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ABSTRACT

In this paper, the implications of a sudden release of a large number of cosmic rays as in a supernova burst are considered in the light of the conditions for containment of cosmic rays in the galactic disk. Reasons are given to show that a significant portion of the cosmic rays could be lost quickly (< 10^4 years) after a burst, and the question of whether most of the cosmic rays remaining in the galaxy ultimately escape as the result of pressure effects rather than diffusion effects is considered. Two experimental tests already discussed in the literature in a somewhat different context could separate these two possibilities. In considering the question of a possible cosmic ray anisotropy, it is noted that the high degree of isotropy observed could be the result of cosmic rays existing at what is effectively their density saturated limit with no easy escape. Finally, it is point out that cosmic rays could be being supplied to intergalactic space at a level substantially above that deduced from diffusion theory, thereby more easily explaining what was previously thought to be a possible "high" intergalactic electron flux.

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ABSTRACT

In this paper, the implications of a sudden release of a large number of cosmic rays as in a supernova burst are considered in the light of the conditions for containment of cosmic rays in the galactic disk. Reasons are given to show that a significant portion of the cosmic rays could be lost quickly ($< 10^4$ years) after a burst, and the question of whether most of the cosmic rays remaining in the galaxy ultimately escape as the result of pressure effects rather than diffusion effects is considered. Two experimental tests already discussed in the literature in a somewhat different context could separate these two possibilities. In considering the question of a possible cosmic ray anisotropy, it is noted that the high degree of isotropy observed could be the result of cosmic rays existing at what is effectively their density saturated limit with no easy escape. Finally, it is point out that cosmic rays could be being supplied to intergalactic space at a level substantially above that deduced from diffusion theory, thereby more easily explaining what was previously thought to be a possible "high" intergalactic electron flux.

I. Introduction

The problem of the history of cosmic rays after their release at the sources is a very intriguing one because of the large energy content of these particles, and consequently the important role they play in the galaxy and possibly intergalactic space. The dynamics associated with the containment of cosmic rays in the galactic disk has often been considered, as has the concept of the possible sudden initial release of a large number of cosmic rays as in a supernova burst. It is the purpose of this note to examine the implications when the two are considered together.

In particular, it is the intent of this paper to examine some implications of the sudden release of a large number of cosmic rays by a source in the galaxy, then to consider possible experimental tests to determine whether the cosmic rays observed in the galaxy ultimately leave primarily as a result of pressure or diffusion, and finally to consider the consequences of the apparently likely possibility that the galactic sources produce more cosmic rays than can be held in the galaxy.

II. The Basic Considerations Related to the Sudden Release of a Large Number of Cosmic Rays in the Galaxy

The first basic assumption to be made is that the cosmic ray energy density observed in our galaxy far exceeds that outside, and, by implication, the majority of the cosmic rays are therefore not "universal", but local to our galaxy. The merits of this view as opposed to the other concept of a universal uniform density of cosmic rays will not be argued here except to say that this view arises generally, but not solely, from consideretion of the likely production capability of sources. Assuming this point of view, Parker (1966) has emphasized that the cosmic rays, the motion of matter, and the magnetic fields all contribute to a pressure to expand the galactic disk which is opposed only by the gravitational force of the mass in the disk. It appears that the energy density of the cosmic radiation is about the same as that of the magnetic fields in the galaxy, namely about 1 eV/cm^3, and also the kinetic energy of motion of matter. If the cosmic ray energy density were significantly larger, the cosmic rays could not be contained by the magnetic fields. Of the three expansive pressures mentioned, that due to the cosmic rays is the only one which seems likely to have the capability of changing markedly over short periods (less than 10^4 years in this context), if some of the most accepted current concepts of the origin of cosmic rays are correct.

The most likely source of cosmic rays now appears to be supernovae. A total energy in the form of cosmic rays of between 10^{50} and 10^{52} ergs is estimated to be released according to the hydrodynamic shock acceleration theory of Colgate and Johnson (1960), Colgate and White (1963) and Colgate (1965). The minimum energy which has to be supplied simply to replace that carried away by escaping cosmic rays is 0.1 to 2 x 10^{50} ergs, if the average cosmic ray escapes from the galactic disk in a period of from 3 to 50 million years as suggested by the experimental measures of cosmic ray secondaries and various propagation studies (e.g., Reames and Fichtel, 1968; Shapiro et al., 1969; Ramaty et al., 1970), and the average time between supernovae in our galaxy is 10^2 years. The volume of the disk from the standpoint of cosmic ray containment is assumed to be approximately 10^{67} cm^3, i.e., about 15 kiloparsecs in radius and .5 kiloparsecs thick. The supernova energy released in the form of cosmic rays could, of course, be much larger than this minimum value because the "excess cosmic rays", which would cause the energy density of cosmic radiation to substantially exceed that of the magnetic field, would inflate the magnetic field and escape quickly.

Let us assume for the moment that the cosmic ray energy for a supernova is 10^{50} ergs, for example. The cosmic rays will initially expand very quickly simply because there is nothing to stop them. The density of the interstellar material is, of course, far too low, and the interstellar magnetic field energy density is extremely small compared to the initial cosmic ray energy density. Hence, the situation is clearly one of virtual free expansion at the beginning and is clearly not one represented by diffusion theory. If one took the naive point of view that they expanded until their energy density was about 1 eV/cm^3, the energy density of the unperturbed magnetic fields, they would fill a volume of almost 10^{62} cm^3, which if it were a sphere would have a diameter of about 170 pc, nearly the thickness of the disk (and would do so in the order of 10^2 years). In fact, the cosmic rays will interact with the existing fields and cosmic rays, ultimately slowing down the expansion of the new cosmic rays and leading to many effects such as shock waves, energy transfer, and a general mixing of the new and old cosmic rays. Nonetheless, for some period the energy density of the cosmic rays far exceeds that of any other form and during that period the cosmic rays expand very rapidly. (It is perhaps worth mentioning here that the relatively slow expansion of a supernova, several parsecs in a thousand years, discussed by Shklovsky (1968) for example, refers to the large hot gas of the shell behind the front interacting with the interstellar medium and hence is not related to the thin top layer of cosmic rays. The only way cosmic rays could be held by the supernova remnant would be by its magnetic fields, but such huge fields seem unlikely to be consistent with the prior implosion and subsequent explosion of the supernova.)

Finally, the energy density of the cosmic rays will fall to nearly the general level. There is probably a general tendency during the latter phase (when the cosmic ray energy density begins to approach that of the magnitude field--at least within an order of magnitude) for cosmic rays to expand along the field lines; yet the initial phase presumably still leads to sufficient expansion perpendicular to the field lines to cause a bulging of the field near the source similar to that described by Parker (1966) for the milder quasi-equilibrium picture and a subsequent substantial loss of cosmic rays. If the energy release is actually 10^{51} or 10^{52} ergs, the effects of the cosmic ray release will obviously be extremely disruptive with most of the recently released cosmic rays presumably escaping from the galactic disk in a very short time.

From the point of view that will be discussed here, whether cosmic ray acceleration occurs in a fraction of a second as in the hydrodynamic shock theory or in 10^2 to 10^3 years in the post-supernova explosion phase, the energy release shall still be called "sudden", since, in relation to the galaxy, a very large amount of energy is deposited in a time very short compared to that which is thought to be the average time spent in the galaxy by those cosmic rays which do not escape quickly in the manner discussed in the last paragraph. Hence, here "short" when applied to release and expansion will mean less than 10^4 years (and probably less than 10^3 years) and "long" will mean of the order of 10^7 years or greater.

III. Cosmic Ray Pressure Effects and Diffusion

With this discussion as a background, an interesting question is whether cosmic ray pressure or diffusion effects play the dominant role in cosmic ray particle escape from the galaxy for the particles observed by experiments. It is, of course, possible, as discussed earlier that the total cosmic ray energy released by any one source may be so great that a major fraction of the cosmic rays escape from the galaxy very quickly (a few thousand years). The region of the disk near the supernova, however, presumably returns to a quasi-equilibrium situation afterwards and remains that way until the next burst of new cosmic rays in the same region. If the cosmic rays already in the disk escape primarily as a result of the pressure of new cosmic rays pushing them to the side where they find weak bulges in the field of the type described by Parker (1966), the average lifetime of the cosmic rays will be basically a time dependent phenomenon, and the average path length will therefore be proportional to velocity. If, on the other hand, the primary mode of escape is diffusion along the field lines, which are nearly parallel to the plane, but ultimately reach the sides of the disk after a distance along a hypothetically smooth field line of the order of a kiloparsec, the escape will be predominantly determined by the average length traveled. (For a treatment of a model of this type, see for example, Kulsrand and Pearce, 1969.) This length could be rigidity dependent in principle; so it is even possible for low energy particles to have longer rather than shorter path lengths, as in the other alternative.

Before discussing some possible experimental tests, the processes by which cosmic rays diffuse in the galaxy if there has not been a recent supernova will be stated briefly. The cosmic rays diffuse as a result of scattering on magnetic irregularities (as first proposed by Fermi (1949, 1954) and investigated more quantitatively by Morrison et al. (1954) and in great depth recently by many authors), cyclotron resonance scattering off small wavelength Alfven waves (as discussed by Tidman (1966), Kulsrand and Pearce (1969) and others), and self scattering by the hydromagnetic waves generated by the cosmic rays themselves (Lerche, 1967; Wentzel, 1968). If the diffusion length is long enough, the cosmic rays can proceed along field lines until they reach the weaker fields near the sides of the galaxy and expand these weak spots into bubbles, as described by Parker (1966, 1967a, and 1967b), which ultimately allow the cosmic rays to escape. However, a study of the diffusion processes mentioned above indicates that the diffusion may be very slow. Thus, the experimental tests to be discussed now relates to whether these processes will allow cosmic rays to diffuse from the galaxy fast enough to represent the primary escape mode or not.

There are, at least, two possible ways that this question can be examined experimentally. Both are capable of determining whether the cosmic ray distribution is a result of pressure and hence time dependent effects, or diffusion and hence path length and rigidity effects.

One is the determination of the relative abundance of unstable secondary components as a function of energy and the other is the study of the relative abundance of the stable secondaries. In the former case, there are two isotopes which are known to have lifetimes in the range of interest and to be significant secondary components. One of these is Be^{10}. The production of this component and its subsequent decay has been studied extensively (e.g. Shapiro and Silberberg, 1968) and recently considerable attention has been devoted to measuring the appropriate cross-sections. Reames (1970) has noted that Mn^{53} is another unstable nucleus which can be examined in the same way. It is a very significant secondary component of Fe so that it is only necessary to measure the Mn abundance relative to Cr and not to perform the very difficult task of separating isotopes. Thus far, a truly definitive experiment to measure the lifetime of the cosmic rays as a function of energy (or velocity) has not been made using either of the isotopes, but such a test could separate path length from time effects.

Another approach to the problem is the study of the stable nucleon secondaries as a function of energy/nucleon. The propagation of cosmic ray nuclei has been studied by many authors, including for example Cowsik et al. (1967), Fichtel and Reames (1966 and 1968), Shapiro et al. (1969), and Yiou et al. (1968). The results of this work show that the ratios of many secondary components to what was initially a predominantly parent species vary with energy in a way which is strongly dependent on the assumption which is made about the lifetime being time dependent or diffusion dependent. As a specific example, the approach of Fichtel and Reames (1968) was used here with the additional recent cross-section data of Yiou (1968) and Shapiro et al. (1969) to obtain the boron to oxygen ratio under various assumptions. These results are displayed in Figure 1. For the path length distributions, simple functions with one adjustable parameter determining the rate of decrease of the probability with increasing path length, x, were chosen. These are:

$$P(x) = C_1 \exp\left[-x/(\beta x_o)\right] \quad (1a)$$

$$P(x) = C_2 \exp\left[-x/x_o\right] \quad (1b)$$

$$P(x) = C_3 \exp\left[-(\beta x)/x_o\right] \quad (1c)$$

which, in addition to their simplicity, are often quoted in the literature (e.g. Cowsik et al., 1968; Shapiro et al., 1969) and can be shown to be very close to the results of several more complicated diffusion models. (1a) is a time dependent distribution, with the property that the average potential path length decreases for lower velocities; (1b) describes a path length dependent probability; (1c) is a distribution which attempts to introduce rigidity dependent effects at low energies since β is proportional to momentum at low energies and a constant at high energies. For the energy spectra,

$$dJ/dW = j_o W^{-2.5} \quad (2)$$

was used for the present, but as the next paragraph indicates we are not sure that it will be the best choice ultimately.

Before these tests can be applied, however, the effects of solar modulation must be removed. Whereas diffusion effects are relatively insignificant since the ratios just discussed involve nuclei of the same, or nearly the same, charge to mass ratio, the deceleration effect is likely to be significant. Parker (1963) has considered the problem of the deceleration of the cosmic rays within the solar system and shown that it could be quite significant. More recently, Goldstein et al. (1970) have considered the problem in more detail and shown that the loss in energy is probably quite large possibly of the order of one to a few hundred MeV/nucleon) at low energies. Since an exact quantitative prediction of the amount of deceleration seems difficult from present knowledge, we shall probably have to wait until satellites carrying cosmic ray detectors reach several astronomical units from the sun and thereby provide the data needed to determine the cosmic ray properties before solar modulation. Since satellites of this type are not too far in the future, a test of whether pressure or diffusion plays the dominant escape role should soon be at hand.

IV. Cosmic Ray Pressure and Anisotropy

The role of the balance of pressures is of importance in another way, in that it prevents the cosmic ray density from exceeding a level which can be held by the magnetic field. Thereby, there is a density equalizing effect which tends to eliminate any significant spatial variations resulting from a re`ease of cosmic rays in some region. After equilibrium then, the only net flow of cosmic rays will be the very slow one resulting from the escape of cosmic rays from the sides of the disk, if indeed this is significant at all. This implies that in the central plane of the galactic disk the net flow and, hence, the anisotropy, is essentially zero. A one-dimensional model developed by Kulsrand and Pearce (1969) can be adopted to this problem if one interprets their uniform source along the tube as being the cosmic ray pressure effect or more simply sets the source equal to zero. The net result is an anisotropy given by

$$\delta = \frac{2\lambda z}{L^2 - z^2} \approx \frac{2\lambda}{L} \frac{z}{L}, \text{ for } z^2 \ll L^2 \qquad (3)$$

which approaches zero as $z \to 0$. Here, z is the distance from the plane along the field line, L is the length of the field line to its end on the surface of the disk, and λ is the mean free path. For $\lambda = 10^{-1}$ pcs or less, as suggested by Ramaty et al. (1970), and L = 1 kiloparsec, then $\delta \lesssim 2 \cdot 10^{-4}$ (z/L). This one dimensional picture is presumably reasonably accurate since motion across field lines is probably due more to gyrofrequency scattering from field lines to an adjacent one rather than particle scattering on irregularities, and the scattering is almost certainly basically random. This general question plus the diffusion along the line is discussed by both Wentzel (1968) and Kulsrand and Pearce (1969). The significant point relative to the discussion here is that the pressure effect prevents large, long lasting anisotropies which might otherwise result from the release of particles from point sources in a medium when diffusion was the principle consideration and there was no consideration of the cosmic ray pressure.

From the point of view developed here then, what is often referred to as the "remarkable" isotropy of cosmic rays is really the result of the cosmic rays existing at what is effectively their density saturated level with no easy escape. When there is an infusion of new cosmic rays into a region, the excess, a mixture of new and some old particles, escape quickly by their own pressure. The magnetic fields then readjust and equilibrium is reestablished.

V. <u>The "Excess" Cosmic Rays</u>

In Section II it was noted that the hydrodynamic theory of supernova cosmic ray origin indicates that it is easily possible that supernovae produce substantially more cosmic rays than are needed simply to replenish those which are escaping. As indicated at that point this cosmic ray excess escapes relatively quickly into intergalactic space. If the more optimistic predictions of the hydromagnetic origin theory are correct, the rate at which cosmic rays are being supplied to interstellar space could then be one to two orders of magnitude higher than estimated from leakage considerations alone.

Brecher and Morrison (1969) have previously shown that the diffuse cosmic x-ray source might be explained by leakage of electrons from normal galaxies and their subsequent interaction with the black body radiation, assuming the cosmic ray electron to proton ratio to be 1 to 10^2 in energy density as it is in our galaxy. The leakage rate from a galaxy would have to be substantially more than our own, however. They noted that our own galaxy is a rather weak radio source, about

1/10 the mean, and therefore it is not unreasonable to assume that a correspondingly higher electron flux would be expected from the average galaxy. The comments of the previous sections indicate that our own galaxy could in fact also be a substantial, or average in the context just discussed, source of intergalactic electrons. The difference would then lie in our galaxy having a weaker average magnetic field and correspondingly less intense cosmic ray flux. Recall that as the magnetic field increases the cosmic ray density that may be held increases, and that the synchrotron radiation would increase as the product of the two. We feel that the concept of the increased cosmic ray contribution to the metagalaxy as a result of the process mentioned above strengthens the explanation of the metagalactic x-ray flux being explicable by electron leakage from the galaxy. It is also worth noting that, if these considerations are correct, the injected intergalactic cosmic ray nucleon and electron spectra may represent only the result of initial acceleration and expansion, and not any subsequent energy loss effects due to propagation in the disk. As a result, for example, the intergalactic electron spectrum could be flatter than expected previously.

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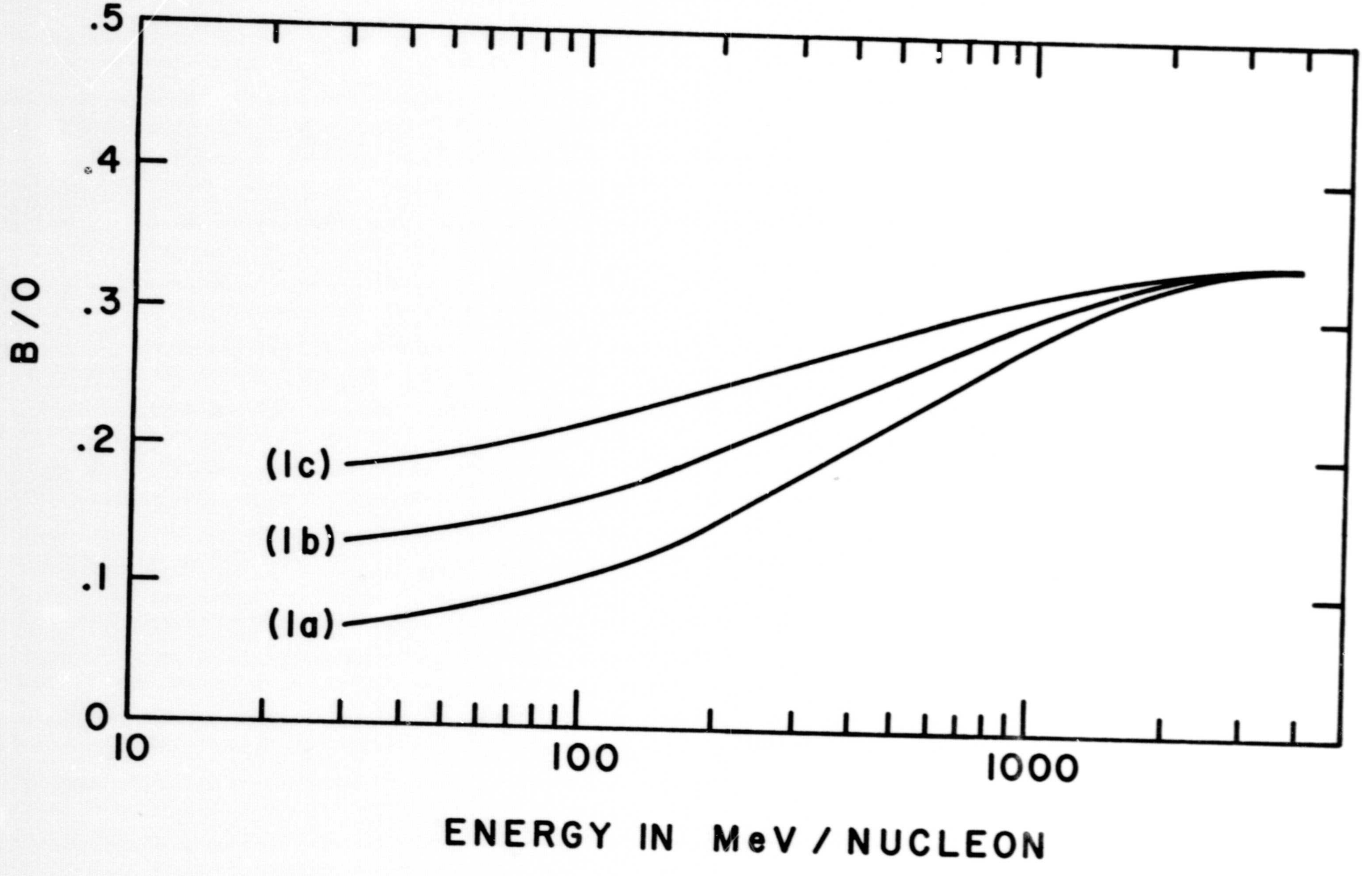
Figure Caption

Fig. 1 Cosmic ray boron to oxygen ratio calculated before solar modulation and deceleration as a function of energy per nucleon in accordance with the procedure described in the text. The curves marked (1a), (1b), and (1c) correspond to the equations designated the same way in the text.



B/O
.5
.4
.3
.2
.1
0
10
100
1000
ENERGY IN MeV / NUCLEON
(Ic)
(Ib)
(Ia)