models and on observations of H II regions with known electron temperatures (Edmunds and Pagel 1984).

The empirical calibration for a given I([O II]+[O III]) /I(Hβ) ratio yields two very different O/H abundance ratios. Hunter and Gallagher (1985) chose the high abundance value based on: a) the relatively low degree of ionization of A10 and A17 and, b) the strong correlation present in *giant* H II regions, in the sense that a higher O/H abundance ratio corresponds to a lower degree of ionization.

The correlation between the degree of ionization and the O/H abundance ratio holds for giant H II regions, and not for those ionized by stars with spectral types equal or later than O8. Moreover, the empirical calibration of nebular line intensities and the oxygen abundance for regions of O/H < 2×10^{-4} holds only for giant H II regions with I(5007)/I(Hβ) ratios larger than 2. Due to these two reasons we cannot apply the empirical calibration by Edmunds and Pagel for faint H II regions ionized by stars equal or later than O8.

From the ionization model structures of Stasinska (1980, 1982) it is found that model FA2 provides a good fit to the observations of region A17. Model FA2 has the following characteristics: T* = 35000 K, N_e = 100 cm^{-3} and O/H = 5×10^{-5}. By comparing models EA2 with EA1 and EA2 with FA2, it follows that a slightly lower density, around 30 cm^{-3}, and a slightly higher abundance, O/H = 6.3×10^{-5}, provides a better fit to A17. The degree of ionization of region A10 is considerably lower, and there is no model by Stasinska that would provide an adequate fit for it. What is needed is a group of models in the 32000 ⩽ T* ⩽ 35000 K range and in the 10 ⩽ N_e ⩽ 100 cm^{-3} range to fit regions A10 and S11, and to verify whether the latter is an H II region.

V. CONCLUSIONS

S8 has been probably produced by a type II supernova explosion. Its total energy is 2×10^{51} erg and the swept-up mass around 2000 $M_\odot$. The pre-shock conditions indicate that $N_0 \approx 20$ cm^{-3} and $B_0 \approx 5.6$ μG. The high density is in agreement with a region of recent star formation, as expected for the location of a type II supernova.

It is interesting to compare the average magnetic field in IC 1613 with that at the solar vicinity. The magnetic field and the particle density are related by an expression of the type

$$B \propto N^{\alpha} \quad , \qquad (6)$$

where α = 2/3 for an isotropic contraction, but between 1/2 and 1/3 since the contracting mass will tend to accumulate in the direction parallel to the magnetic field lines (Mouschovias 1976; Spitzer 1978). In our own galaxy, the relative distribution of synchrotron radiation and γ-rays of energy larger than 100 MeV, leads to α = 1/2 (Paul, Cassé and Cęsarsky 1976). We will take α = 1/2 (thermal pressure proportional to magnetic pressure in an isothermal gas) as the most likely value. Canonical values for the density and the magnetic field in the solar vicinity are N_H = 0.2 cm^{-3} and B = 2.5 μG (Reynolds 1984; Manchester 1974). From equation (6) and the pre-shock values for S8, it follows that if N_H = 0.2 cm^{-3} then B = 0.56 μG, a factor of five smaller than in the solar vicinity. Notice that for N_0 densities smaller than 20 cm^{-3}, equations (3) and (6) predict an even smaller B value for N_H = 0.2 cm^{-3}. Therefore, we conclude that for the same density of the interstellar medium, the magnetic field of IC 1613 is smaller than in the solar vicinity.

The S8 emission line spectrum in the optical range is produced in an outer shell that includes about 1% of the swep-up mass. It is argued that this outer shell has not been contaminated by the ejected mass and that its chemical composition corresponds to that of the interstellar medium into which the SNR is expanding.

The derived O/H abundance ratios, and consequently the Z values, of S8, S3 and A17 are very similar to each other and somewhat smaller than the ones found in the SMC and NGC 2363; moreover, these abundances are about an order of magnitude smaller than those of the Orion nebula and the Sun (see Table 5).

IC 1613 follows the trend that the higher the mass of the galaxy, the higher the metallicity (Lequeux *et al.* 1979; Talent 1980; Skillman *et al.* 1988). This result is in disagreement with the conclusions of Hunter and Gallagher (1985).

The helium abundance of IC 1613 should be very close to the pre-galactic helium abundance by mass, Y_p. From the Y value in Table 5 for S8, and the $\Delta Y/\Delta Z$ value for objects with low Z (Peimbert *et al.* 1986) it follows that $Y_p = 0.227 \pm 0.025$. Most of the error is due to the uncertainty in the comparison between observations and models. It might be possible to obtain a better adjustment from a set of models with chemical abundances appropriate for S8.

The Y_p value from the observations of S3 by Davidson and Kinman (1982) amounts to 0.223 ± 0.02. This result should be reevaluated for two reasons: a) the nonlinearity of the IIDS (Peimbert and Torres-Peimbert 1987) should be considered as this effect would be in the direction of increasing Y_p and, b) the possibility of contamination of S3 by helium rich material from the ionizing Wolf-Rayet star. The slightly higher N/O ratio derived for S3 than for S8 might be significant in this context.

Deeper spectra are required, for instance in the [S II] and [O II] lines, to determine whether S11, A10 and A17 are H II regions, SNR's or wind driven nebulae.

A grid of H II region models for $30000 \leqslant T^* \leqslant 35000$ K, $10 \leqslant N_e \leqslant 100$ cm^{-3} and low O/H ratios is needed to establish an empirical relation between the oxygen nebular line intensities and the oxygen abundance. This relation would be of importance in the study of small and faint H II regions of Local Group galaxies.

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