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FOSSIL STRÖMGREN SPHERES FROM SUPERNOVA EXPLOSIONS

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ABSTRACT

Brandt *et al.* have shown that consistency in the combined observations of the Gum Nebula requires a giant H II region, presumably formed by the Vela X supernova explosion. Morrison and Sartori had concluded on the basis of their He II fluorescence theory of Type I supernovae that a giant H II region would be formed as result of the ultraviolet burst. (Bottcher *et al.*, by integrating over the light curve, expect a smaller H II region.) We present here in brief some consequences of the fluorescence model as illustrated by the Vela X and the Tycho supernovae. We conclude that such giant H II regions might not in general be as easily detectable as the Vela X region. The Tycho region may just be detectable in the O II, O III forbidden optical lines or as a "hole" in the 21-cm emission-line profiles (the latter is already suggested in the data). These giant H II regions last appreciably longer than the continuum radio sources within them. Since no very large H II region is likely to be associated with a Type II supernova explosion, detection of giant H II regions around the Galaxy could give us the frequency of Type I explosions.

I. INTRODUCTION

In the fluorescence model of Morrison and Sartori (1969), only a small part of the total energy is emitted in the visible (the "bolometric correction" is about 8 mag). Most of the total energy leaves the supernova neighborhood in the form of He II Lα photons ($h\nu = 40.8$ eV). The estimated photon number is $\sim 10^{62}$, a value corresponding to a primary energy of $\sim 10^{52}$ ergs. The mean free path of these photons at $N_{\rm H} = 1$ cm^{-3} is a couple of parsecs. An H II region with a sharp boundary will be formed, its radius at $N_{\rm H} = 1$ cm^{-3} being about 100 pc. (X-ray photons would produce a partially ionized region outside the region formed by the ultraviolet burst if they leave in substantial numbers initially; however, the present X-ray flux from strong sources, like the Crab, cannot produce such large H II regions.)

Equipartition between electrons and protons is established in a few years. Therefore, the initial temperature is about 10^5 ° K (we assume the bulk of the ultraviolet radiation to be in the He II Lα line). Once the H II region is formed, it cools because there is no further radiation ionizing the gas; and it grows slowly in size, since the emission during cooling is predominantly beyond the Lyman limit of hydrogen.

II. FORBIDDEN LINES OF OXYGEN

Cox and Tucker (1969) showed that the cooling of a collisionally ionized interstellar gas at $T \sim 10^5$ ° K is due mostly to the ions O II, O III, O IV, and to the corresponding ions of carbon. These ions, once collisionally excited from the ground state, relax back to the ground state by allowed radiative transitions. The ions O II and O III also emit in the forbidden lines at 3727, 3729 and 5007, 4959 Å, respectively. The emissivity of the forbidden lines is an order of magnitude less than that of the allowed lines. On the other hand, they can be detected because they are in the optical rather than in the far-ultraviolet part of the spectrum, where the predominant cooling lines lie (in O III, the leading transition is the $2s$–$2p$ at $\lambda = 833$ Å). Since the ionization potential of O III is 54.8 eV whereas that of O II is 35.1 eV, we expect the He II Lα and Lβ radiation to ionize O II but not O III; i.e., most of the oxygen should initially be in the doubly ionized stage.

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The rate of energy loss from forbidden-line emission[1] (see Pottasch 1965; Aller and Liller 1968) of O II, O III at low densities ($N_e < 10^5$ cm^{-3}) is[2]

$$E \sim 7.73 \times 10^{-9} \frac{E_{21}}{\omega_2} T_e^{-1/2} \exp\left(-E_{21}/kT_e\right)\Omega_{21} N_e^2 \frac{N(\mathrm{O}^{+i})}{N(\mathrm{O})_T} \text{ ergs cm}^{-3}\text{ sec}^{-1}, \quad (1)$$

where the subscript 2 refers to the ^1D level in O III, and where the subscript 1 refers to the ^3P level in O III and to the ^2D and ^4S levels in O II. The rate of energy loss depends on $N(\mathrm{O}^{+i})/N(\mathrm{O})_T$ ($i = 1, 2$), the relative abundance of O II, O III. If collisional ionizations balance recombinations, then these relative ion abundances are found from Cox and Tucker (1969). Their "steady state" theory holds as long as approximate equilibrium has time to be established. In this case the abundance ratio for any ion of z an element i is

$$\frac{N_z}{N_{z+1}} = \frac{\alpha^{Di}{}_{z+1,z}(T) + \alpha^{Ri}{}_{z+1,z}(T)}{C^i{}_{z,z+1}(T)} = \frac{\alpha^i{}_{z+1,z}}{C^i{}_{z,z+1}},$$

where $C^i{}_{z,z+1}$ is the collisional-ionization coefficient of ion z and $\alpha^i{}_{z+1,z}$ is the total—dielectronic and radiative—recombination coefficient of ion $z + 1$. (Note that this ratio is a function of T only.)

On the other hand, if the gas cools with no heat input to keep the temperature more or less constant (as in the present case, where after the initial sudden ultraviolet ionization there is no further heat or ionization input, other than collisions in the gas), then the ionic abundances are found from the solution of the coupled system of equations:

$$\begin{aligned} dT/dt &= -\Lambda(T, \ldots, N^i{}_z, \ldots) \qquad \text{(all } z\text{, all } i\text{)}, \\ dN_z{}^i/dt &= -\alpha_z{}^i N_z{}^i N_e + \alpha^i{}_{z+1} N^i{}_{z+1} N_e - C_z{}^i N_z{}^i N_e + C^i{}_{z-1} N^i{}_{z-1} N_e, \qquad (2) \end{aligned}$$

where $\alpha_z{}^i$, $C_z{}^i$ refers to $\alpha^i{}_{z,z-1}$, $C^i{}_{z,z+1}$. Thermal expansion in system (2) is assumed negligible; i.e., $N_T = N_e + N_\mathrm{H} =$ const. The ionic abundances found from system (2) might be different from the Cox and Tucker abundances. This is particularly prominent in hydrogen. If $dT/dt = T/f(T)$ is the Cox and Tucker rate of energy loss, then the total cooling time $t_c = \int f(T)dT/T$ to cool down to 15000° K is $t_c \sim 7.5 \times 10^3/N_T$ years, if $T \sim 10^5$ ° K initially. According to the steady-state model, hydrogen is half neutral at 15000° K. The time for half of hydrogen to recombine is about $10^5/N_T$ years; i.e., it cools down to 15000° K before it recombines appreciably. We thus expect the collisionally induced hydrogen Lα cooling, which in the steady state is peaked around 20000° K, to be appreciably reduced. Hydrogen provides the predominant cooling for $T \lesssim 2.5 \times 10^4$ ° K.

Above 30000° K the situation is as follows. As long as the abundances of the most important cooling ions at a given T are close to the Cox and Tucker values, we expect the radiative power loss of system (2) to be close to the "steady state" curve. This is true at 10^5 ° K (e.g., O III, the most important cooler, has an assumed initial relative abundance of 1, while the equilibrium abundance is 0.73). Even though the rate of energy loss of system (2) might be close to the Cox and Tucker at given T, this fact does not fix the abundances of ions which do not contribute appreciably to the rate of energy loss (e.g., O III might not have an abundance close to the steady state below ~60000° K, at which T the carbon ions C II, C III are the most important coolers).

System (2) is not easy to solve exactly if all the abundant elements are included, since this would require the solution of a system of at least twenty equations. To get a quick estimate here of the O II, O III abundances in the light of the remarks above, we made the simplifying assumption that $dT/dt = -\Lambda(T)$, where $\Lambda(T) \propto T^{1.857}$. This energy-loss

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[1] The collision strengths Ω_{21} that were used were those of Billings *et al.* (1967).

[2] The cosmic oxygen abundance $N(\mathrm{O})/N(\mathrm{H}) = 10^{0.95-4}$ of Aller (1961) is assumed.

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rate follows closely the Cox and Tucker curve except below 30000° K (it lacks the strong peak of the rate of collisional energy loss of H I at 20000° K). System (2) was solved with the above form of dT/dt and O I, O II, O III, O IV only; the same system was solved by taking the exact hydrogen cooling into account below 25000° K, and it was found that the two solutions provide similar results for $T \gtrsim 15000°$ K (it takes $\sim 10^4$ years for a region of $N_e = 1$ cm^{-3} to cool down to 15000° K, and this time span suffices for all our subsequent analysis). In Figure 1 the Cox and Tucker curve for radiative power loss is shown along with our assumed model. The solution of system (2) is shown in Figure 2 with initial conditions $N(\text{O I}) = N(\text{O II}) = N(\text{O IV}) = 0$, $N(\text{O III}) = 1$, $T = 10^5$ ° K. (The density N_e was assumed at $N_e = 1$ cm^{-3}. For other N_e notice that the transformation $t' = \lambda^{-1}t$, $N'_e = \lambda N_e$ leaves system [2] unchanged.) We used the hydrogenic radiative recombination coefficients of Seaton (1959) and the formula of Burgess (1965) (see also Allen and Dupree 1969) for the dielectronic recombination coefficients. The collisional ionization coefficients were those of Cox and Tucker (1969). Having roughly determined the relative abundances of the oxygen ions, one can find the brightness of a nebula in the O II, O III lines as a function of time.

III. APPLICATION TO TYCHO

The Tycho and Kepler galactic supernovae are the only recent ones known to be of Type I. Kepler is farther away than Tycho; therefore, we will limit ourselves to Tycho (the Crab supernova is not examined here because in some ways it is a unique object, and it is even uncertain whether it is of Type I).

The Tycho remnant is only 400 years old. We expect the H II region to be quite hot still. Menon and Williams (1966) determined a distance of 3.5 kpc to Tycho, from their 21-cm absorption-line measurements and a density of $N_H \sim 0.1$ cm^{-3}, at a distance about 100 pc above the galactic plane. Minkowski (1964, 1968) uses the distance 5 kpc and interstellar absorption for the remnant of ~ 2.1 mag. (There is still considerable uncertainty at present as to the correct value of distance, Williams 1971.) We present

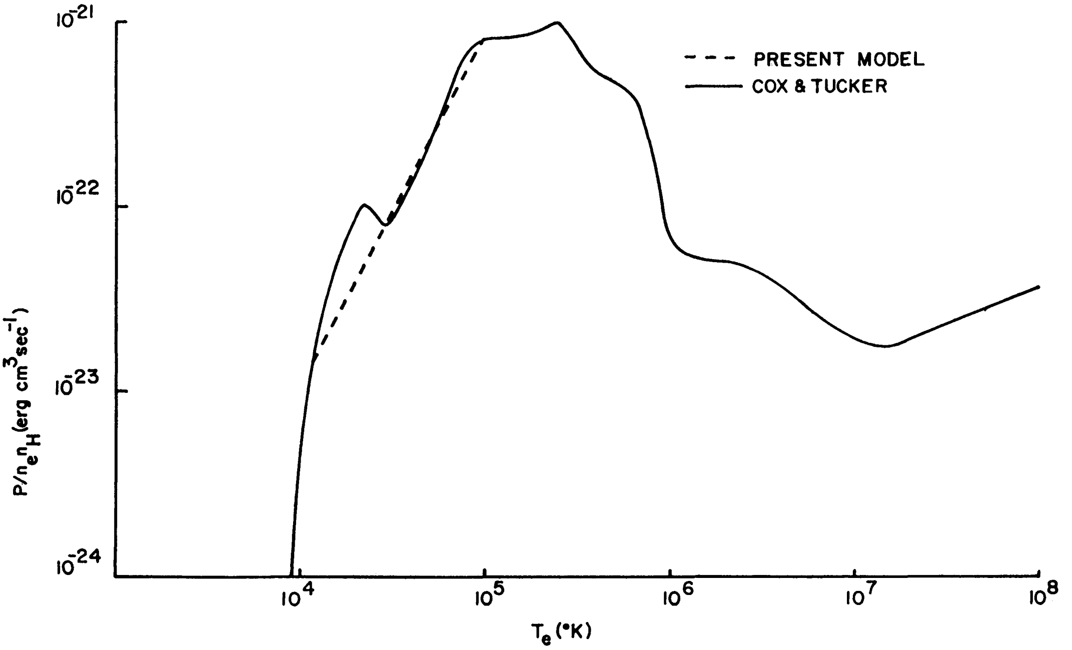

FIG. 1.—Total radiative power loss if cosmic abundances are assumed. Solid curve is by Cox and Tucker (1969); dotted curve is our assumed model.

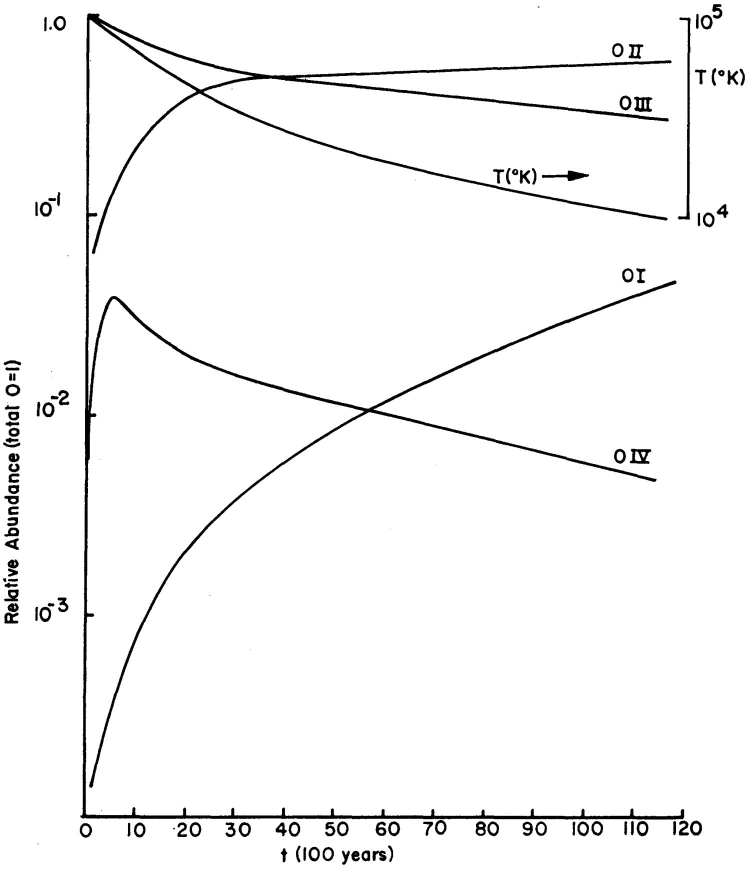

FIG. 2.—Relative abundances of oxygen ions and temperature as a function of time according to our assumptions (initial conditions $T = 10^5$ ° K, N(O III) = 1).

in Table 1 the expected surface brightness of the large H II region (for $N_e = 1$ and 0.1 cm^{-3} and 10^{62} ultraviolet photons), as well as denser, small clouds ($N_e = 10$ cm^{-3}), in the O II, O III lines for Tycho at present. A constant optical absorption of 2 mag was assumed. We also show the expected[3] Hα surface brightness for the above regions and the observed surface brightness of some weak normal H II regions in the Hα (see Pottasch 1965).

We conclude the following: If $N_e \sim 0.1$ cm^{-3}, then the H II region will not be seen in any optical lines. If $N_e \sim 1$ cm^{-3}, it may be possible to detect it in the O III lines $\lambda\lambda$5007, 4959. Finally, small clouds with $N_e \sim 10$ cm^{-3}, $R \sim 10$ pc (which should lie within 40 pc from the supernova in order to become completely ionized) would probably be seen in the O II, O III lines. No Hα or Hβ radiation is detectable, except for the denser clouds; i.e., those regions will not show the characteristic Hα, Hβ radiation of an H II region. The $R = 10$ pc, $N_e = 10$ cm^{-3} clouds would have a free-free radio flux of 1.5 f.u. at 1000 MHz (3 f.u. if $d = 3.5$ kpc) while the flux from the giant region ($R \sim 100$ pc, $N_e \sim 1$ cm^{-3}) is 10 f.u. (20 f.u. if $d = 3.5$ kpc). The fluxes from the small clouds are too weak to be detected, while the giant H II region is so large that it may be hard to distinguish from the background or from other sources (the remnant itself has a flux of 40 f.u. at 1400 MHz).

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[3] As long as $x = N_e/(N_e + N_H)$ is close to the equilibrium value, the Hα emissivity is as calculated by Parker (1964) for collisional excitation; this was found to be the case for $T \gtrsim 30000^\circ$ K.

TABLE 1

EXPECTED SURFACE BRIGHTNESS S OF TYCHO MODEL REGIONS AND OBSERVED S IN Hα FOR NORMAL H II REGIONS

N_e (cm^{-3}) (assumed)	R (pc)	T (° K) (expected)	ANGULAR RADIUS (arc min) FOR TWO DISTANCES		SURFACE BRIGHTNESS (ergs cm^{-2} sec^{-1})		
			$d=3.5$ kpc	$d=5$ kpc	$S_{\rm O\,III}$	$S_{\rm O\,II}$	$S_{\rm H\alpha}$
Tycho Model Region (Calculated Properties)							
1.......	95	80000	94	66	$3\ \times10^{-4}$	7×10^{-5}	8×10^{-7}
0.1	130*	10^5	127	90	$5\ \times10^{-6}$	2×10^{-7}	7×10^{-9}
10.......	10	27000	10	7	1.3×10^{-3}	2×10^{-3}	10^{-4}
Normal H II Regions (Observed Properties)							
28†......	3.2	...	16 ($d=0.7$, 0.525 kpc)			5×10^{-4}	
10‡......	11	...	100 ($d=0.37$, 0.4 kpc)			3×10^{-4}	
16§......	19	...	65 ($d=1$, 1.13 kpc)			8×10^{-4}	

* The light flash has only had time to travel 400 light years (130 pc) since the supernova occurred, although the expected equilibrium radius is ~200 pc. The H II region would still be growing with the speed of light if the density were this low.

† IC 405. ‡ λ Ori. § NGC 7000.

The situation might be more promising if one approached it from another viewpoint—i.e., one could check to see if there is any lack of 21-cm emission (or absorption) from the neighborhood of the supernova. At the position of Tycho, the velocity gradient across the cloud will be several km s^{-1}, comparable to the Doppler broadening at 100° K. Such a "hole" in 21-cm line profiles would be hard to detect, but not impossible. Williams and Weaver (Williams 1971) have perhaps detected the H II region around Tycho. Their survey indicates that there is no doubt that a 21-cm deficiency exists around Tycho, but it is uncertain whether it has anything to do with the supernova. The feature they see shows for several km s^{-1} either side on the -45.2 km s^{-1} velocity map; its diameter is approximately 1°.5. Williams and Weaver see similar holes in places where there is no known supernova remnant (see below for discussion on this point). There is no known pulsar in Tycho. Indeed, the combination of various different measurements that yielded the identification of the Gum Nebula as being due to the Vela X supernova is probably rare. In the case of Tycho, the 21-cm measurements might be the only way of detecting the giant H II region.

IV. VELA X

Brandt *et al.* (1970), by combining the known emission measure, the dispersion measure of the pulsar in Vela X, the neutral-hydrogen measure, and the optical extinction, reach the conclusion that a giant H II region of low density ($\langle N_e \rangle \sim 0.16$ cm^{-3}, $R \sim 400$ pc) engulfs the Gum Nebula, while its edge is only about 60 pc away from the Sun.

The filaments seem to have densities appreciably higher than the mean. The age of the pulsar PSR 0833−45 (Reichley, Downs, and Morris 1970) is 1.1×10^4 years. Milne (1968*a*, *b*) has found the temperature of certain filaments near the pulsar to be quite high ($T \geq 10^4$ ° K). Since these filaments are quite dense ($N_e \sim 300$ cm^{-3}), we expect them to cool down fairly fast after the initial explosion. Their present temperature cannot be due only to the original ultraviolet blast; also, it seems that the heating provided by the diffuse region, $\langle N_e \rangle \sim 0.16$ cm^{-3}, is insufficient to keep filaments, such as those considered by Milne, at $T \sim 10^4$ ° K. Indeed, those filaments are probably collisionally excited by the remnant itself, like the filaments of the Cygnus Loop. The giant H II region should have $T \sim 50000°$ K at present, while regions of $N_e \sim 1$ cm^{-3} would still be about 10^4 ° K. Higher-density regions are either excited by the expanding shell or heated by γ^2 Vel and ζ Pup (as pointed out by Brandt *et al.* 1970). In any case, the Gum Nebula is fairly rich in H II emission clouds, stars, etc. Certainly not everything there is due to the supernova.

The estimated total number of electrons in the H II region is, according to Brandt *et al.* (1970), about 2×10^{62} at present. The region, in cooling from 10^5 ° K to its present $T \sim 50000°$ K, doubles its size, since the predominant radiation during cooling is beyond the hydrogen Lyman limit. This gives[4] $\sim 10^{62}$ for the number of initial ultraviolet photons, which is in accordance with the Morrison-Sartori estimates. We therefore conclude that the Vela X supernova was probably of Type I.

V. CONCLUSION

The Vela X H II region is made easy to detect by a combination of fortunate circumstances. The Tycho region, if it exists, would be quite hard to detect, except perhaps in the O II, O III optical emission. A region of ionized hydrogen may already have been seen as a deficiency in 21-cm emission around Tycho (Williams 1971).

It should be noted that other models not involving immediate ionization of the interstellar gas (such as cosmic-ray ionization or ionization by ultraviolet and X-ray photons produced by the blast wave of the explosion) may explain the present ionization of the Gum Nebula; however, it is the most recent supernovae, like Tycho, which are critical in deciding whether or not the supernova explosion produces an ionized region much later than the time of the explosion.

The importance of supernova explosions in the economy of the galactic gas (heating, cloud formation) was shown by Bottcher *et al.* (1970).

Once an H II region is formed, it lasts 10^6–10^7 years (if $N_e \sim 0.1$–1 cm^{-3}). On the other hand, the observable lifetime of a supernova remnant is probably not larger than 10^5 years (Milne 1970). We therefore expect appreciably more H I "holes" to be seen than Type I supernova remnants, in the same way that many pulsars (with a lifetime of $\sim 10^7$ years, Hewish 1970) are not associated with observable remnants.

Finally, the H II regions produced by Type II supernova explosions might be smaller (as little as 1/100 of the corresponding volume for the regions produced by Type I supernovae). Therefore, the detection of giant H II regions around the Galaxy could eventually provide direct information as to the frequency of Type I explosions.

Note.—Van den Bergh (1968) used the term "fossil H II regions" to describe H II regions (formed by O-type stars) which are not visible any more except for dense regions (like "wormtracks" and "globules") that are the results of complex interactions between the H II region and the interstellar gas. This term should not be confused with "fossil Strömgren spheres" used by Brandt *et al.* (1971).

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[4] The total mass changes by at most a factor of 4 in the recent work of Alexander *et al.* (1971).

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