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GAMMA-RAY EMISSION AND NUCLEOSYNTHESIS OF LITHIUM BY YOUNG PULSARS

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ABSTRACT

We propose that ^{7}Li is produced in the Galaxy primarily by α-α collisions surrounding newly born pulsars. About 10 percent of the pulsar energy losses are converted to medium-energy α-particles which collide in a dominantly He nebula. The problem of the origin of lithium would be solved by the scenario, and clear-cut tests by nuclear γ-ray astronomy are described.

Subject headings: gamma rays: general — nucleosynthesis — pulsars

I. INTRODUCTION

We propose that ^{7}Li is produced in the Galaxy primarily by collisions of α-particles accelerated by young pulsars with helium nuclei in a helium-rich shell. Arnett's (1975) discussion of presupernova evolution indicates the likelihood in many cases of the ejection of several solar masses of He, and observations of the Crab Nebula had been interpreted (Woltjer 1958; Davidson and Tucker 1970) as revealing such a dominance of He in the ejecta. The early pulsar is quite energetic, and because of the scarcity of H in the neutron star the primary ions accelerated by the rotating magnetosphere will probably be He (Michel 1975; Rosen and Cameron 1972), Therefore the nuclear collisions will be primarily $\alpha + \alpha$, with specific production of ^{7}Li and ^{6}Li as a consequence. The difficulties in producing ^{7}Li by other scenarios are well known and have been reviewed, for example, by Reeves (1974) and Audouze, Meneguzzi, and Reeves (1975). Our proposed scenario is particularly efficient for ^{7}Li production and seems the best suited of all proposed scenarios to overcome the energetic difficulty discussed by Ryter *et al.* (1970). It may be observationally confirmed by nuclear γ-ray astronomy.

We assume that the abundance observed in young stars, $^7\mathrm{Li/H} \approx 1.5 \times 10^{-9}$ (Cameron 1973), is of a galactic nature rather than the result of a local autogenetic process within the stars themselves. Taking the mass of the interstellar medium to be $10^{10}\ M_\odot$ of H then implies 105 $M_\odot$ of interstellar ^{7}Li. If the interstellar medium is incorporated into stars with an e-folding time of 5×10^9 yr, and if the galactic rate of pulsar-forming events is $(30\ \mathrm{yr})^{-1}$ (Gunn and Ostriker 1970), it follows that each event must synthesize 1.0×10^{50} ^{7}Li atoms in order to be a significant source of ^{7}Li.

II. PULSAR ENERGETICS

We imagine that at $t = 0$ a supernova explosion leaves a rotating neutron star within an expanding shell of ejected matter that is primarily He. The newly formed pulsar loses rotational energy in the form of magnetic dipole radiation that is capable of accelerating ambient He (Gunn and Ostriker 1969; Kulsrud, Ostriker, and Gunn 1972) or in the form of plasma ejection from the rotating magnetosphere (Michel 1974). As much as 10^{-3} to $10^{-4}\ M_\odot$ of He ions need be accelerated to energies of order 50 MeV in order to produce the required 1×10^{50} nuclei of ^{7}Li. To model this idea we postulate that a fraction α_{CR} of the pulsar energy losses is converted to medium-energy cosmic-ray α-particles, almost none of which will ever escape the surrounding He nebulosity. The requirement of about 10 percent conversion efficiency to medium-energy α-particles is the most difficult to justify of the several requirements of this model.

The rate of injection of α-particles is written as $\alpha_{\mathrm{CR}}L(t)$, where $L(t)$ is the total power output of the pulsar, which can be represented by (Ostriker and Gunn 1971)

$$L(t) = L_0(1 + t/\tau_0)^{-2}\,, \tag{1}$$

where τ_0 is here chosen to be one-half of the τ defined by them. With that choice the total energy to be radiated becomes

$$E = \int_0^\infty L dt = L_0\tau_0\,.$$

L_0 is the initial pulsar luminosity. A conventional choice of parameters (Bodenheimer and Ostriker 1974) is: $L_0 = 10^{43}$ ergs s^{-1} and $\tau_0 = 3$ yr. With this choice of parameters the total energy of the pulsar liberated over its lifetime amounts to $\sim 10^{51}$ ergs.

III. COSMIC-RAY ENERGETICS

We let $E_{\mathrm{CR}}(t)$ be the total energy of the He cosmic rays in the nebula. The change in E_{CR} is given by

$$\frac{dE_{\mathrm{CR}}}{dt} = \alpha_{\mathrm{CR}}L(t) - \frac{dQ}{dt} - \frac{dW}{dt} - \left(\frac{dE_{\mathrm{CR}}}{dt}\right)_e, \tag{2}$$

where dQ/dt is the rate of energy loss due to collisions in the nebula, dW/dt is the rate of energy loss due to the expansion of the nebula, and $(dE_{\mathrm{CR}}/dt)_e$ is the rate of energy loss due to the α-particles escaping from the nebula.

For simplicity only we assume a steady-state cosmic-ray spectrum; that is, the net effect of the acceleration and of the energy losses listed previously is the maintenance of a power-law spectrum:

$$N(E, t)dE = kE^{-\gamma}dE\,, \quad E > E_c\,, \tag{3}$$

where $N(E, t)dE$ represents the total number of particles in the nebula in the energy interval between E and $E + dE$ at time t, and k can be easily expressed in terms of the low-energy cutoff E_c, the spectral index γ, and the total energy E_{CR}. With this simplification we can write

$$\frac{dQ}{dt} = \int_{E_c}^{\infty} \left(\frac{dE}{dt}\right)_{\mathrm{coll}} N(E)dE\,, \tag{4}$$

where for $(dE/dt)_{\mathrm{coll}}$ we use an approximation for the energy loss in ionized matter given by Ryter *et al.* (1970),

$$\left(\frac{dE}{dt}\right)_{\mathrm{coll}} \approx 9.0 \times 10^{-11} \frac{n(t)}{E^{1/2}(\mathrm{MeV})}\ \mathrm{MeV\ s^{-1}}\,, \tag{5}$$

where $n(t)$ is the number density of the expanding nebula and E is the energy of the α-particle.

Assuming a constant expansion rate, we find that the rate of energy loss due to the expansion is simply

$$\frac{dW}{dt} = 2\frac{E_{\mathrm{CR}}}{t}\,. \tag{6}$$

To evaluate the escape losses, we must know the magnetic field in the nebula. We constructed a random-walk escape model using the model described by Pacini and Salvati (1973) for the evolution of the magnetic field. However, we found that for time scales of our interest, that is, before the α-α reaction rate drops significantly, escape losses are not important, and they will therefore be neglected.

In the early stages of the expansion collision losses will dominate, decreasing as $n(t)$, so that at sufficiently low densities expansion losses will dominate. Consequently we define a time t_{coll} at which these two losses are equal:

$$\left(\frac{dQ}{dt}\right)_{t_{\mathrm{coll}}} = \left(\frac{dW}{dt}\right)_{t_{\mathrm{coll}}}\,. \tag{7}$$

The expression for t_{coll} becomes

$$t_{\mathrm{coll}} = 1.8 \times 10^{9} \left(\frac{\gamma - 2}{\gamma - \frac{1}{2}}\right)^{1/2} E_c^{-3/4} \frac{(M_{\mathrm{ej}}/M_{\odot})^{1/2}}{v_9^{3/2}}\ \mathrm{s}\,, \tag{8}$$

where E_c is in units of MeV and the expression is scaled for a nebula of 1 $M_{\odot}$ expanding at a velocity of 10^9 cm s^{-1}. As can be seen, t_{coll} depends weakly on γ, and for E_c in the range of 10–100 MeV we find that t_{coll} lies in the range 1–8 yr, a time scale comparable to τ_0.

We explicitly solve the energy equation (2) by neglecting escape losses with the aid of an integrating factor:

$$E_{\mathrm{CR}}(t) = \alpha_{\mathrm{CR}} L_0 \tau_0 \frac{\exp\,(a/2u^2)}{u^2} \times \int_0^u \frac{x^2 \exp\,(-a/2x^2)}{(1 + x)^2}\,dx\,, \tag{9}$$

where $u \equiv t/\tau_0$ and $a \equiv 2t_{\mathrm{coll}}{}^2/\tau_0{}^2$. Since the time t_{coll} during which collisional energy loss dominates is of the same order as τ_0, the limits $t \ll \tau_0$ and $t \gg \tau_0$ correspond to times for which the energy losses are physically different, and the relevant limits of (9) are:

a) $t \ll \tau_0$ (*collision losses dominate*)

$$E_{\mathrm{CR}}(t) = \alpha_{\mathrm{CR}} \frac{L_0 t^3}{2t_{\mathrm{coll}}{}^2(1 + t/\tau_0)^2}\,. \tag{9a}$$

b) $t \gg \tau_0$ (*expansion losses dominate*)

$$E_{\mathrm{CR}} = \alpha_{\mathrm{CR}} L_0 \tau_0 \frac{1}{u}\left[1 - \frac{2\ln\,(1 + u)}{u} + \frac{1}{1 + u}\right]. \tag{9b}$$

IV. LITHIUM PRODUCTION

The advantages of our proposed model are (1) that the young pulsar radiates a lot of energy and (2) that helium cosmic rays within a He nebula produce ^{7}Li specifically. In comparing our work with that of others, it is useful to follow Ryter *et al.* (1970) in defining a quantity η as the energy expended in electronic collisions per ^{7}Li nucleus created. In keeping with our original simplifying assumption that the injection spectrum is just what is needed to maintain the power-law spectrum (eq. [3]) at all times, we define the time-independent ratio

$$\eta \equiv \frac{dQ/dt}{dN(^7\,\mathrm{Li})/dt} \tag{10}$$

as an average over that power-law spectrum. Table 1 contains values of η calculated in this way for several different parametrizations of the power-law spectrum. We used the α-α cross sections of King *et al.* (1975) and a standard energy-loss cross section for fast α-particles moving through ionized He. These values of η are considerably lower than those given, for example, by Canal, Isern, and Sanahuja (1975), specifically because of the favorable nature of the purely α-α scenario.

The number of ^{7}Li nuclei created per unit time will also be of importance for γ-ray emission and can be written

$$\frac{dN(^7\mathrm{Li})}{dt} = n(^4\mathrm{He}) \int_Q^{\infty} N(E)\sigma(E)v(E)dE\,, \tag{11}$$

TABLE 1

Spectrum	η(MeV/^{7} Li)	$N(^7\mathrm{Li})/\alpha_{\mathrm{CR}}$	^{7}Li/^{6}Li
$E_c = 10$ MeV:			
$\gamma = 2.5$..........	5.0×10^{5}	6.1×10^{50}	5.8
$\gamma = 4.0$..........	3.0×10^{6}	1.4×10^{50}	7.5
$\gamma = 6.0$..........	4.2×10^{7}	6.8×10^{48}	10.7
$E_c = 25$ MeV:			
$\gamma = 2.5$..........	6.6×10^{4}	2.6×10^{51}	5.8
$\gamma = 4.0$..........	1.1×10^{5}	2.5×10^{51}	7.5
$\gamma = 6.0$..........	2.4×10^{5}	1.4×10^{51}	10.7
$E_c = 40$ MeV:			
$\gamma = 2.5$..........	2.8×10^{4}	5.0×10^{51}	5.2
$\gamma = 4.0$..........	2.4×10^{4}	1.0×10^{52}	6.3
$\gamma = 6.0$..........	2.2×10^{4}	1.5×10^{52}	8.4

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which for the steadily maintained power-law spectrum becomes

$$\frac{dN(^7\mathrm{Li})}{dt} = n(^4\mathrm{He})(\gamma - 2)\,\frac{E_{\mathrm{CR}}(t)}{E_c} \times \int_{Q/E_c}^{\infty} \left(\frac{E}{E_c}\right)^{-\gamma} \sigma v d\left(\frac{E}{E_c}\right), \quad (12)$$

where the density $n(^4\mathrm{He})$ of ambient helium will dilute as t^{-3} due to uniform expansion. We integrated this equation numerically, as we did also for $E_{\mathrm{CR}}(t)$ in equation (9). Another integration over time gives $N(^7\mathrm{Li})$, the total number produced by the event. These yields are also listed in Table 1 for several values of E_c and γ; in that example we chose $n(^4\mathrm{He})$ to correspond to 1 $M_\odot$ of nebular He expanding at 10^9 cm s^{-1}. The entries there are in fact upper limits because they are calculated with $\alpha_{\mathrm{CR}} = 1$. Realistic results are obtained by multiplying those entries by the appropriate value of α_{CR}.

The same α-α collisions will also produce ^{6}Li, although that threshold $Q(^6\mathrm{Li}) = 44.75$ MeV is 10 MeV greater than that for production of ^{7}Li, for which $Q = 34.70$ MeV. As a result, for a given low-energy cutoff, steeper spectra produce larger $^7\mathrm{Li}/^6\mathrm{Li}$ ratios. We have computed this ratio for the same parametrized form of the power-law spectra, and the results are also included in Table 1. We took our estimates for the cross section for production of ^{6}Li from Kozlovsky and Ramaty (1974) and included the contribution from the (α, pn) reaction, using the estimates given in Mitler (1972). One sees from Table 1 that the calculated ratio may by typically about $^7\mathrm{Li}/^6\mathrm{Li} \approx 6$ to 10, an encouragingly large number, though still not as large as the terrestrial ratio of 12.5. A production ratio that large would require a very steep spectrum, roughly $\gamma > 7$. It therefore seems likely that an additional source for part of ^{7}Li would still be needed.

V. GAMMA-RAY EMISSION

Kozlovsky and Ramaty (1974) first pointed out that α-α collisions might be quite important for nuclear γ-ray astronomy. If the scenario favors α-α collisions, as our present one does, those collisions will be more important than the H + $^7\mathrm{Li}_{\mathrm{CR}}$ collisions proposed by Fishman and Clayton (1972) as the source of the excited states of ^{7}Li and ^{7}Be that one might hope to see with γ-ray telescopes. We follow Kozlovsky and Ramaty by assuming that the excited states $^7\mathrm{Li}^*$ (478 keV) and $^7\mathrm{Be}^*$ (431 keV) are produced equally in α-α collisions, and that their production is also equal to that for production in the ground states directly. Each de-excitation produces a γ-ray of 478 or 431 keV energy, so that the total rate of emission of such γ-rays is $r_\gamma = \frac{1}{2}dN(^7\mathrm{Li})/dt$. Equation (12) gives this result, when combined in our model with equation (9) for $E_{\mathrm{CR}}(t)$. Just for example, in the case $\gamma = 2.5$ and $E_c = 10$ MeV, one obtains

$$\begin{aligned} r_\gamma &= 3.0 \times 10^{10}\,\frac{E_{\mathrm{CR}}(\mathrm{MeV})}{t^3(\mathrm{s})}\ \mathrm{s}^{-1} \\ &= \alpha_{\mathrm{CR}} 2.3 \times 10^{43}[3.12(1+u)^2]^{-1}\ \mathrm{s}^{-1} \quad (u \ll 1) \\ &= \alpha_{\mathrm{CR}} 2.3 \times 10^{43}\,\frac{1}{u^4} \\ &\quad \times \left[1 - \frac{2\ln(1+u)}{u} + \frac{1}{1+u}\right] \quad (u \gg 1)\,. \quad (13) \end{aligned}$$

This particular model is illustrated by F_γ in Figure 1, where $F_\gamma = r_\gamma/4\pi D^2$ and the object is at $D = 4$ kpc. That particular distance is chosen simply so that F_γ will be comparable in magnitude to the flux of such an observed feature in the general direction of the galactic center.

At early times the γ-rays cannot escape from the nebula in which they are being produced. To illustrate the effect of this self-absorption we followed Clayton (1974). The early rise of F_γ in Figure 1 is due to the thinning of the initially dense nebula until it becomes transparent near $t \approx 1$ yr.

The three error bars on Figure 1 represent the observed fluxes in the 0.5 MeV feature from the galactic center, as observed by Johnson and Haymes (1973) and by Haymes *et al.* (1975). We do not wish here to argue that the time dependence of their 0.5 MeV feature is due to our model, especially since the authors advanced other plausible explanations of their results. But their feature was initially interpreted (Fishman and Clayton 1972) as being the de-excitation of $^7\mathrm{Li}^*$ and $^7\mathrm{Be}^*$, and their observations could conceivably be a single point source having a time-dependent emission, so we have included their data points as an example of such a possibility in γ-ray astronomy. The choice $D = 4$ kpc in Figure 1 was made specifically to normalize our emission to their observed flux. Their data points on this picture would have required a galactic supernova in their overlapping fields of view to have occurred about 140 days before their first observation in 1970 November.

VI. RELATED PHENOMENA

Because dQ/dt due to the cosmic rays is such a very large number, the disposition of this energy would be a matter of astrophysical importance. In Figure 1 we also sketched in the blue luminosity of typical Type I supernova observations on the right-hand scale applying to dQ/dt. One sees that dQ/dt is comparable in magnitude to the early light curve, while the nebula is still opaque to γ-radiation (and therefore also to X-radiation and ultraviolet). It may very well be, as Bodenheimer and Ostriker (1974) noted, that dQ/dt contributes to the early light curve and, in even larger total energy amounts, to the heating and continuing acceleration of the expanding nebula.

As the nebula becomes transparent, the luminosity in the optical region will decline, and radiation in the ultraviolet and X-ray will be noticeable.

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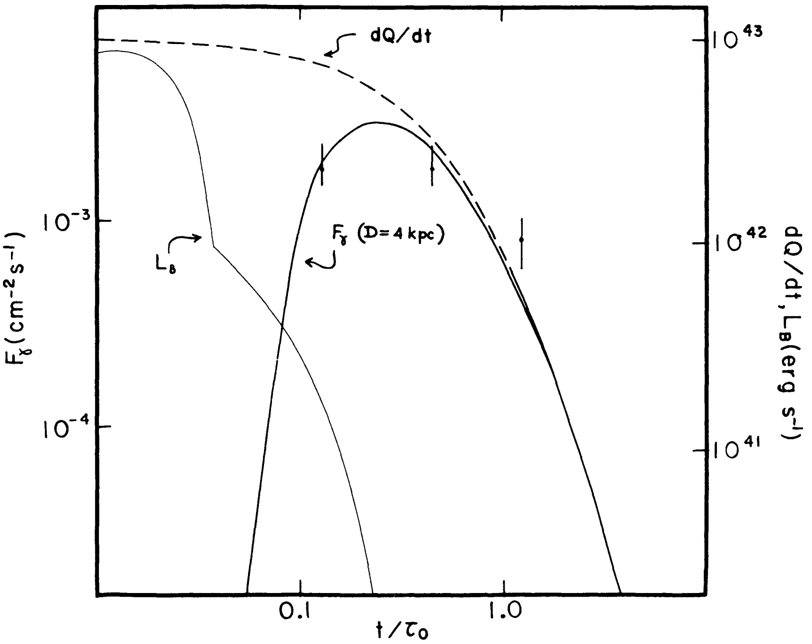

FIG. 1.—The γ-ray flux F_γ due to ^{7}Li* and ^{7}Be* is read on the left ordinate scale for a typical object at a distance $D = 4$ kpc. We used the values of $E_c = 10$ MeV and $\gamma = 2.5$ for this example. Its early rise is due to decreasing self-absorption, which is estimated for the model-dependent choice, $L_0\tau_0 = 10^{51}$ ergs, $\tau_0 = 3$ yrs, $M = 1\ M_\odot$, and $v = 10^9$ cm s^{-1}. The transmission $T(t)$ reaches unity as F_γ coincides with the curve dQ/dt, whose value is read on the right ordinate scale. The curves are then proportional to each other, inasmuch as $dQ/dt = 2\eta\ 4\pi D^2 F_\gamma$, and we merge them into a single curve by our normalizations of the ordinate scales. The flux in an observed 0.5 MeV feature (Haymes *et al.* 1975) is shown by three data points placed with the choice $\tau_0 = 3$ yr.

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