THE ELECTRON-PROTON ABUNDANCE RATIO IN COSMIC RAYS

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1. Introduction

The source material for galactic cosmic rays is expected to be bulk-neutral to start with; hence the apparent scarcity of electrons compared to protons observed in the terrestrial vicinity calls for a suitable explanation and proper understanding. In fact, because of the large rest mass difference between the proton and the electron, it is not clear whether their abundance ratio should be expressed as a function of kinetic energy E, rigidity R, or total energy in units of rest mass γ (Lorentz factor). Whichever way this is done, the abundance ratio is found to be orders of magnitude different from unity. A gainful direction in which one may seek an understanding of this would be to examine whether the processes associated with the injection, acceleration and propagation of cosmic rays could lead to the observed fractionation. In the present paper we attempt to do this within the framework of a plausible model that can explain the observed electron-proton relative abundance in a self-consistent manner. In this model, electrons and protons are accelerated in a leaky source region which modulates and injects them into interstellar space. The leaky source model has been considered by Cowsik and Wilson (1973; 1975) in connection with the energy dependent matter traversed by cosmic ray nuclei, and by Higdon (1975) in an attempt to explain the form of the electron energy spectrum.

2. The Interstellar Spectra

The electron energy spectrum near the Earth has now been well determined between about 100 MeV and hundreds of GeV and is shown as OBS-E_e in Figure 1 for the period of solar minimum. Using this data and the extensive observations on the

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certainty in the calculated secondary electrons at energies $\gtrsim 100$ MeV, though significant, is somewhat smaller compared to other errors. (For further references see Daniel and Stephens, 1975.)

In the case of protons, while the spectrum observed near the Earth at energies $\gtrsim 10$ GeV is expected to be preserved in interstellar space, as in the case of electrons, the only method of inferring the interstellar spectrum below this energy is to demodulate for solar influence the spectrum determined during the period of solar minimum (shown as curve OBS-E_p in Figure 1) using procedures which are reasonably well understood now; in this manner it is possible to deduce the interstellar proton spectrum meaningfully down to about a few hundred MeV (Meyer, 1969; Ramaty and Lingenfelter, 1969; Comstock *et al.*, 1972; Garcia-Munoz *et al.*, 1975) and is shown as IS-E_p in Figure 1. The errors shown in this curve reflect the uncertainty in the estimates for the effect of solar modulation calculated by various authors, but it decreases with increasing energy, and above a few GeV only measurement errors of 10–20% exist. Since there is no physical process which can give rise to any significant number of high energy protons of secondary origin in interstellar space, the demodulated proton energy spectrum will also be the one injected into interstellar space from source regions.

Mention may be made here that the electron and proton spectra injected into interstellar space are unlikely to be modified further at these energies during their propagation therein until the time they enter the solar system except perhaps at very low energies. Energy losses due to processes other than ionization are expected to be negligible both for electrons and protons at these energies. For example, the ionization loss for protons traversing a few g cm^{-2} of interstellar matter will result in only about a 10% decrease in intensity at about 100 MeV compared to that at the source at the same energy. For this reason, and since reliable information is presently available only

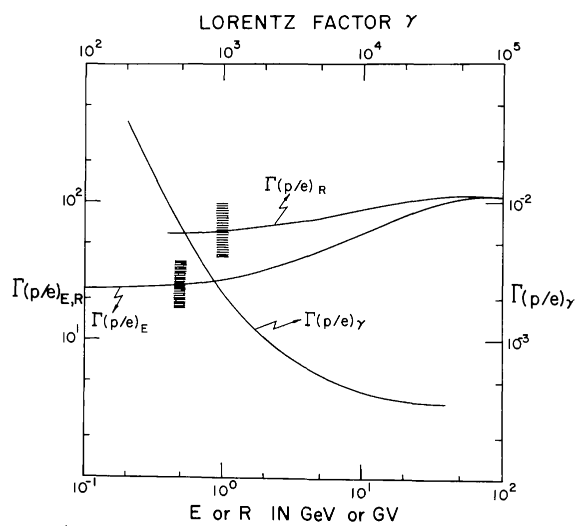

Fig. 2. The abundance ratio of protons to electrons $\Gamma(p/e)$ at the boundary of the 'source' is shown as a function of γ, R and E.

above 100 MeV, all our consideration here will be restricted to the energy region roughly between about a few hundred MeV and 1000 GeV. The proton and electron kinetic energy spectra injected into the interstellar space expressed in terms of rigidity R and total energy in units of rest mass γ, are also included in Figure 1. Furthermore, since all experiments on protons and electrons at energies between roughly 10 and 1000 GeV lead to power law spectra with an exponent of -2.6 within errors, we have used this value justifiably for both protons and electrons in this energy domain.

It was suggested by Brunstein and Cline (1966) that cosmic rays observed near the Earth are essentially neutral in bulk. This was based on insufficient data at that time and it can be shown that whichever way we consider it, cosmic rays near Earth or that which exists in interstellar space is not neutral in bulk. This is seen clearly from Figure 2 where the ratios of intensities of protons and electrons injected into interstellar space $\Gamma(p/e)$ are plotted in terms of E, R and γ.

3. Spectra in the Source Regions

Having deduced the spectrum of protons and electrons injected into interstellar space, the next step is to attempt to take them inside the source region. However, since we have no means of obtaining reliable direct information on the spectral shapes of particles within, we will adopt a procedure of plausibility and self-consistency for doing this. Because it seems most probable that the mechanism for containment and leakage of particles from the source region is due to magnetic fields, the probability of their escaping from the source region will be a rigidity dependent one. At the end of this section, we will provide evidence for the unlikelihood of fractionation at the source boundary due to Z/A dependent effects; here Z is the charge and A the mass of particle in units of proton charge and mass. Therefore, we will first assume straight

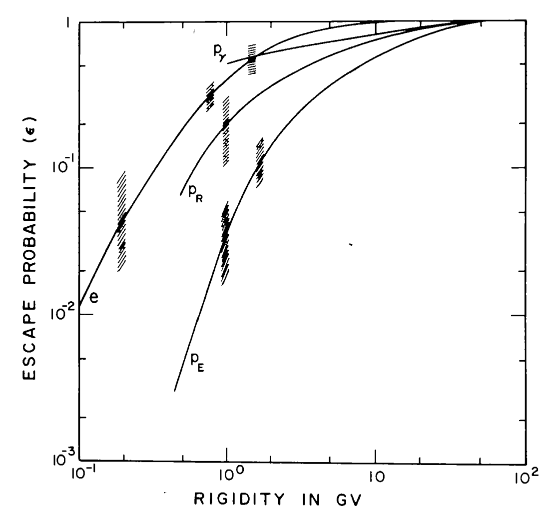

Fig. 3. The integrated escape probability as a function of rigidity. The electron curve is denoted by e and the proton curves by p. The three curves for protons correspond to γ, R and E.

line power law spectra inside the source obtained by extrapolating those at high energies down to hundreds of MeV and calculate the integrated escape probability ε defined as the ratio of the intensity in interstellar space (IS-p and PRIM-e of Figure 1) to that corresponding to the source power law. This has been carried out in the case of power laws in γ, R and E and the escape probability in each case is plotted against rigidity in Figure 3; the electrons have only one curve in this plot since all three cases become identical at the rigidities under consideration. We have been encouraged to adopt a straight line power law extrapolation from about 10 GeV to a few hundred MeV because: (i) solar demodulation tends to raise the observed spectrum closer to a power law and it is suggestive that a further restoration may happen when the IS-spectrum is taken into the source region; and (ii) more importantly, young supernova remnants which are shown to be likely sources of such cosmic rays in our model have good straight line radio spectra with an exponent of ≈ 0.7 down to about 20 MHz in the case of Cas A, Kepler and Tycho supernovae (Shklovsky, 1968), revealing thereby an electron power-law source spectrum down to 100 MeV, and perhaps even lower, with an exponent in excellent agreement with that observed at high energies in cosmic rays in the terrestrial neighbourhood (see also Section 5 for further comments).

If our assumption about the rigidity-dependent particle escape is correct, then those alternatives which lead to the same shape of ε-R curves (within errors) for electrons and protons will be mutually compatible if the shape of the spectrum of electrons and protons in the source region is the same. In Figure 3, the errors associated with curves e, p_E, p_R and p_γ corresponding to those in the IS-curves of Figure 1 are indicated by the hatched regions. A careful examination of Figure 3 clearly shows that while p_R and p_γ are consistent with curve e within errors, p_E is evidently incompatible with it. Furthermore, a power law source spectrum in kinetic energy encounters serious difficulties in the understanding of the heavy nuclei on the basis of which such a spectrum is usually not considered seriously or rejected (Ramadurai, 1970; Tandon, 1970; Comstock *et al.*, 1972; Webber and Lezniak, 1974). The question of what happens to low energy particles which are unable to leak out of the source region is discussed in Section 5.

In order to examine any possible Z/A dependence of the escape probability, we adopted similar procedures for the interstellar spectrum deduced for He nuclei (Meyer, 1969; Garcia-Munoz *et al.*, 1975). Since the interstellar helium nuclei have a spectral shape in kinetic energy the same as the proton spectrum within errors but with an intensity smaller by a factor of roughly 10, one finds that ε for helium nuclei is the same as that for protons. However, at about 1.5 GV the helium escape probabilities are likely to be about 20% higher than that for protons because of the correction of intensity due to ionization effects for helium nuclei in interstellar space; this correction will then raise the curve for He-nuclei at low R and bring it even closer to the electron curve. With increasing energy this effect will gradually become unimportant. It is thus seen that the escape probability curves for p, e and He are the same within the uncertainties involved and hence provide evidence against Z/A dependence of ε.

4. Injection and Acceleration

The reasoning made in the earlier section has enabled us to discredit with reasonable confidence accelerating mechanisms leading to a power law in kinetic energy. Of the two remaining alternatives, if the source spectrum is a power law in rigidity, we will have to explain the near constant value of $\Gamma(p/e)_R \approx 100$ and on the other hand, if it is a power law in total energy we will have to understand the electron excess leading to $\Gamma(p/e)_\gamma \approx 4 \times 10^{-4}$ as inferred from Figure 2.

Four possible particle acceleration processes which are extensively discussed in the literature (Ginzburg and Syrovatskii, 1964; Hayakawa *et al.*, 1964) are: (i) the Fermi mechanism; (ii) the betatron mechanism; (iii) the hydromagnetic wave acceleration; and (iv) the shock acceleration. Of the four, the last one is presently the least amenable for quantitative understanding but it is expected to lead directly to charge neutrality of the accelerated radiation, that is $N_p \approx N_e$, without the need for any injection prior to acceleration; also it yields a power law in γ for both protons and electrons. Since, however, we find clearly that a power law source spectrum in γ demands an electron excess to the extent of 10^3–10^4, and since we are unable to identify a physical process which can subsequently fractionate the protons and electrons in favour of the latter to such an extent, we will not consider this process further. Acceleration by hydromagnetic waves leads to power law in momentum. However, in the case of protons and electrons with the same charge, they are equivalent to power law in rigidity. Hence, for the present purpose, considerations adopted for betatron acceleration will also apply equally well for hydromagnetic wave acceleration. Mention may be made here that the pulsar acceleration mechanism (Gunn and Ostriker, 1969) which primarily gives rise to high energy particles, also leads to similar spectra in γ for protons and electrons, even though some fractionation may be introduced due to the mass dependent maximum energy to which particles are accelerated. However, it is generally believed that pulsar acceleration cannot lead to particle acceleration down to energies where we are interested presently (Rengarajan, 1975).

4.1. The injection mechanism

The rate at which a particle gains energy by the acceleration processes, Fermi or betatron, can be expressed in the simplest case as

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = a\beta\gamma \tag{1}$$

or

$$\frac{\mathrm{d}R}{\mathrm{d}t} = bR, \tag{2}$$

respectively. Here a and b are the acceleration parameters associated with the two mechanisms, and β is the ratio of the velocity of the particle to that of light. A pure

Fermi acceleration process will lead to a power law in γ while a pure betraton process will result in a power law in R. Since simultaneously with the acceleration from low energies, electrons and protons will also be losing energy through ionizing collisions, a net positive acceleration can take place only if the rate of energy gain exceeds the rate of energy loss; this in turn will essentially depend on the acceleration parameter a or b as the case may be. The threshold, or injection energy, above which only net acceleration can occur can be calculated by equating the rate of energy gain due to acceleration with the rate of energy loss due to ionization, since at injection energies of the order of tens of keV, ionization is the most dominant energy loss process for both electrons and protons. In the model within which we are working here, it seems that a probable process to provide initial injection of particles is a thermal source with a temperature high enough to provide enough number of particles above the threshold energy in the Maxwellian distribution. (Other possible injection mechanisms are referred to in Section 5.) One then has to examine whether plausible conditions exist in the source region for the injection of the particles followed by acceleration such that they can lead to the proton to electron ratios expected from considerations in Sections 2 and 3.

4.2. The acceleration process

We shall now examine the Fermi and betatron acceleration processes, to enquire whether they could lead to the required source ratio implied by the corresponding power laws for protons and electrons. Since the accelerated particles are distributed throughout the energy spectrum, the injection ratio will be equal to the ratio of protons and electrons integrated over the entire spectrum from the injection energy to the highest energies. In order to do this the source spectrum should be known right down to the injection energies. In the following we start by using a power law spectrum down to injection energies (realizing well that it may not be so) and after taking cognizance of the results they lead to, discuss in Section 4.2.3 the possible deviations of low energy spectra from a power law, and their implications.

4.2.1. *Fermi Acceleration*

In the nonrelativistic domain where the initial injection and acceleration processes take place, we can rewrite Equation (1) in terms of kinetic energy E of the accelerated particle as

$$\frac{\mathrm{d}E}{\mathrm{d}t} = a\sqrt{2Mc^2E}, \tag{3}$$

and energy loss due to ionization (Ginzburg and Syrovatskii, 1964) as

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = -7 \times 10^{-9} nL\sqrt{2Mc^2/E}\ \mathrm{eV\ s^{-1}}, \tag{4}$$

where L is a logarithmic factor with a value of the order of 10, M the mass of the accelerated particle and n the density of atoms in the region of acceleration. If we equate Equations 3 and 4, the value of the injection energy is obtained as

$$E^{i.F} \approx 7 \times 10^{-9} \frac{L \times n}{a}. \tag{5}$$

Clearly, one sees from this that $E^{i.F}$ is independent of the mass of the particle being accelerated. Furthermore, since the Maxwellian distribution in kinetic energy for protons and electrons at a given temperature is the same, and the injection energies in units of γ for electrons and protons are close to 1, we can write the ratio of the total number of protons accelerated to that of electrons as

$$\frac{N_p^{i.F}}{N_e^{i.F}} = \frac{K_p}{K_e} \frac{\int_1^\infty \gamma_p^{-2.6}\, \mathrm{d}\gamma_p}{\int_1^\infty \gamma_e^{-2.6}\, \mathrm{d}\gamma_e}. \tag{6}$$

Since we find that $K_p/K_e \approx 4 \times 10^{-4}$, the relation is grossly violated and casts serious difficulty for the Fermi process to be primarily responsible for the acceleration of both electrons and protons.

4.2.2. *Betatron Process*

In the nonrelativistic situation, we can rewrite Equation (2) as

$$\frac{\mathrm{d}E}{\mathrm{d}t} = bE. \tag{7}$$

As in the case of the Fermi process, we can obtain a relation for the injection energy by equating Equations (4) and (7) as

$$E^{i.B} \approx \left(\frac{7 \times 10^{-9} nL}{b}\right)^{2/3} (2Mc^2)^{1/3}. \tag{8}$$

Further, from Equation (8), it can be seen that the injection energy for protons is higher than that for electrons, and their ratio for a given b and n can be written as

$$E_p^{i.B}/E_e^{i.B} \approx \left(\frac{M_p}{M_e}\right)^{1/3} \sim 10; \tag{9}$$

and in terms of injection rigidities one can write

$$R_p^{i.B}/R_e^{i.B} \approx \left(\frac{M_p}{M_e}\right)^{2/3} \sim 10^2. \tag{10}$$

In order to examine whether such injection energies for p and e can lead to the kind of proton excess expected for a power law source spectrum in rigidity, we can write for the ratio of the total number of injected protons to that of electrons as

$$\frac{N_p^{i,B}}{N_e^{i,B}} = \frac{K_p}{K_e} \frac{\int_{R_p^{i,B}}^{\infty} R_p^{-2.6}\, \mathrm{d}R_p}{\int_{R_e^{i,B}}^{\infty} R_e^{-2.6}\, \mathrm{d}R_e}, \tag{11}$$

where K_p and K_e are the respective constants in the rigidity power-law spectra in the source region. Equation (11) reduces to

$$\frac{N_p^{i,B}}{N_e^{i,B}} = \frac{K_p}{K_e} \left(\frac{R_e^{i,B}}{R_p^{i,B}}\right)^{1.6}. \tag{12}$$

In this relation, when we substitute the value of $K_p/K_e \approx 100$ from Figure 2, and the value of 10^{-2} from Equation (10) for the ratio of the injection rigidity, we get $N_p^{i,B}/N_e^{i,B} \approx 10^{-1.2}$. Such a requirement can best be achieved if: (i) $E_p^{i,B}$ has a value close to the energy corresponding to the maximum in the Maxwellian distribution of the hot gas; and (ii) the acceleration parameter b has a value such that the rate of energy gain is less than the maximum in the proton ionization loss so that not all protons are accelerated and the necessary fractionation can occur. The maximum energy loss for protons occurs at about 60 keV yielding a value $b \lesssim 6 \times 10^{-9}\ \mathrm{s}^{-1}$. Thus the lowest possible injection energy is of the order of 60 keV corresponding to a temperature of $\sim 10^8$ K. Though this is a rather high temperature, it can possibly occur in special situations such as in a gas heated by a shock or if the heating is sudden as in coronal condensations (Hayakawa, 1969). It seems possible then in principle to have the required ratio of electrons and protons in a pure betatron acceleration model if such hot spots are either continuously present or are fairly frequently produced during the period of acceleration (~ 100 yr, see below) in order to obtain a power law spectrum.

4.2.3. *Consequences of Deviation from Power-Law at Low Energies*

The nature of energy spectra at low energies arising from Fermi acceleration has been discussed by Ramadurai (1971). It is easy to see from his formulation that similar considerations should hold for betatron acceleration as well. The spectra tend to deviate upwards from a power law with decreasing energy, the extent of deviation being determined by the severity of the energy loss processes. Under the astrophysical conditions of matter density and magnetic fields encountered in the accelerating regions, the dominant energy loss process for low energy protons and electrons is ionization. Even so, close to the injection energy of ~ 100 keV, ionization energy loss is much larger for protons resulting in a greater upward deviation from a power law spectrum for protons than for electrons. This implies that the value of the right-hand side of Equations (11) and (6) will be even larger than that obtained assuming a power law in R or γ. This will accentuate the difficulty for pure Fermi process as mentioned at the end of Section 4.2.1. In the case of betatron acceleration the ratio $N_p^{i,B}/N_e^{i,B}$ will now turn out to be even larger than $10^{-1.2}$. In order to achieve it the injection temperature has to be even higher than 10^8 K, thereby making it even more improbable as the sole accelerating mechanism.

4.3.4. *Mixed Acceleration*

In the above, we considered pure Fermi and betatron accelerations only. However, in a real situation both may operate either concurrently or in sequence in varying degrees of importance. This is because acceleration occurs in the Fermi case from the scattering of particles by moving magnetic irregularities, while changing magnetic fields needed for betatron acceleration are produced by the coherent movement of magnetic irregularities. The Fermi mechanism generally favours protons while the betatron favours electrons so that it is possible that the required ratio of electrons to protons can be achieved by a suitable mixture of the two. This mixing of the two acceleration processes avoids the necessity for extreme temperatures of injection as in the pure betatron process. It seems that though in principle a quantitative evaluation of the mixing of the two mechanisms to explain the observations is possible, it is not considered worthwhile at this stage considering the large uncertainties in the mean parameters involved. There is however a severe constraint, namely the power spectra of both protons and electrons after acceleration should have the index close to -2.6. This equality of the power law index leads to the relation $a\tau_a \sim b\tau_b$. Here τ_a and τ_b are the time periods for which the Fermi and betatron acceleration processes operate in the source and are probably not more than few hundred years. Since $b \sim v_m/1$ where v_m is the velocity of the magnetic irregularities and 1 is the scale length, and $a \sim v_m^2/c \times 1$, we have $b/a \sim c/v_m$ which is always greater than 1, implying that $\tau_b < \tau_a$. This is understandable since the effective operation of the betatron mechanism requires coherence of magnetic variations which may not last long. However, it is not clear why the product $b\tau_b$ should turn out to be approximately equal to $a\tau_a$ and whether it has a deeper significance. A mixed acceleration of the type considered here is likely to lead to a particle spectrum which is a mixture of power laws in rigidity and total energy; the effect of this mixing can become evident only at low energies. In fact there seems to be evidence that the spectrum of heavy nuclei needed for explaining the observations is a mixture of power laws in rigidity and total energy (Ramadurai, 1970; Tandon, 1970).

5. Conclusions and Discussions

We have shown that starting with a power law source spectrum in E, R and γ above a few hundred MeV, existing observations on cosmic ray electrons and protons between a few hundred MeV and about 1000 GeV can be well understood in a model wherein: (i) particles are accelerated in a mixed mechanism involving both betatron and Fermi processes with injection at a relatively lower temperature; (ii) particles then escape into interstellar space from the source region in a rigidity dependent fashion; and (iii) the apparent excess of protons over electrons and its dependence with energy result from a combination of effects due to injection, acceleration, and modulation in the source region and the solar system. Further, we are able to demonstrate with a good degree of confidence that acceleration processes which lead to a pure power law either in kinetic energy or total energy for electrons and protons are not consistent with observations. We have also drawn attention in Section 3 to observations which provide consistency arguments in support of a power law or near power law source spectrum down to about hundred MeV.

It is evident that the physical conditions which can meet the requirements of pure betatron or mixed acceleration and subsequent modulated injection into interstellar space needed to explain the observations, are likely to exist in the expanding nebula of a supernova remnant during the first few hundred years after the initial explosion. Such a requirement will also be consistent with recent findings on the trends in the variations of the ratios of the intensities of 'parent nuclei', such as carbon, oxygen and iron, to that of 'daughter nuclei', such as lithium, beryllium, boron and nitrogen (Juliusson *et al.*, 1972; Smith *et al.*, 1973; Balasubrahmanyan and Ormes, 1973; Webber *et al.*, 1973) which have been attractively interpreted as due to the heavy nuclei having traversed an energy dependent few g cm^{-2} of matter in the source region (Cowsik and Wilson, 1973, 1975); the high matter density needed for this is more likely to exist in the early phase of supernova remnants. However, the current experimental errors and variations between the results of different observers are too large to permit a quantitative comparison of this effect with that expected from the escape probabilities estimated for the protons and electrons.

If therefore, young supernova remnants are good candidates for cosmic ray acceleration during the first few hundred years of their lifetime, it is natural to expect that it should be reflected in their radio spectra which should have a power index of ≈ 0.8. Indeed the three known young galactic supernovae: namely, Cas A (1725 A.D.), Kepler (1604 A.D.) and Tycho Brahe (1572 A.D.) have spectral indices of -0.8, -0.62 and -0.67, respectively (Shklovsky, 1968). However, as Higdon (1975) has pointed out, if one considers all supernova remnants, their radio spectral indices lie between -0.25 and 0.8 and for an understanding of this, one may have to look for processes which either harden the parent electron spectra with age or, as is happening in the crab nebula, accelerate new electrons.

The escape probabilities we have deduced for electrons and protons for the source region clearly indicate that it is approaching a value close to 1 in the tens of GeV region. In the leaky source model we have used here, there are likely to be two important implications for this: (i) particles accelerated and injected into space from such sources would have spectra which are likely to steepen perhaps at energies $\gtrsim 1000$ GeV; and (ii) there would be a need for other acceleration processes and/or other sources for the higher energy particles. While it is true that in the case of the nuclei, available data do not indicate any significantly abrupt change of spectral shape in this energy region (10^{12}–10^{13} eV), it is also precisely the region which is not yet accessible either to direct measurement or to reliable indirect estimates from extensive air showers; an observation in the future of even a small discontinuity in the energy spectrum of protons in this energy region may provide an important corroboration and support for our model. In the case of electrons, the situation is compounded by the expectation for a steepening due to energy loss processes during propagation to occur at about the same energy region. Current experimental attempts to determine the energy spectrum of electrons around 1000 GeV and above are likely to lead to definitive observational information in the near future, though their interpretation may not be straightforward.

The small escape probabilities we have obtained from Figure 3 at rigidities less than a few GV imply that a fair fraction of these particles are trapped in the source itself. Since, at the same time, a continuous build up of particle intensities at these energies is inconsistent with observations, they have to be effectively drained of their energy in a suitable time period. One very likely mechanism for this is the adiabatic expansion of the remnant (Shklovsky, 1968) whereby the particle energy is transferred to the expanding envelope sweeping up interstellar matter in front. If young supernovae are to be the main sources of cosmic rays, the total energy in these low energy particles is about 10^{49}–10^{50} erg (Ginzburg and Syrovatskii, 1964), a fair fraction of which is trapped in the source. The energy involved in the expanding remnant is also of the same order (Trimble and Rees, 1970) consistent with the suggestion made above. In spite of all this, we recognize that such an explanation would imply the need for a delicate balance between the time scales involved in acceleration, escape and energy draining of the particles. For a rigorous theory to obtain information on the energy spectrum of particles injected into interstellar space, all three effects should be incorporated simultaneously.

Finally, we have considered in this paper only injection from a Maxwellian distribution of a hot gas. Other possible injection processes include stochastic acceleration of particles by non-static electric fields (Cowsik and Lerche, 1976) and acceleration by radiation fields (Tsytovich, 1964); both processes lead to injection preferentially of electrons over protons. However, as of now we neither know whether the requisite electric and radiation fields occur long enough over the required acceleration period to yield the observed power law spectra, nor are they amenable to quantitative treatment to understand the fractionation of electrons and protons. Consequently, we have not considered these mechanisms here.

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References

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968, *Nature* **217**, 25.
Balasubrahmanyan, V. K. and Ormes, J. F.: 1973, *Astrophys. J.* **186**, 109.

Beuermann, K. P., Rice, C. J., Stone, E. C., and Vogt, R. E.: 1969, *Phys. Rev. Lett.* **22**, 412.
Brunstein, K. A. and Cline, T. L.: 1966, *Nature* **209**, 1186.
Comstock, G. K., Hsieh, K. C., and Simpson, J. A.: 1972, *Astrophys. J.* **173**, 691.
Cowsik, R. and Lerche, I.: 1976 (preprint).
Cowsik, R. and Wilson, L. W.: 1973, *Proc. 13th Int. Conf. Cosmic Rays* **1**, 500.
Cowsik, R. and Wilson, L. W.: 1975, *Proc. 14th Int. Conf. Cosmic Rays* **2**, 659.
Cummings, A. C., Stone, E. C., and Vogt, R. E.: 1973, *Proc. 13th Int. Conf. Cosmic Rays* **1**, 335.
Daniel, R. R. and Stephens, S. A.: 1969, *Proc. 11th Int. Conf. Cosmic Rays, Acta Phys. Acad. Sci. Hungaricae* **29**, 531.
Daniel, R. R. and Stephens, S. A.: 1975, *Space Sci. Rev.* **17**, 45.
Garcia-Munoz, F. M., Mason, G. M., and Simpson, J. A.: 1975, *Astrophys. J.* **202**, 265.
Ginzburg, V. and Syrovatskii, S. I.: 1964, *Origin of Cosmic Rays*, Pergamon Press, New York.
Gunn, J. E. and Ostriker, J. P.: 1969, *Phys. Rev. Lett.* **22**, 728.
Hayakawa, S.: 1969, *Cosmic Ray Physics*, John Wiley, New York.
Hayakawa, S., Nishimura, J., Obayashi, H., and Sato, H.: 1964, *Suppl. Prog. Theor. Phys.* **30**, 86.
Higdon, J. C.: 1975, *Proc. 14th Int. Conf. Cosmic Rays* **2**, 469.
Juliusson, E., Meyer, P., and Muller, D.: 1972, *Phys. Rev. Lett.* **29**, 445.
Lezniak, J. A. and Webber, W. R.: 1971, *J. Geophys. Res.* **76**, 1605.
Meyer, P.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 1.
Ramadurai, S.: 1970, Ph.D. Thesis, Bombay University, India: 'Cosmic Rays in Interplanetary and Interstellar Space and in Source Regions'.
Ramadurai, S.: 1971, *Proc. of 12th Int. Conf. on Cosmic Rays* **1**, 384.
Ramaty, R. and Lingenfelter, R. E.: 1969, *Astrophys. J.* **155**, 587.
Rengarajan, T. N.: 1975, *Astrophys. Space Sci.* **32**, 55.
Shklovsky, I.: 1968, *Supernovae*, John Wiley, New York.
Smith, L. H., Buffington, A., Smoot, G. F., and Alwarez, L. W.: 1973, *Astrophys. J.* **180**, 987.
Tandon, S. N.: 1970, Ph.D. Thesis, Bombay University, India: 'On Propagation of Cosmic Rays'.
Trimble, V. and Rees, M. J.: 1970, *Astrophys. Lett.* **5**, 93.
Tsytovich, V. N.: 1964, 'Soviet Astronomy', *Astron. J.* **7**, 471.
Verma, S. D.: 1968, *Astrophys. J.* **152**, 537.
Webber, W. R. and Lezniak, J. A.: 1974, *Astrophys. Space Sci.* **30**, 361.
Webber, W. R., Lezniak, J. A., Kish, J. C., and Damle, S. V.: 1973, *Nature Phys. Sci.* **241**, 96.