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IONIZATION AND HEATING OF THE GUM NEBULA BY ENERGETIC PARTICLES FROM THE VELA X SUPERNOVA

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IONIZATION AND HEATING OF THE GUM NEBULA BY ENERGETIC PARTICLES FROM THE VELA X SUPERNOVA

by

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ABSTRACT

We investigate a model in which the Gum Nebula is ionized and heated by energetic particles from the supernova associated with the Vela X remnant. We find that the observed ionization could be produced in 10^4 to 2×10^4 years by the ejection of about 1 to 2 $M_\odot$ of the products of silicon burning at a mean energy of a few MeV/nucleon. We investigate the consequences of this model for the ionization and heating of the interstellar medium, the generation of the light elements, X-ray production, and observable cosmic rays.

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ANALYTICAL STUDIES OF LUNI-SOLAR EFFECTS ON THE MOTION OF ARTIFICIAL SATELLITES

THEODORE L. FELSENTREGER
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MARCH 1971

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INTRODUCTION

A physical model of the Gum Nebula has recently been presented by Brandt et al. (1971) in which the nebula contains about 2×10^{62} free electrons and is assumed to be a fossil Strömgren sphere of the Vela X supernova. These authors indicate that if the ionization were produced by ultraviolet photons released by the supernova outburst at an average energy of 15 eV per ionizing photon, then the total energy in the ultraviolet required to ionize the nebula is 5×10^{51} ergs. In a more recent publication, Alexander et al. (1971) raise the possibility of a reduction in size by up to a factor of 2, thereby reducing the total ionized matter by as much as a factor of 4 and reducing the total energy of the ionizing photons to the range of 1 to 5×10^{51} ergs.

In this communication, we wish to discuss the alternative possibility, namely that the ionization may have been produced by fast charged particles released by the supernova. Since a fast particle of energy $\gtrsim$ 0.1 MeV/nucleon expends some 36 eV to produce an ion pair in cold matter (Dalgarno and Griffing, 1958), the energetic particle output of Vela X must have been at least 2 to 10×10^{51} ergs in order to produce the ions in the Gum Nebula. This is not inconsistent with estimates of the total energy release of supernovae.

As we shall presently see, however, the required ionization and its spatial distribution depend on the assumed charge, mass and energy of the ionizing nuclei, on the age of the supernova and on the matter distribution in the nebula, as well as on the propagation mode of the charged particles.

SUPERNOVA EJECTA

The supernova phenomena is still only qualitatively understood and indeed, current controversy centers around the relative importance of the C^{12} thermonuclear detonation (Arnett 1969) versus neutron star production, (Colgate and White, 1966). In the present case, the formation of the neutron star cannot be disputed, but regardless, the ejected composition and velocity distribution should not be drastically different for the two cases. The thermonuclear detonation of a carbon star (1.5 $M_{\odot}$) releases approximately 2×10^{51} ergs. The formation of the Gum Nebula requires roughly 1 to 5 times this energy in ionization, an amount which is certainly within the probable error of the explosion energy added by the dynamical formation of the neutron star. A fraction of the binding energy of the neutron star ($\simeq 10^{53}$ ergs) is presumably available to augment the thermonuclear detonation.

The velocity distribution of the ejected matter is affected in the mean by the total explosive energy available, but the form is only slightly affected by the two processes. The simplest assumption is that the exploding gas expands as a uniform sphere (velocities calculated numerically are indeed in agreement with this model). The presence of the neutron star perturbs the trajectories of a small inner mass fraction (Colgate 1971) and indeed the re-implosion of the central high density matter removes from observation what otherwise would be a prohibitive mass of neutron-rich matter.

In addition to the uniform expansion approximation, we take note of the increasing strength of the explosion shock wave in the envelope of the star. Again numerical calculations show that this speed-up can be

roughly approximated by a power law in mass fraction, F, where F is the fraction of the stellar mass external to the Lagrange coordinate position in question.

Then:

$$v = \begin{cases} v_1 (1 - F)^{1/3} & ; \quad 0.75 \geq F \geq F_0 = 3/7 \\ 0.67\, v_1\, F^{-1/4} & ; \quad F \leq F_0 \end{cases} \tag{1}$$

The corresponding number spectrum of nuclei of mass number A in the non-relativistic region is given by

$$N_0(\varepsilon) = \frac{6}{7} \frac{M_{ej}(A)}{A m_p} \frac{1}{\varepsilon} \begin{cases} (\varepsilon/\varepsilon_0)^{3/2} & ; \quad \varepsilon < \varepsilon_0 \\ (\varepsilon_0/\varepsilon)^2 & ; \quad \varepsilon > \varepsilon_0 \end{cases} \tag{2}$$

where m_p and Mej(A) are the proton mass and the total ejected mass in nuclei of mass number A, respectively, and ε is kinetic energy per nucleon. The total energy output of the supernova in particles of mass number A depends on the transition energy ε_0 (which we assume to be the same for all nuclei) and is given by

$$W = \frac{6}{5} \frac{M_{ej}(A)}{m_p} \varepsilon_0 . \tag{3}$$

Using this velocity distribution, Colgate and McKee (1969) showed that the light curve of a type I supernova could be created with a best fit to observations assuming

1. The products of silicon-burning resulted in the ejection of Ni^{56} and Si^{28} in a ratio of 1 to 2 .
2. An initial pre-supernova star ejects approximately 1/2 its mass composed of the above products.
3. That the velocity v_1 is chosen such that the heat given off by

$Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$ is released by the progressive transparency of expansion resulting in the approximate conditions $\mathcal{E}_o \simeq (Mej/M\odot)^2$ MeV/nucleon and $W \simeq 2 \times 10^{51} (Mej/M\odot)^3$ ergs. Therefore, a small adjustment in the ejected mass in the range 1 to 2 $M\odot$ will cover the range of required ionization energies. The maximum possible energy is likely to be limited by the neutron star binding energy $W \lesssim 10^{53}$ ergs or $\mathcal{E}_o \lesssim 30$ MeV/nucleon. In subsequent calculations we shall adopt $\mathcal{E}_o$ equal to 2, 10 and 20 MeV/nucleon.

THE NEBULA

The time elapsed since the supernova explosion can be estimated from the age of the pulsar PSR 0833-45, which is generally believed to be the neutron star remnant of the Vela X supernova. This age can be determined from the present period and rate of increase of the period and equals 11,500 years (Reichley, Downs and Morris, 1970). Shklovsky (1970), however, suggests that the age of the supernova remnant as deduced from its radio surface brightness is about 30000 to 50000 years, and that the discrepancy can be understood in terms of repeated speedups of the Vela pulsar. We shall assume that $t = 10^4$ years is a reasonable lower limit to the age of the nebula, with $t < 5 \times 10^4$ years a possible upper limit.

According to Brandt et al. (1971) the comparison of the emission measure of the Gum Nebula and the dispersion measure of the pulsars in or behind the nebula indicates that the matter is concentrated into clumps or clouds. Let $(n_e)_c$ and $(n_H)_c$ be the electron and hydrogen densities in the clouds and $(n_e)_c = (n_e)_c + (n_H)_c$. According to the

measurements summarized by Brandt et al. (1971), the present values of the spatial averages, $\langle n_e \rangle$, $\langle n_e^2 \rangle$ and $\langle n_H \rangle$ are about 0.16 cm^{-3}, 1.63 cm^{-6}, and 0.062 cm^{-3} respectively, so that $\langle n_o \rangle \simeq 0.22$. Under the assumption that all the matter is concentrated into the clouds, these averages can be written as

$$\langle n_e \rangle = \frac{V_{eff}}{V}(n_e)_c \; ; \langle n_e^2 \rangle = \frac{V_{eff}}{V}(n_e)_c^2 \; ; \langle n_H \rangle = \frac{V_{eff}}{V}(n_H)_c \qquad (4)$$

where V is the nebular volume and V_{eff} is the total volume of the clouds. The ratio $X = V/V_{eff}$ is then given by $X = \langle n_e^2 \rangle / \langle n_e \rangle^2 \simeq 65$.

If the clouds are spherical objects with a random spatial distribution, the mean distance ℓ between clouds along an arbitrary direction is $\ell \simeq \frac{4}{3} r X \simeq 87 r$, where r is the radius of a cloud. For a "standard cloud" (Spitzer, 1968) r = 7 pc so that $\ell \simeq 600$ pc. The comparison of the emission and dispersion measures toward the Vela X pulsar indicates that the line of sight in that direction intersects at least one cloud. Since ℓ cannot be larger than the distance to the pulsar, $r \lesssim 5$ pc. Obviously, both r and ℓ may be highly variable throughout the nebula.

The mode of propagation of the energetic particles in the Gum Nebula is essentially unknown. The high degree of isotropy ($\delta \lesssim 3 \times 10^{-4}$) of the galactic cosmic rays with energies > 10^{11} eV (Elliot, Thambyahpillai and Peacock, 1970) implies that the streaming velocity in interstellar space at these energies is less than ~ 20 km /sec or 2 x 10^{-5} pc/year. This velocity is obviously much too low to account for the ionization in < 5 x 10^4 years of the entire Gum Nebula which appears to extend some 400 pc in the galactic disk (Brandt et al. 1971). The low anisotropy

of the galactic cosmic rays has recently been interpreted by Lingenfelter, Ramaty, and Fisk (1971) in terms of particle propagation by compound diffusion. Such diffusion combines the effects of random walk of the field lines (Jokipii and Parker, 1969) with one-dimensional diffusion along field lines. The net spatial displacement of particles undergoing compound diffusion is proportional to $t^{1/4}$ as opposed to the dependence proportional to $t^{1/2}$ as encountered in ordinary diffusion. This leads to a low cosmic ray propagation velocity and can account for the isotropy observed at high energies.

Since diffusive propagation along field lines is the result of scattering of the particles by magnetic irregularities, it is possible that in the few MeV/nucleon range the gyroradii are much smaller than the scale size of the irregularities, hence particles will no longer be scattered and diffusive propagation will reduce to regular motion. In addition, shortly after the supernova explosion, the energy density in low energy particles is much larger than that in field irregularities, so that even if scatterings were important, the irregularities are expected to be swept along the field lines by the particles. In both cases, the particles propagate along the field lines with a mean velocity $c\beta$, where $\beta = 0.15$ for $\mathcal{E} = 10$ MeV/nucleon. If the characteristic length of the random field distribution in the Gum Nebula is of the order of the mean distance between clouds, particles could propagate to the edge of the nebula with essentially rectilinear motion and be stopped or deflected only by collisions with clouds. With $\beta = 0.15$, particles will traverse 400 pc in 8200 years, a time which is less than the lower limit on the age of the nebula.

Whereas the motion of the particles in the intercloud medium is essentially regular motion along the field lines, penetration into the clouds is probably governed by wave-particle interactions. As the particles stream down a density gradient they produce hydromagnetic waves which scatter the particles and limit the streaming (Wentzel, 1969; Kulsrud, and Pearce, 1969). The limiting streaming velocity v_R can be obtained by balancing the growth rate and damping rate of the waves, and is approximately given by (Kulsrud and Cesarsky 1971)

$$v_R = v_A \left[1 + \frac{4}{\pi} \frac{m_p c}{Z e B} \frac{R(n_H)_c (n_e)_c}{n_{cr}(>p)} \right] \tag{5}$$

Here v_A is the Alfven speed; B is the magnetic field in clouds; $R(n_H)_c$ is the damping rate which is temperature dependent and equals 1.5×10^{-9} $(n_H)_c$ sec^{-1} at 100 K and about 1.5×10^{-8} $(n_H)_c$ sec^{-1} at 5×10^4 K; p is the momentum at which the streaming is evaluated; and $n_{cr}(>p)$ is the density of energetic particles with momenta greater than p.

Consider the initial interaction of the energetic particles with HI clouds. As a lower limit for the particle density in clouds, we take $n_{cr} = N_o/V$ where N_o is the total particle output of the supernova and V is the total volume of the nebula. For N_o corresponding to $M_\odot$ Si^{28} + 0.25 $M_\odot$ Fe^{56} and $V = 1.35 \times 10^{63}$ cm^3 (Brandt et al.,1971) we get $v_R = v_A [1 + 0.6 (n_e)_c (n_H)_c / B(\mu g)]$ for neutral clouds at 100 K, and $v_R = v_A [1 + 6 (n_e)_c (n_H)_c / B(\mu g)]$ for ionized clouds at 5×10^4 K. Let us assume that the initially neutral clumps in the Gum Nebula are similar to ordinary HI clouds for which $(n_e)_c \simeq 0.03\ cm^{-3}$ (Hjellming, Gordon, and Gordon 1969). For these clouds in the Gum Nebula $(n_H)_c \simeq 14\ cm^{-3}$, so that for $B = 3\ \mu g$, $v_R \simeq 42$ km/sec. For ionized clouds in the Gum Nebula $(n_e)_c \simeq 10\ cm^{-3}$ and $(n_H)_c \simeq 4\ cm^{-3}$, so that for $B = 3\ \mu g$, $v_R \simeq 226$ km/sec. If we assume that the average transit

distance across a cloud is of the order 5 pc, the transit times in neutral and ionized clouds become about 10^5 and 7×10^3 years, respectively.

These times can be compared with the energy loss times in the clouds. The energy loss per nucleon of a nonrelativistic particle of charge Ze in partially ionized hydrogen is given by (Hayakawa and Kitao 1956)

$$\frac{d\varepsilon}{dt} \simeq 1.46 \times 10^{-12} \frac{Z^2}{A} \left[(n_H)_c + 4(n_e)_c \right] \varepsilon^{-0.3} \text{ MeV/nucl. sec}^{-1} \tag{6}$$

where ε is in MeV/nucleon. The time in which a silicon nucleus of 10 MeV/nucleon will lose half its energy in neutral or ionized clouds, is about 2000 years and 640 years, respectively. Both these times are much shorter than the transit times across clouds, so that once a particle penetrates a cloud, it will stop and deposite its energy on a time scale less than about 2000 years.

We now consider the energy deposition and ionization. The total energy loss to both ionization and heating, E_t, of particles with initial spectrum $N_o(\varepsilon')$ in a fixed time t is given by

$$E_t = \int_0^\infty d\varepsilon' \, N_o(\varepsilon') \, A \left[\varepsilon' - \varepsilon(\varepsilon', t) \right] \tag{7}$$

where $\varepsilon(\varepsilon', t)$ is the energy per nucleon as a function of time of a particle of initial energy per nucleon ε'. Because both $(n_e)_c$ and $(n_H)_c$ are time dependent as a result of the varying degree of ionization of the clouds as a function of time, the solution of equation (6) has to be written as

$$\varepsilon(\varepsilon', t) = \varepsilon' \left[1 - \frac{Z^2}{A} \frac{\overline{(n_H + 4n_e)} \, t}{\varepsilon'^{1.3} \times 1.8 \times 10^4} \right]^{1/1.3} \tag{8}$$

where t is in years, $\mathcal{E}$ and $\mathcal{E}'$ in MeV/nucleon, and

$$\overline{n_H + 4n_e} \equiv \int_0^t \left[(n_H)_c + 4(n_e)_c \right] dt' . \tag{9}$$

The energy loss to ionization alone is given by

$$E_i = \int_0^\infty d\mathcal{E}' N_0(\mathcal{E}') \int_0^t \frac{(n_H)_c}{(n_H)_c + 4(n_e)_c} \frac{d\mathcal{E}}{dt} dt' \tag{10}$$

where $d\mathcal{E}/dt$ is given by equation (6). By introducing the average quantity

$$\overline{\left(\frac{n_H}{n_H + 4n_e}\right)} \equiv \left[\mathcal{E}' - \mathcal{E}(\mathcal{E}' t) \right]^{-1} \int_0^t \frac{(n_H)_c}{(n_H)_c + 4(n_e)_c} \frac{d\mathcal{E}}{dt} dt' , \tag{11}$$

the energy loss to ionization can be written as

$$E_i = \overline{\left(\frac{n_H}{n_H + 4n_e}\right)} E_t . \tag{12}$$

We have evaluated equation (12) with E_t given by equation (7), N_0 by equation (2) and $\mathcal{E}$ by equation (8). The results, for various values of $\mathcal{E}_0$, are shown in Figure 1 as functions of $t\overline{(n_H + 4n_e)}$. The solid line is the energy loss of 0.5 M⊙ Si^{28} + 0.25 M⊙ Fe^{56} and the dashed line is the energy loss of 0.75 M⊙ H^1. As can be seen, all curves assumptotically approach the total energy W given by equation (3).

The total energy loss to ionization required to produce the 2×10^{62} ion pairs in the Gum Nebula is about 10^{52} ergs. We neglect recombination in clouds, since for an electron temperature greater than about 5×10^4 K (Alexander et al. 1971) the recombination time ($t_{rec} \simeq 130 T^{0.7}/(n_e)_c$ years, Bates and Dalgarno, 1962) is greater than about 2×10^4 years. If the particles lose their energy predominantly in neutral hydrogen ($\bar{n}_e \ll \bar{n}_H$)

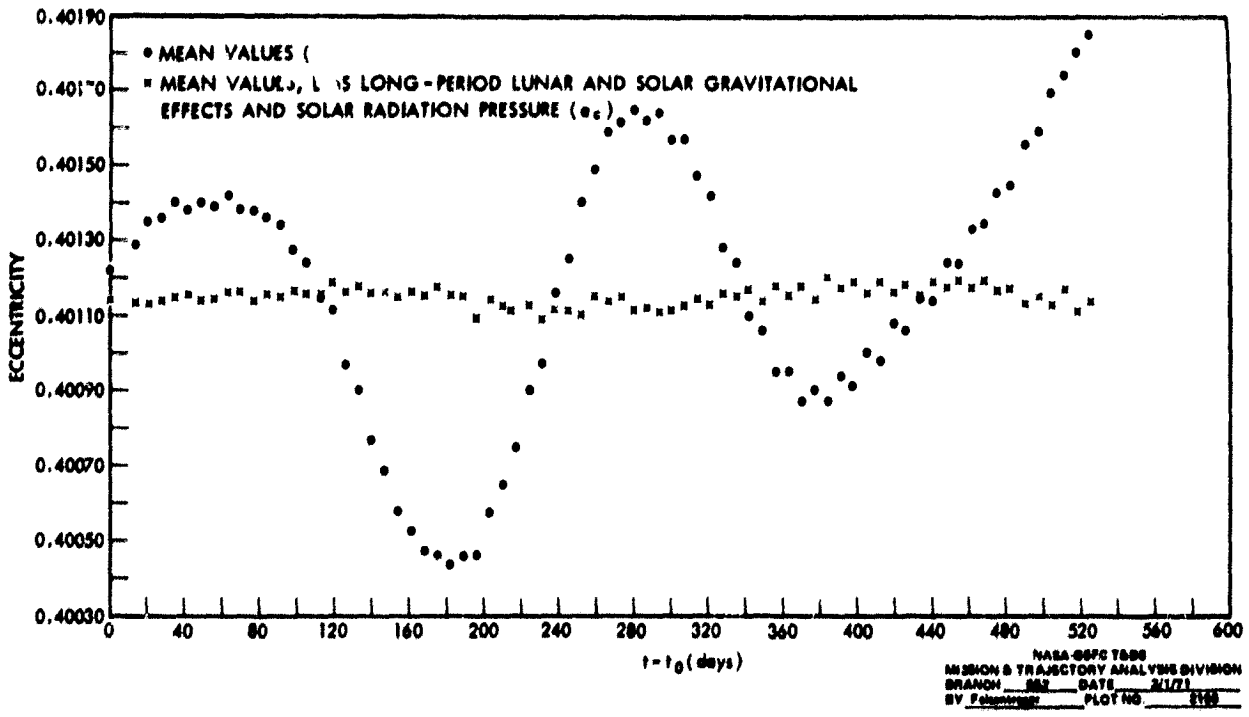

Figure 3. Eccentricity of Telstar 2.

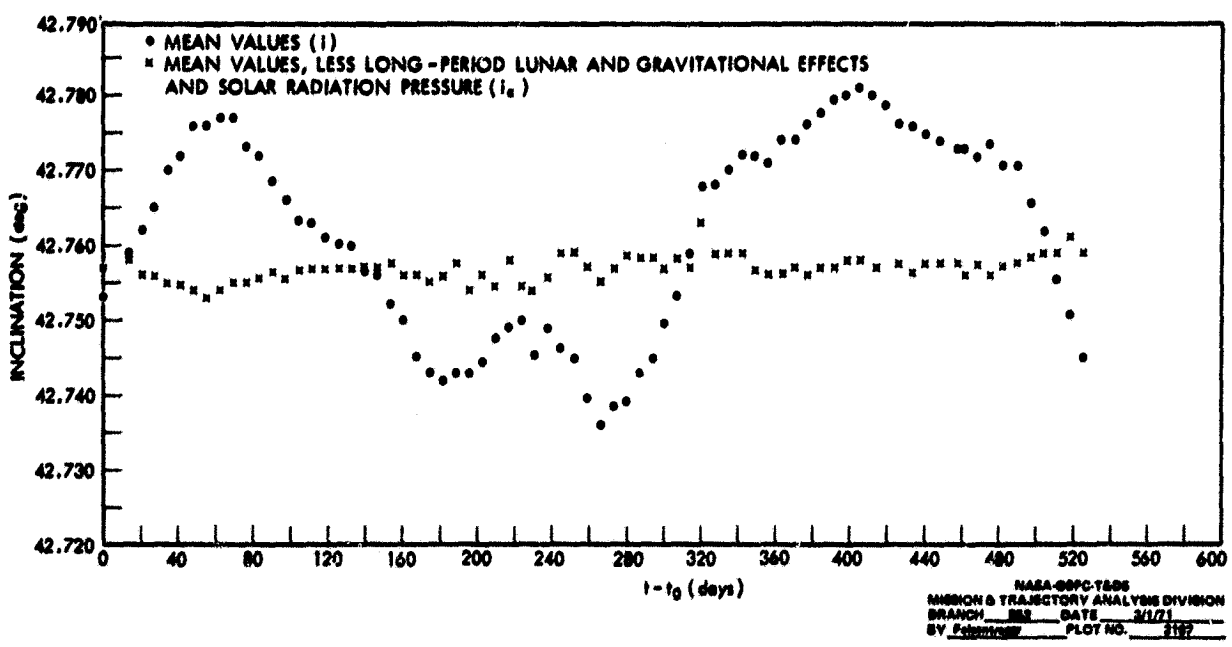

Figure 4. Inclination of Telstar 2.

and the ionization is produced by silicon and iron nuclei with $\mathcal{E}_0$ between 10 and 20 MeV/nucleon, $t\bar{n}_H$ must be about 4.5×10^4 cm^{-3} years. For $\bar{n}_H = 14$ cm^{-3}, t = 3200 years. This is consistent with the total time spent by the particles in clouds.

If the ionization is produced by protons with a spectrum of similar $\mathcal{E}_0$ and $\bar{n}_H = 14$ cm^{-3}, t is about 24,000 years which exceeds the lower limit on the age as determined from the pulsar observations. Furthermore, as pointed out by Alexander et al. (1971) since only 1/65 of space in the nebula is occupied by matter, pressure equilibrium has not yet been established between the clouds and the intercloud medium so that the ionization had to occur over a relatively short time. It is therefore more likely that the ionization and heating in the Gum Nebula have been produced by low energy silicon and iron nuclei on a time scale in clouds of less than 2000 years and not by low energy protons on a time scale of more than 10^4 years.

COMPARISON WITH RELATED OBSERVATIONS

We now consider some of the consequences of this model regarding the heating and ionization of the interstellar medium, the generation of light elements, observable X-ray production and the detectability of charged particles at earth.

Several recent theoretical descriptions (Pikel'ner 1967; Balasubrahmanyan et al. 1968; Spitzer and Tomasko 1968; Spitzer and Scott 1969; Goldsmith, Habing, and Field 1969) of ionization and thermal equilibria for interstellar HI regions, based upon current models for the interstellar gas, indicate that the rate of ionization per hydrogen atom is

$\zeta \simeq 10^{-15}$ (sec H atom)$^{-1}$. Hjellming, Gordon, and Gordon (1969) find that observed pulsar dispersion measures may be best fitted with such a model for $\zeta = (2.5 \pm 0.5) \times 10^{-15}$ (sec H atom)$^{-1}$. For an equilibrium situation, the rate of electron-ion recombination is the most direct measure of ζ ; recent observations of Hβ hydrogen line emission from interstellar HI (Reynolds 1971) yield a direct measure of the recombination rate, and the corresponding ionization rate in the regions examined could be as high as 10^{-14} (sec H atom)$^{-1}$.

Since essentially all the gas in the Gum Nebula has been ionized by the supernova explosion, the average rate of ionization in interstellar hydrogen by such events would be given by

$$\langle \zeta n_H \rangle \simeq f_{SN} V_{SN} \langle n_e \rangle \tag{13}$$

where V_{SN} is the volume of the HII region formed by the supernova explosion and f_{SN} is the average supernova frequency per unit volume in the galaxy. If supernovae occur at a rate of 1 per 100 years in a volume of 4×10^{66} cm^3, $f_{SN} \simeq 8 \times 10^{-77}$ cm^{-3}sec^{-1}. For $V_{SN} \langle n_e \rangle \simeq 2 \times 10^{62}$ electrons (Brandt et al. 1971), we obtain $\langle \zeta n_H \rangle \simeq 1.6 \times 10^{-14}$ sec^{-1} cm^{-3}. Radio observations at 21 cm indicate a mean value for the neutral hydrogen density in the galactic plane of about 0.7 cm^{-3} (Spitzer 1968); however, optical depth effects probably raise $\langle n_H \rangle$ to ~ 1 cm^{-3}. A further increase by about a factor of 2 in the value of $\langle n_H \rangle$ may be due to the presence of molecular hydrogen in dense clouds. Hence the mean galactic value of ζ as indicated by the parameters deduced for the Vela X supernova is about 10^{-14} sec^{-1} (H atom)$^{-1}$. This ionization rate could be reduced if the frequency of supernova explosions of the type that produced

the Gum Nebula is lower than the assumed rate of 1 per 100 years or if the actual free electron content of the Gum Nebula is less than that estimated by Brandt et al. (1971). Furthermore, even if the average supernova output is similar to that of Vela X but occurs in a region with larger magnetic fields, so that the particles propagate over a shorter distance before they lose their energy, the ionized volume produced by the supernova would be smaller than that of the Gum Nebula. In this case, the total ionization per supernova would be reduced since a larger fraction of the total energy would go into heating. Also, those supernovae which occur at more than about 100 pc away from the galactic plane (e.g. the Crab) will produce energetic particles which may escape from the disk without producing significant ionization.

In order for HII regions such as the Gum Nebula to merge into the HI of the interstellar medium, the cooling time of the clouds should be much less than the time between supernova explosions in the volume of the nebula. For $f_{SN} = 8 \times 10^{-77} cm^{-3} sec^{-1}$ and $V_{SN} = 1.35 \times 10^{63} cm^3$, this time equals 3×10^5 years. However, as we shall see from the calculations of Cox and Tucker (1969), the cooling time in clouds could be several orders of magnitude shorter. For a gas of cosmic abundances in ionization equilibrium at 5×10^4 K, the radiative loss rate is $P \simeq 2 \times 10^{-22} (n_e)_c (n_H)_c$ ergs $cm^{-3} sec^{-1}$. The corresponding cooling time is $t_c \simeq 3/2 (n_e)_c kT/P \simeq 1700/(n_H)_c$ years. For $(n_H)_c = 4\ cm^{-3}$, $t_c \simeq 420$ years. Although this cooling time is much shorter than the age of the nebula, contemporary heating by cosmic rays could in fact maintain the observed high temperature (Alexander et al. 1971). In contrast, the rapid cooling would be in conflict with ionization by ultraviolet photons which deposit their energy

in the first thousand years after the supernova explosion. However, if the abundances of the principal ions responsible for the cooling are depleted below their values corresponding to ionization equilibrium with $n_H = 4\ cm^{-3}$, the cooling time could be proportionally increased. In addition, if the dimensions of the clouds are sufficiently large, there is the possibility of the entrapment of the resonant radiation which leads to the cooling. This phenomenon may further increase the cooling time obtained from Cox and Tucker's (1969) calculation.

We now consider the production of the light elements. According to Fowler, Reeves and Silk (1970) the average ionization rate of the interstellar gas by cosmic-ray protons of energies greater than 5 MeV/nucleon has to be less than about 10^{-16} (sec H atom)$^{-1}$. A higher ionization rate by such cosmic rays would result in the production of lithium, beryllium, and boron, with abundances in excess of the observed values. However, if the interstellar gas is ionized by low energy heavy nuclei which have lower spallation cross sections for the production of Li, Be, and B than do protons and the medium nuclei (C,N.O), a much higher ionization rate is permissible.

Consider the production of lithium by Si^{28} nuclei. The total number of Li nuclei produced by the Vela X supernova is $\sigma\ (n_o)_c \langle c\beta \rangle\ t\ N_o\ (>\mathcal{E}_{th})$, where σ is the production cross section, t is the time spent in clouds by the silicon nuclei with energies greater than the threshold energy $\mathcal{E}_{th}$, and N_o is given by equation (2). Neglecting escape or destruction, the total lithium content of the galaxy N_{Li} equals the total production over its lifetime Tg, i.e.,

$$N_{Li} \simeq \sigma (n_o)_c \langle c\beta \rangle (t/T)\ N_o(>\mathcal{E}_{th})\ T_g \tag{14}$$

where T is the average time between supernova explosions in the galaxy. The lower limit on the threshold for lithium production from Si^{28} on hydrogen is about 20 MeV/nucleon and the cross section at 150 MeV/nucleon is about 2.5 mb (Shapiro and Silverberg 1970). From equation (2) with $\mathcal{E}_o$ = 10 MeV/nucleon and $\mathcal{E}_{th}$ = 20 MeV/nucleon we get N_o ($>\mathcal{E}_{th}$) $\simeq$ 0.1 Mej/(Am_p). For $T_g = 10^{10}$ years, $\langle\beta\rangle$ = 0.2 and Mej = 0.75 M⊙ we get that $N_{Li} \simeq 2 \times 10^{56}$(t/T). The hydrogen content of the interstellar medium is about 4×10^{66} so that the ratio Li/H is 5×10^{-11} (t/T). According to the data summarized by Reeves, Fowler, and Hoyle (1970), Li/H is less than about 10^{-9} so that t/T is less than 20. Since the time spent in clouds by silicon nuclei above threshold energy is on the order of the energy loss time, which for a 20 MeV/nucleon particle may vary from about 1600 years to 5000 years, the lower limit on T ranges from about 80 years to 250 years. This result can be compared with the supernova rate required to produce the iron content of the galaxy. According to Clayton, Colgate and Fishman (1969), the galaxy contains about 3×10^7 M⊙ Fe^{56}. If each supernova produces 0.25 M⊙ Ni^{56}, which decay into iron, for Tg = 10^{10} years, T is about 80 years. We conclude that the rate of production of light elements from supernova ejecta of the type that produced the Gum Nebula is not in conflict with the observed upper limits on the abundances of light elements. This conclusion is independent of whether the particles lose their energy in a predominantly neutral or ionized medium.

X-ray emission is a necessary consequence of ionization and heating by cosmic rays (Boldt and Serlemitsos 1969). In clouds, the volume emissivity of bremsstrahlung X-rays arising from the collisions of energetic nuclei with ambient electrons (free or atomic) is given by

$$\eta_c = \frac{2\alpha}{\pi} Z^2 \sigma_o m_e c^2 (n_o)_c \int_o^\infty c\beta n_{cr}(\varepsilon) d\varepsilon \tag{15}$$

where $\sigma_o = 6.7 \times 10^{-25}$ cm^2, $\alpha = 1/137$, m_e is the electron mass and n_{cr} is the differential number density of the energetic particles in clouds. In order to estimate an upper limit to the X-ray production, we shall assume that all the energetic particles ejected by Vela X are currently in clouds at the characteristic energy ε_o. The resulting X-ray energy spectrum is then essentially flat with an end point $h\nu = (m_e/m_p)\,\varepsilon_o$; for $\varepsilon_o = 20$ MeV/nucleon, $h\nu = 10$ keV.

According to the geometry of the Gum Nebula described by Brandt et al. (1971), we expect it to appear as a disk source of X-rays, extended in galactic longitude ($\Delta\ell \simeq 90°$) and relatively thin in galactic latitude ($\Delta b \simeq 7°$). Collecting radiation from an interval of length L penetrating the nebula, the intensity viewed by a detector of aperture $(\Delta b)_o < \Delta b$ would be expressed by

$$\frac{dI}{d\ell} = \frac{(\Delta b)_o}{4\pi} \eta L \quad \text{ergs sec}^{-1}\,\text{cm}^{-2}\,\text{rad}^{-1}. \tag{16}$$

Here $\eta = \eta_c\, V_{eff}/V$ is the average volume emissivity of the nebula and, with η_c given by equation (15), may be expressed as

$$\eta = \frac{2\alpha}{\pi} \frac{Z^2}{A} \sigma_o m_e c^2 \frac{(n_o)_c}{V} \frac{M_{ej}}{m_p} \langle \beta c \rangle \tag{17}$$

where $\langle c\beta \rangle$ is the average velocity over the particle spectrum. For $M_{ej} = 0.5\, M_\odot\, Si^{28} + 0.25\, M_\odot\, Fe^{56}$ and $\langle \beta \rangle = 0.2$, $\eta = 1.2 \times 10^{-27}$ ergs cm^{-3} sec^{-1}. Using a detector of $(\Delta b)_o = 4°$, viewing at $\ell \simeq (260 \pm 40)°$, which spans the Gum Nebula, Cooke, Griffiths and Pounds (1969) observed an enhanced X-ray emission associated with the galactic disk of about

3×10^{-9} ergs $(cm^2 \text{ sec rad})^{-1}$ above 1.4 keV, with an essentially flat energy spectrum extending to about 10 keV. The upper limits to this flux at energies above 12.5 keV, as set by Hudson, Peterson, and Schwartz (1971), provide evidence that the spectrum is characterized by a break in the vicinity of about 10 keV. Using the volume emissivity as obtained from equation (17), L = 400 pc and $(\Delta b)_o = 4°$, we get $dI/d\ell = 8 \times 10^{-9}$ ergs $sec^{-1}cm^{-2}rad^{-1}$. The fact that this upper limit is a few times larger than the observed X-ray flux means that a significant fraction of the particles ejected by the supernova have already lost their energy or that the characteristic energy ε_o is smaller than the value of 20 MeV/nucleon that we have used in this calculation.

In addition to bremsstrahlung, X-rays in the Gum Nebula should also be produced as line emission. These lines are produced by charge exchange between the energetic nuclei and neutral H atoms, resulting in the capture of electrons to excited states. Cascades down to the ground state occur, which produce the analogue of $Ly\alpha$ and $Ly\beta$ emission for the case of capture of K-electrons. Silk and Steigman (1969) have given a discussion of this process, with application to low energy galactic cosmic rays.

If we assume that each nucleus captures two electrons in the lifetime of the nebula and hence produces two X-ray photons, the time averaged volume emissivity is

$$\eta(h\nu) = 2 \frac{M_{ej}}{A m_p} \frac{h\nu}{Vt} \tag{18}$$

where V and t are the volume and age of the nebula, respectively, and $h\upsilon \simeq 2$ keV for silicon and $h\upsilon \simeq 7$ keV for iron. For Mej = 0.5 M⊙ Si^{28} + 0.25 M⊙ Fe^{56}, t = 10^4 years and V = 1.63×10^{63} cm^3, η (2 keV) $\simeq 3.4 \times 10^{-28}$ ergs $cm^{-3}sec^{-1}$ and η (7 keV) $\simeq 6 \times 10^{-28}$ ergs $cm^{-3}sec^{-1}$. Using equation (16), we find that the total X-ray flux in line emission is comparable to or somewhat greater than the total observed X-ray flux from the direction of the Gum Nebula. However, since charge exchange occurs only in neutral hydrogen, the contemporary X-ray flux in line emission could be smaller than the time-averaged flux that we have estimated. Since the energy of the nuclei at capture is not expected to be more than about 20 MeV/nucleon, the line broadening should be less than 20%. Therefore, detectable X-ray line emission could be observed with detectors of moderate energy resolution.

Finally, we consider the implications of our model on direct cosmic ray observations at earth. The observability of low energy ($\lesssim$ 100 MeV/nucleon) heavy nuclei from the supernova depends on whether these particles escape from the nebula before stopping in a cloud and on a rather large but unknown amount of solar modulation which may include a substantial energy loss in the interplanetary medium (Goldstein, Fisk, and Ramaty 1970). Above 100 MeV/nucleon, however, these nuclei are not expected to stop in clouds in a time which is short compared to the average time between supernova explosions. Therefore, it would appear that our model predicts silicon and iron intensities in the galactic

cosmic rays which exceed their observed values (e.g. Meyer 1969). However, current ideas concerning pre-supernova structure (Arnett 1970, S.A. Colgate, and G. LeFebre, in preparation) are compatible with a change in composition for mass fractions $F \lesssim 10^{-4}$. For these mass fractions the composition could be consistent with that of the observed galactic cosmic rays. The energy corresponding to $F = 10^{-4}$ is about 500 MeV/nucleon for $\mathcal{E}_0 = 10$ MeV/nucleon. However, adiabatic energy losses associated with the expanding magnetic field in the vicinity of the supernova may decelerate these nuclei below ~ 100 MeV/nucleon, where energy losses in the interstellar and/or interplanetary medium prevent us from observing the particles.

SUMMARY

The ionization and heating of the Gum Nebula could be produced by the dissipation of the energy of about 1 to 2 $M_\odot$ of the products of silicon burning ejected by the supernova Vela X on a time scale of the order 10^4 years. The characteristic energy at injection of these particles is on the order of a few MeV/nucleon so that the total supernova energy in charged particles is a few times 10^{52} ergs. The propagation of these particles in the Gum Nebula is essentially regular motion along field lines so that the particles fill up the nebula on a time scale comparable to its age. For the complete ionization of the nebula, it is essential that a majority of the particles should have stopped in clouds.

The average rate of ionization per hydrogen atom in the interstellar medium due to the formation of HII regions similar to the Gum Nebula, at a rate of 1 per 100 years in the galaxy, is about 10^{-14} (sec H atom)$^{-1}$. This is independent of the nature of the ionizing radiation, (i.e., photons or charged particles). However, ionization and heating by charged particles allows a cooling time in clouds which is shorter than the age of the Gum Nebula. Contemporary heating by particles would result in X-ray production. The upper limit to the expected X-ray flux from the direction of the Gum Nebula exceeds the measurements by about a factor of 2 to 3. Therefore, even though there may still be continuous heating of the clouds in the nebula, a significant fraction of the initial energy has already been dissipated.

The amount of light nuclei produced during the ionization and heating of the Gum Nebula is consistent with the observed abundances of the light elements if supernovae similar to Vela X occur at a rate of about 1 per 100 years in the galaxy. The heating of the interstellar gas by low energy silicon and iron nuclei is therefore not in conflict with the abundances of lithium, beryllium, and boron in the interstellar medium.

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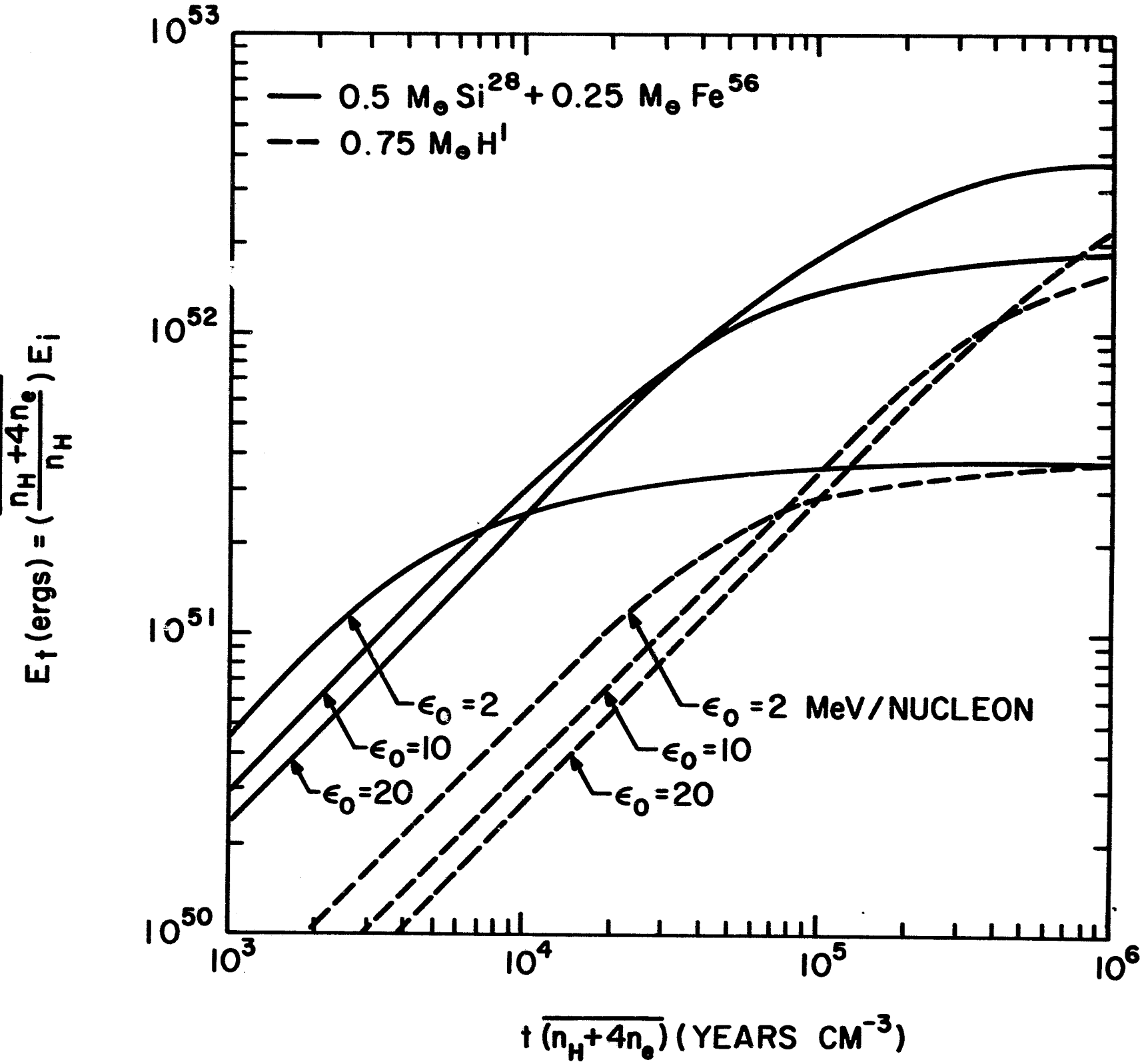
0.5 $M_\odot$ Si^{28} + 0.25 $M_\odot$ Fe^{56}
0.75 $M_\odot$ H^1
ϵ_0 = 2
ϵ_0 = 10
ϵ_0 = 20
ϵ_0 = 2 MeV/NUCLEON
ϵ_0 = 10
ϵ_0 = 20
10^{53}
10^{52}
10^{51}
10^{50}
10^3
10^4
10^5
10^6
E_t (ergs) = $\left(\frac{n_H + 4n_e}{n_H}\right) E_i$
$t\,\overline{(n_H + 4n_e)}$ (YEARS CM^{-3})

FIGURE CAPTION

1. The total energy loss, E_t, and the energy loss to ionization, E_i, as a function of the age and average gas densities in clouds. The quantities $\overline{n_H + 4\ n_e}$ and $\overline{(n_H + 4\ n_e)/n_H}$ are defined in equations (9) and (11), respectively; ξ_o is the characteristic transition energy defined in equations (2) and (3).