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GALACTIC PROPAGATION OF COSMIC RAYS

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ABSTRACT

After introducing various phenomenological models of cosmic ray propagation in the galaxy, we examine how some of them fare when compared to the data. We show that a model based on resonant diffusion of cosmic rays off an interstellar spectrum of hydromagnetic waves can account for the presently available evidence on cosmic rays and the interstellar medium.

FOREWORD

Throughout this lecture, whenever possible, we refer to cosmic ray rigidities, rather than to energy per nucleon E or total energy E_t. The rigidity of a nucleus of charge Z is defined by: R = pc/eZ GV, where p = momentum, c = velocity of light, e = electron charge. The rigidity of a particle is proportional to its gyroradius r_e in the presence of a magnetic field: $R = r_e Bc$, where B is the magnetic field strength, so that the rigidity is the relevant quantity for describing the dynamics of charged particles in the presence of magnetic fields. At relativistic energies ($E >> mc^2$), for protons, R(GV) = E(GeV) = E_t(GeV). For most of the other nuclei, $A/Z \simeq 2$, and R(GV) $\simeq$ 2E(GeV/n).

In the interstellar medium, the magnetic field strength is ~ 3 μG, so that the gyroradius is $r_e \simeq 10^{12}\, R_{GV}$ cm.

PHENOMENOLOGICAL MODELS

Models of cosmic ray confinement are essentially motivated by the observed isotropy of the radiation, and by composition data. Some of the most widely discussed models are (see (1) for a more complete discussion, and list of references)

a) Closed model: cosmic rays cannot leave the galaxy; hence, they eventually loose all their energy through collisions with interstellar medium particles.

b) Leaky box model: cosmic rays are trapped within reflecting boundaries surrounding the galaxy, but here there is a finite probability of escape into extragalactic space. In the above two models, the cosmic ray density is uniform throughout the confinement volume.

c) Nested leaky box model: cosmic rays are trapped both near their sources and at the boundaries of the galaxy, with a finite probability of escape from each.

d) Diffusion models: cosmic rays leave the galaxy by diffusing through magnetic field irregularities.

e) Galactic wind models: the cosmic rays and the galactic magnetic field are continuously being convected away with gas expelled from the galaxy. (These will not be examined here.)

f) Continuous acceleration model: acceleration and nuclear interactions with ambient particles occur simultaneously in the interstellar medium.

COSMIC RAY DATA AND PROPAGATION MODELS

A. Elemental Abundances

As cosmic-ray nuclei travel through interstellar space, they suffer inelastic collisions with interstellar medium nuclei; in this way "primary" cosmic-ray nuclei emitted by sources break up into lighter "secondary" nuclei. The amount of interstellar matter traversed by cosmic rays can be estimated by measuring the abundances of certain species expected to be absent in the primary spectrum.

At energies greater than a few GeV/nucleon, the effects of solar modulation and of Coulomb interactions in the interstellar medium are negligible and the cross sections of the spallation reactions affecting the cosmic ray composition are energy-independent. In the leaky-box model, assuming an interstellar medium of pure hydrogen, the flux f_i of a species i (where i is the atomic number) is simply related to the source term Q_i (cm^{-3} s^{-1}) and the mean escape length λ_e (g cm^{-2}) through

$$f_i = \frac{Q_i/n_H m + \sum_{j>i} \sigma_{j,i} f_j/m}{(\lambda_{di})^{-1} + (\lambda_e)^{-1}} \quad (1)$$

where $\sigma_{j,i}$ is the cross section of the spallation reaction j(p,)i induced by the element j on interstellar hydrogen atoms, and λ_{di} the pathlength for nuclear destruction of nuclei i on hydrogen; λ_{di} decreases when i increases [e.g. λ_d(He) = 17 g cm^{-2}, λ_d(C) = 7 g cm^{-2}, λ_d(Fe) = 2.5 g cm^{-2}]. For purely secondary species, such as the light elements lithium, beryllium, and boron, $Q_j \equiv 0$ and the knowledge of the fluxes f_i and of the nuclear cross sections involved is sufficient to determine the mean escape length λ_e.

Several balloon measurements of cosmic ray composition at energies up to 150 GeV/n have shown that the ratio of secondary to primary abundances decreases as the energy increases (2); also, the spectra of heavy primary species are flatter than those of lighter ones (see also first lecture by W. Webber). More recently, the French-Danish spectrometer on the satellite HEAO-3 has provided extremely accurate data on the cosmic ray elemental composition from carbon to zinc (boron and beryllium abundances will become available as well) in the energy range 0.8-20 GeV/n (3).

All this data makes it possible to calculate λ_e as a function of E or R, in the leaky box model. It is important to realize that eq. (1), written for each secondary element, strongly overdetermines λ_e. It is, therefore, surprising--and quite a success for the simple leaky box formalism--that one single expression of λ_e appears to fit adequately all the available data. The procedure used by the HEAO-3-C2 investigators was first to derive $\lambda_e(R)$ from data on iron secondaries from scandium to chromium (4). They propose, for a best fit, that λ_e = 15 $R^{-0.5}$ g/cm^2 (of hydrogen), corresponding to 6.4 g/cm^2 of hydrogen at E = 2 GeV/n for nuclei with A/Z = 2. Fig. 1a and b show how this law fits the observed abundances of some iron secondaries. Subsequently, Perror <u>et</u> <u>al.</u> (5) found that the energy variations of the abundances of lighter secondary elements, such as K, Cl and F, as well as the observed primary to primary ratios, down to carbon, were also well accounted for by this simple model (figure 2a,b,c). The higher energy observations quoted earlier have a much greater dispersion than the HEAO-3-C2 observations, but they also suggest an energy dependence of the escape length $\lambda_e \propto E^{-b}$, with b in the range 0.3-0.6 (2,6). What happens at even higher energies, or rigidities, such as R $\gtrsim$ 1000 GV? The ratio of secondary to

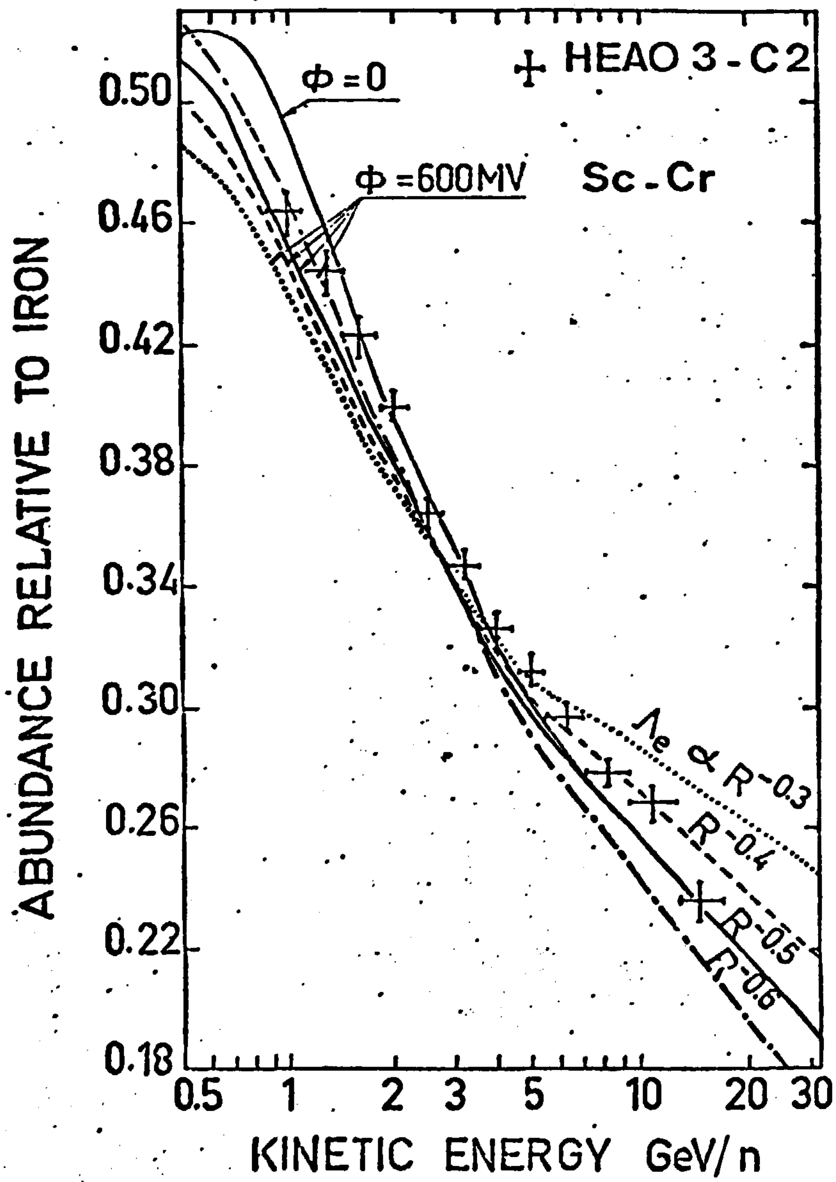


Fig. 1: (from ref. 4) Observations of the abundances of some iron secondaries by the HEAO-3 C-2 instrument. The calculated curves correspond to leaky box propagation models, with $\lambda_e \propto R^{-0.3}$ to $R^{-0.5}$. For the sake of clarity, only curves corrected for solar modulation have been shown, except in the case of $\lambda_e \propto R^{-0.5}$, for which the unmodulated abundance is also shown.

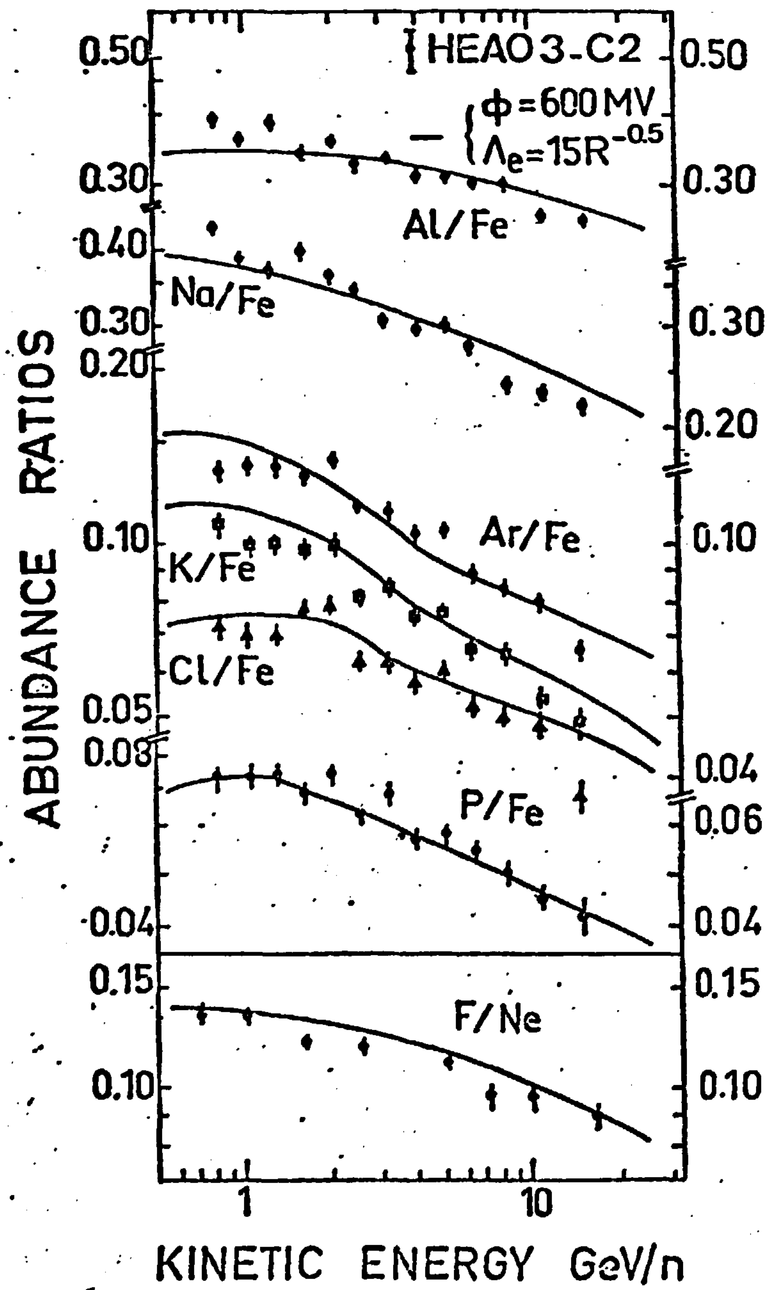
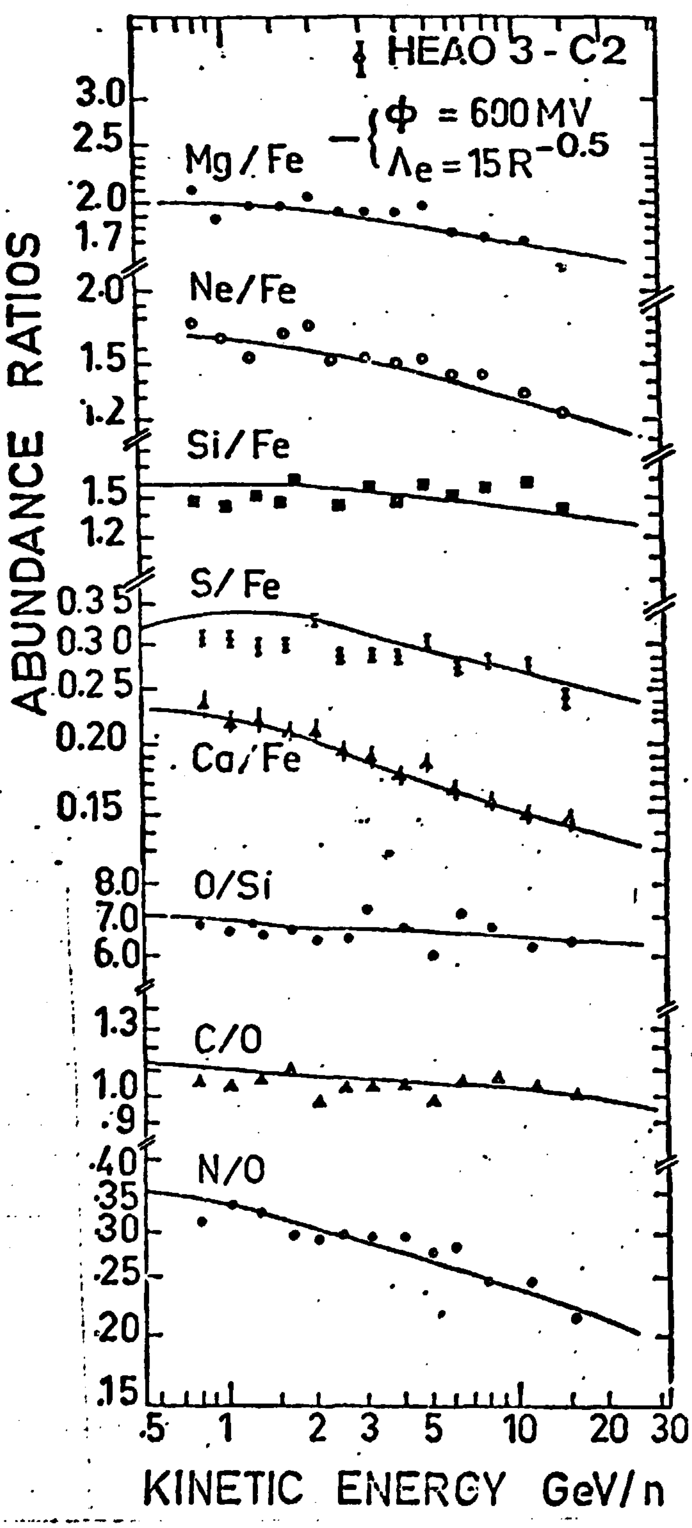


Fig. 2: (from ref. 5) Comparison of relative abundances observed by HEAO-3 C-2 and calculations in the leaky box model approximation. The calculated curves correspond to parameter values as indicated.


HEAO 3 - C2
— { Φ = 600 MV
Λe = 15 R^-0.5
Mg / Fe
Ne/Fe
Si / Fe
S / Fe
Ca / Fe
O/Si
C/O
N/O
ABUNDANCE RATIOS
KINETIC ENERGY GeV/n
.5 1 2 3 5 10 20 30
3.0 2.5 2.0 1.7
2.0 1.5 1.2
1.5 1.2
0.35 0.30 0.25 0.20 0.15
8.0 7.0 6.0
1.3 1.0 .9
.40 .35 .30 .25 .20 .15

primary element abundances have not yet been measured at such rigidities. The prediction of the leaky box model is rather stringent (6): even though the all-particle integral spectrum may show some structure at $E_t > 10^{14}$ eV (see lectures by J. Linsley), the proton differential spectrum does not appear to suffer any drastic change of slope in the $50-10^6$ GeV region. In the leaky box model, the mean confinement time of particles, τ_e, is proportional to λ_e. Neglecting nuclear losses, the cosmic ray density N is related to the source term S through $N = S\tau_e$. Under the plausible assumption that the source spectrum is a power law, $\tau_e(R)$ must also be a power law at least up to $\sim 10^6$ GV.

In the nested leaky box model (7), cosmic rays traverse an amount of matter λ_s in their sources, before pervading the galaxy, and it is the probability of escape from the source that is supposed to be energy or rigidity dependent. For $R < 150$ GV, the composition and the spectra of primaries and secondaries are essentially undistinguishable from those obtained with the energy-dependent leaky box model, but in this case the galactic proton spectrum is identical to the injection spectrum, independent of the form of $\lambda_s(R)$.

In the leaky box model, the distribution of pathlengths around the mean is exponential. In contrast, the nested leaky box model predicts a deficiency of short pathlengths. The present results of the HEAO-3-C2 experiment, together with earlier results, can be accounted for with an exponential distribution of pathlengths (4,5,8).

In most diffusion models, the elemental composition of cosmic rays is also determined almost exclusively by one parameter, λ_e, related to the amount of matter traversed by the particles before escape; in general, λ_e is inversely proportional to the diffusion coefficient K (in one-dimensional models, or in three-dimensional models with scalar diffusion) or to the component of the diffusion tensor perpendicular to the galactic plane. The constant of proportionality contains all the information on the distribution of the sources and on the boundaries of the containment region. For instance, let us consider one-dimensional models, where the cosmic ray sources are embedded in the gas disk of uniform density n_o and of height h; cosmic rays diffuse outwards through a halo of height $H \gg h$(9). The diffusion coefficient K is assumed to be constant in space. Then K is related to the mean escape length λ_e, calculated with the leaky box formula (1) by:

$$K = (n_o H h v m)/\lambda_e. \qquad (2)$$

In terms of diffusion models, then, the elemental composition of cosmic rays can be interpreted as implying that either $K \propto vR^{0.5}$

(my preferred explanation), or that the size of the confinement region decreases with R: $H \propto R^{-0.5}$.

In the original closed model (10), cosmic ray sources do not emit protons. Of all the nuclei received at the earth, 15% would originate from a nearby source, and the rest, which is composed mostly of protons, then must be a very old population. This model cannot fit adequately the cosmic ray composition at a few GeV, nor explain the energy-dependent composition. A modified version was proposed by Peters and Westergaard (11) where cosmic rays are generated in galactic arms and trapped by them in an energy-dependent way. Since they assume the sun to be inside a spiral arm, cosmic ray observations at energies less than 1000 GeV would not distinguish between this model and the leaky box model; at very high energies this modified closed model predicts a much higher proportion of secondary nuclei. This model also makes a distinctive prediction on the particle spectrum. If the injection spectrum is proportional to $R^{-\alpha}$, the low energy spectrum, dominated by young particles, has a slope of $-(\alpha + 0.5)$, as in the leaky box model. But at high energies ($E \gtrsim 10^3$ GeV for protons), the old population dominates, and the spectral index tends to decrease to α. So, if the injection spectrum is a power law, the model predicts a gradual flattening of the proton spectrum as the energy increases, while the observed spectrum tends to steepen in the energy range 10-1000 GeV. But this is not a strong test of the theory, because the injection spectrum may deviate from a power law.

All the models discussed in this section assume that the only energy changes that cosmic rays undergo between production and detection are ionization losses in the interstellar medium, and adiabatic losses during solar modulation. If cosmic rays are accelerated (or decelerated) by some additional mechanism while propagating, secondary particles get transferred to higher (lower) energies, and the (secondary/primary) profile as a function of energy is altered (e.g. 12). The fact that the data is well explained by a simple, constant energy theory, probably indicates that re-acceleration or deceleration is only a minor effect.

B. Radioactive Secondary Nuclei

Measurements of the abundances of unstable secondary nuclei, such as ^{10}Be (with a decay period at rest of $\tau_d = 2.2 \times 10^6$ yr), ^{26}Al ($\tau_d = 0.85 \times 10^6$ yr), and ^{36}Cl ($\tau_d = 0.45 \times 10^6$ yr), can bring some information on the mean age of cosmic rays, and/or help to determine the parameters characterizing the different models. [Another interesting candidate is ^{54}Mn. In the laboratory, it decays by electron capture, with a half-life of 312 days. In space, it may undergo beta decay, as suggested by

Cassé (17), who estimated a partial half-life of 2×10^6 yr. HEAO-3-C2 has found that the spectrum of Mn is flatter than that of the other iron secondaries; we may be observing there the effects of relativistic time dilation (3,4). To be sure, we ought to know with more precision some of the cross sections involved in the propagation calculation, and/or the β decay time of ^{54}Mn, and/or the isotopic composition of Fe and Mn.]

In the framework of the leaky box model, such measurements, combined with the determination of λ_e through the elemental composition, permit us in principle to estimate the mean escape time of cosmic rays and the mean gas density in the box. However, because most measurements are done at low energies, solar modulation again complicates the interpretation of the data. Assuming that λ_e is energy independent, and using their own estimates of solar modulation effects, Garcia-Muñoz et al. (13) derive from their data at 30-150 MeV/n a mean age of $17\ (+24,-8) \times 10^6$ yr, and a mean density $\langle n_H \rangle = 0.18\ (+0.18,-0.11)\ cm^{-3}$. Wiedenbeck and Greiner (14) deduce from their satellite data at 60-185 MeV/n a confinement time of $8.4\ (+4.0,-2.4) \times 10^6$ yr, and a mean density $\langle n_H \rangle = 0.33\ (+0.13,-0.11)\ cm^{-3}$. Since, in the solar neighborhood, the interstellar density (averaged over ~ 1 kpc in the disk) is estimated at 1-2 cm^{-3}, these results are generally interpreted as implying that galactic cosmic rays circulate in a low density halo which is at least 3 times wider than the disk.

In diffusion models with a halo, radioactive isotopes formed in the disk often decay while passing through the halo. In that case, the average confinement time of particles in the galaxy may be much larger than the observed "mean age" (15,9). For instance, in the one-dimensional model described earlier, the abundances of secondary radioactive elements are determined by two combinations of parameters: $(n_o T)$ and (H/h). In principle, observations of the energy dependence of the abundance of isotopes of mean life at rest of ~ 10^6 years, at energies > 1 GeV/n, should help constraining these parameters (e.g. 16).

The relative abundances of radioactive isotopes are greatly affected by continuous acceleration (12,16). The prediction of leaky box models or diffusion models with sudden acceleration, especially when the escape time is energy dependent, is that at high energies the unstable isotopes do not have time to decay, and behave like stable isotopes. If acceleration and propagation occur simultaneously, the particles have a chance to decay while their energy is low, so that a substantial population of decayed particles is transferred to high energies. Let us consider a simple case, where a primary species p gives rise to two secondary species of similar mass: stable secondary s and unstable secondary r. It can be shown that, whether the particles are all injected at an energy E_o or are initially distributed in the power

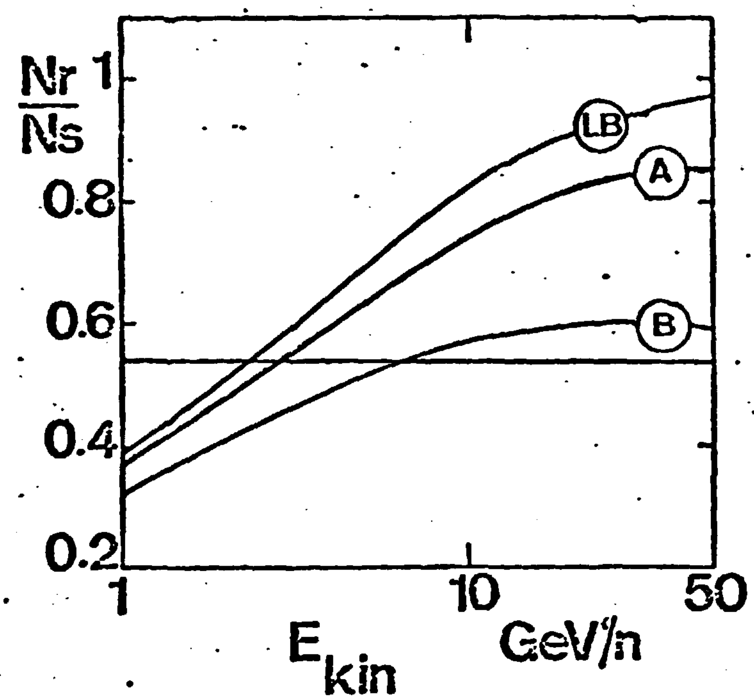


Fig. 3: (from ref. 16) Schematic diagram of the ratio of the abundances of a radioactive isotope of decay time ≈ 1 Myr, and a stable isotope of similar mass as a function of kinetic energy. (LB): leaky box model; (A): reacceleration model with t_r/t_e (1 GeV/n) = 1; (B): model with $t_r/\langle t_e\rangle = 0.1$. The horizontal line is the high-energy limit. The ratio (N_r/N_s) is normalized to the production ratio (σ_{pr}/σ_{ps}).

law characteristic of thé acceleration (and re-acceleration) mechanism, the ratio of the abundances of the radioactive to the stable secondary nuclei is

$$\frac{n_r}{n_s} = \frac{\langle 1/t_e\rangle + 1/t_d}{\langle 1/t_e\rangle + \langle 1/T'\rangle + 1/t_d} \cdot \frac{\sigma_{pr}}{\sigma_{ps}} \qquad (3)$$

where σ_{pr} and σ_{ps} are the spallation cross-sections for formation of these nuclei from the primary nuclei p; (t_d) is the nuclear destruction time (similar for the nuclei p, s and r); T' the life time of the radioactive nucleus r ($T' = T/\ln 2$), and the averages are taken over energy. The energy at which this limit is attained depends on the relative values of t_e, T, t_d and t_r; it is mostly sensitive to the ratio (t_r/t_e), and varies monotonically with it.

C. Electron Spectrum

According to several recent measurements, the electron spectrum is parallel to the proton spectrum in the energy range 2-10 GeV; in this range, the electron flux amounts to ~ 1% of the proton flux. At higher energies, the spectrum steepens to an index greater than 3, and possibly as large as 3.4 at several hundred GeV; however, in some cases the discrepancies between different sets of results are still large (18). A steepening of the high energy spectrum is expected, since the lifetime of a 30 GeV electron against radiation losses in the interstellar medium is ~ 10^7 years.

The observed electron spectrum does not impose strong constraints on the models proposed to explain the cosmic ray composition. It is important to remember that the equations describing the behavior and the energy changes of electrons diffusing through the interstellar medium cannot be approximated by results obtained using the leaky box model. In diffusion models, the distribution of the sources plays an important, or even a predominant role. In addition, the injection spectrum of electrons is not known, and can generally be adjusted to ensure that a given model fits the data.

D. Anti-Protons

Secondary anti-protons are generated in the inelastic conditions between high-energy nuclear cosmic rays and interstellar medium particles (19). The flux of galactic anti-protons has been measured recently by Golden et al. (20), by Bogomolov et al. (21) and by Buffington et al. (22) at various energies (fig. 4). The $\bar{p}$ flux observed is significantly higher than predicted by the leaky box model, especially if the escape length is energy dependent (23). The energy dependent nested leaky box model would predict an even lower flux at high energies (24,25). Roughly, at high energies, the equivalent of equation (1) for anti-protons is:

$$\bar{j}(\bar{E})/j(\bar{E}) = a(\bar{E})/[1/\lambda_e(\bar{E}) + 1/\bar{\lambda}(\bar{E})] \quad (4)$$

where $a(\bar{E})$ is the production function for anti-protons, per gram of material traversed and per unit flux of protons. Using values for λ_e derived earlier, this formula predicts a flux of anti-protons four times below the observed one in the energy range 4-12 GeV. Obviously, the highest anti-proton flux predicted by any uniform model is that of the closed model, where $\lambda_e = \infty$. Then, the yield of formula (4) is twice the observed value.

Even higher $(\bar{p}/p)$ ratios can be obtained if the hypothesis

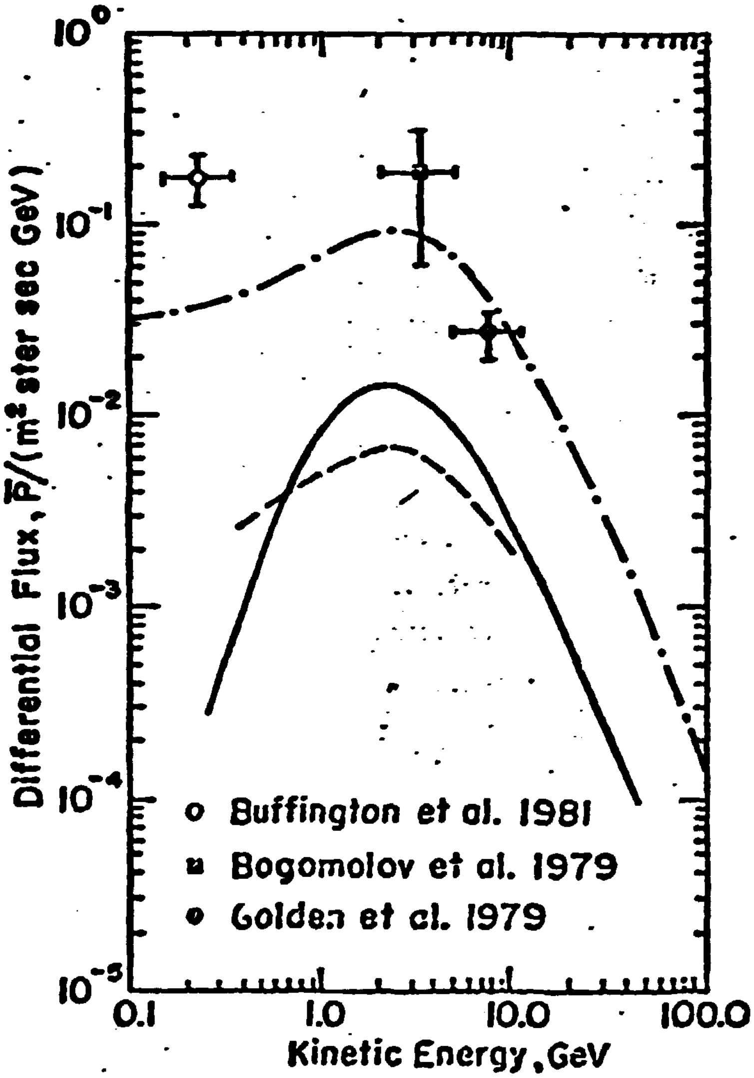


Fig. 4: Summary of measurements and some calculations of the flux of cosmic ray antiprotons. The solid and dashed curves are from ref. (23a), with no solar modulation, and with maximum modulation. The dashed-dot line is a calculation in a closed galaxy model (ref. 26).

of uniformity is dropped. Consider cosmic rays that have to traverse a slab of matter, X g/cm^2 thick, between their source and the interstellar medium. Then,

$$\bar{j}/j = a\bar{\lambda}[\exp(X/\bar{\lambda}) - 1] \quad (5)$$

and can grow without limits. However, if the layer is too thick, protons and anti-protons get considerably depleted. For $X = 50$ g/cm^2, about half of the protons are lost, and the ratio $\bar{p}/p$ is about 5 times above the value obtained by Golden et al. (27).

Thus, two explanations emerge for the high energy point in figure 4: i) adopt the modified closed model, with about 50% of the protons being part of an old, hopelessly trapped population (25,26), but the ratio old/young population required is too high to account for the observed secondary/primary ratios (11); ii) assume that 40% of cosmic ray sources are embedded in dense clouds, so that the corresponding cosmic rays traverse ~ 40 g/cm^2 close to their source. The second explanation, which does not conflict with the usual interpretation of the secondary/primary ratios, also accounts for the gamma ray sources observed by COS B (27,28).

The huge discrepancy between the low energy observation and the predictions of the leaky box model in figure 4 is reduced in the above two models, because when traversing large grammages, anti-protons produced at high energies are shifted to low energies (26,29); this effect is particularly important in the modified closed model. Solar modulation also helps. But, after these corrections, the predicted flux remains too low by a factor > 10 (figure 4). If the observation by Buffington et al. is confirmed, we may have to change considerably the models for cosmic ray propagation, or admit that some cosmic ray anti-protons are actually primary particles.

E. Anisotropy

If the cosmic ray confinement time in the galaxy, or in the local arm, decreases as the energy increases, one expects the cosmic ray anisotropy to increase with energy. The simplest interpretation of the most recent data on the cosmic ray sidereal anisotropy (30) is that, at the sun, cosmic rays in the rigidity range $5 \times 10^{11} - 10^{14}$ GV are all streaming at about the same velocity, ~ 35 km/s. It may be that, in fact, the observed anisotropy is caused by an asymetry in the distribution of cosmic ray sources, which "cover up" the smaller anisotropy related to cosmic ray escape (31).

COSMIC RAY DIFFUSION AND INTERSTELLAR TURBULENCE SPECTRUM

What may cause cosmic rays to diffuse in interstellar space? Fermi (32) had pointed out that large scale ($\gg r_e$), moving inhomogeneities in the magnetic field reflect particles of large pitch angle; this process can lead to both diffusion and acceleration of cosmic rays. But the Fermi acceleration model has difficulties in satisfying the energy requirements, and in explaining the observed abundances of secondary nuclei. In the last ten to fifteen years, the work on cosmic ray propagation has mostly concentrated on another process: resonant scattering of cosmic rays by hydromagnetic waves whose scales are comparable to their radius of gyration (33). This scattering leads to cosmic ray diffusion along the magnetic field lines; there is some energy exchange between cosmic rays and h.m. waves, but only to higher order in v_A/c, where v_A is the Alfven velocity, $(B/\sqrt{4\pi\rho}) \sim$ tens of km/sec.

Let us define F(k) as the the energy density in hydromagnetic waves per logarithmic bandwidth d(log k), relative to the ambient magnetic energy density $(B^2/8\pi)$. Then, in the framework of the quasi-linear theory (applicable if $F \ll 1$), the diffusion coefficient along field lines of particles of rigidity R and velocity v is given by:

$$K(R) = \frac{4}{3\pi} \frac{R/Bc}{F(k = 1/r_e = Bc/R)} . \qquad (4)$$

The spectrum of hydromagnetic turbulence F(k) in the interstellar medium is extremely difficult to determine. Various methods exist that can lead to estimates or upper limits of the density spectrum of irregularities in the distribution of thermal electrons. Presently available results have been compiled by Armstrong et al. (34). These authors conclude that the data is consistent with a power law spectrum of fluctuations, with an index of -3.6 ± 0.2 (fig. 5). If the hydromagnetic spectrum had the same slope, this would be equivalent to $F(k) \propto k^{-0.6\pm0.2}$.

A spectrum of this type may be the result of a cascade of turbulent energy in the interstellar medium, from long scales to successively shorter scales; the turbulence at long scales is fed by cloud motions, which in turn are regenerated by supernova explosions. Kraichnan (35) has argued that a cascade in an incompressible, weakly turbulent magnetized fluid, leads to a spectrum $F(k) \propto k^{-0.5}$. Such a cascade is energetically feasible in the hot phase ($T \sim 10^6$ °K, $n \sim 10^{-3}$ cm^{-3}) of the interstellar medium (1,36). If $F \propto k^{-0.5}$ there, then we see from the formula (4) that the cosmic ray diffusion coefficient $K \propto vR^{0.5}$, this is just the dependence required to account for the observed

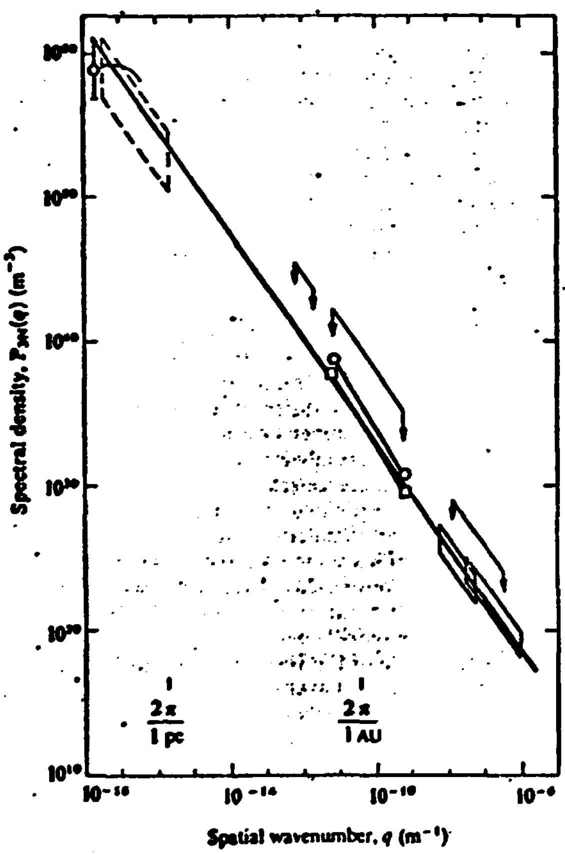


Fig. 5: (from ref. 34) Density power spectrum in the local interstellar medium. Estimates and upper limits at the various scales are shown. The line through the data has a logarithmic slope of (-11/3).

variations of the ratios of secondary to primary nuclei with energy. Thus, the present observations are well accounted for by a model where cosmic rays are scattered by resonant hydromagnetic waves related to the general interstellar turbulence, and diffuse in a region much wider than the disk of the galaxy.

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