N87-24257

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ORIGIN AND PROPAGATION OF GALACTIC COSMIC RAYS

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1. INTRODUCTION

In the few years following the launch of HEAO-C with its two large cosmic ray experiments on board, we have seen significant progress made in our understanding of the origin of energetic particles in the galaxy. This progress was made with large, high resolution instruments above the atmosphere for extended periods. It was Frank McDonald's foresight which led to the initiation of the HEAO project and his energy which helped to lead it to a successful conclusion. It is fitting that on the occasion of Frank's sixtieth birthday we should review our understanding of the problems associated with the origin of cosmic rays, problems which have been so central to his scientific interests and to the solution of which he has contributed so much. These contributions have come not only through his own scientific work, but also through his tireless efforts in promoting space flight opportunities and in the development of new scientific talent. This is evidenced by the range of papers in this volume, and by the impact of the HEAO satellites and their experiments on the discipline of high energy astrophysics. In particular, the role played by

HEAO-3 and the Danish-French experiment in furthering our understanding of cosmic rays will be evident in this paper. C. J. Cesarsky introduced the oral presentation of this paper as follows:

> I started working on cosmic rays in 1969. By then, Frank McDonald was already famous, and I was of course very intimidated to meet him at my first colloquium, which was at Goddard in 1971. I was surprised to find that this man was so unassuming and easy to talk to. Over the years, with scientific meetings, and his frequent trips to France where I had located, a friendship developed, based on common interests: cosmic rays, space experiments, good food, and art. So it is a great pleasure to be here on this occasion.

Heavy elements in the galactic cosmic rays were discovered almost forty years ago now [Freier et al., 1948; Bradt and Peters, 1948], and a large number of balloon and satellite observations have been made in the succeeding years. It is rather remarkable that most of these observations can be understood in the framework of a rather simple theory. It is based on the minimum assumption that there is one type of source and one confinement region in which particles are contained by one mechanism. It also assumes that all species, namely electrons, protons, helium, and the heavier elements which we observe are a consequence of the same processes. We will see that recent observations are making this point of view more and more difficult to maintain. This should come as no surprise. For the first time we have highly accurate data—in some cases the principle errors are coming from uncertainties in cross-sections rather than from the cosmic ray data itself. As the level of detail in our observations increases, in effect we are observing the phenomena in "higher and higher resolution". In fact the remarkable thing is the large number of observations which are understood from the perspective of this simple theory.

The Danish-French experiment on HEAO-3 has provided us with our first detailed observations outside the Earth's magnetosphere of particles above 1 GeV/amu. These observations have shaken the simplest interpretations so that we probably cannot even claim to know the spectrum which is produced by the acceleration mechanism(s), much less to understand the mechanism(s).

An accompanying paper [Binns et al., 1987, this volume] discusses the elemental and isotopic abundances and what they can tell us about the mechanisms for nucleogenesis of cosmic rays and the sites in which they reside before acceleration. Much new has been learned here too, but there are many gaps. The mechanism by which the galaxy is able to concentrate so much of its energy resources in so few of its constituents is the problem of the acceleration mechanism. The future will see it approached not only by working our way backward from the observations, but also by working our way forward from what we know about the sites and mechanisms of nucleosynthesis.

This paper will discuss the observations and their interpretation in context of the physical processes involved. Suggestions for future observations which can be used to attempt to resolve the outstanding questions will form the conclusion.

2. GENERAL BACKGROUND

Energetic particles are ubiquitous in astrophysical plasmas. We see them in the solar system as a result of plasma processes wherever there are motions and magnetic fields. They are accelerated in the magnetospheres of the Earth and Jupiter. They are accelerated by the Sun in magnetic fields associated with solar flares. We see synchrotron radiation which tells us that electrons, and by implication nuclei, are being accelerated in supernova remnants, in pulsar magnetospheres, and in quasars. At the same time we observe particles at Earth which are extremely homogeneous in space and time, apparently coming to us from the galaxy at large.

Historically there have been a number of ideas about the site(s) in which the acceleration of cosmic rays takes place: in the galactic magnetic fields, in supernova remnants, in pulsar magnetospheres, etc., but neither the site nor the acceleration mechanism is well understood. Much theoretical work has been done recently on shock acceleration mechanisms, and examples of shock acceleration are known to be at work in the solar system where they can be studied in situ, but whether these mechanisms can operate on a scale sufficient to account for the galactic cosmic rays is still uncertain. More theoretical work is needed on the transport of particles on a galactic scale. The mechanism must be continuous over at least five or six orders of magnitude, from GeV energies to perhaps 100 or 1000 TeV.

On the other hand objects such as Cygnus X-3 are apparently producing air showers initiated by gamma rays of 1 to 1000 or more TeV energy. There is sufficient power available from this source to fill the galaxy with cosmic rays of 100 TeV or more. Accretion disks and binary stellar systems may be able to accelerate particles too. Any environment involving magnetic fields and motion is a candidate. It may be that a number of different processes accelerate particles which become the cosmic rays observed at Earth.

At energies of 100 TeV and above the cosmic ray air showers are isotropic to a few parts in 10^4 as shown in Figure 1. This implies that the particles are confined in a large column and that particles are not streaming past the solar system at velocities more than a few tens of km/sec. From the radio continuum observations, we know that cosmic ray electrons are present over much of the galaxy and extend beyond the galactic disk into a halo above and below the disk. The radio map of NGC891, an edge on galaxy seen at 21 cm, is shown in Figure 2 superposed on a photograph from the 200-inch telescope from Allen, Baldwin, and Sancisi, 1978. This intensity profile is similar to that which an extragalactic radio astronomer would see if observation were made of our galaxy from a similar perspective. Cosmogenic nucleides in meteorites, nuclei which have been transformed through the bombardment by energetic cosmic ray nuclei during their exposure in space, can be used to estimate the average flux of cosmic rays over their exposure history. This has been done over time scales of 400, 9×10^5, and 10^9 years. These results say that, within a factor of 2, the cosmic ray intensity has been constant over the last billion years. There is some indication that it may have been a factor of two lower on the 10^9 year time scale, and periodic fluctuations of larger amplitude cannot be ruled out. Most of the particles responsible were in the energy range .3 to 3 GeV/amu, so changes in the slope of the well-known observed power law spectrum cannot be ruled out by these observations either.

These considerations led Ginzburg and Syrovatskii [1964] to posit that the galaxy was filled with energetic particles accelerated within the galaxy which

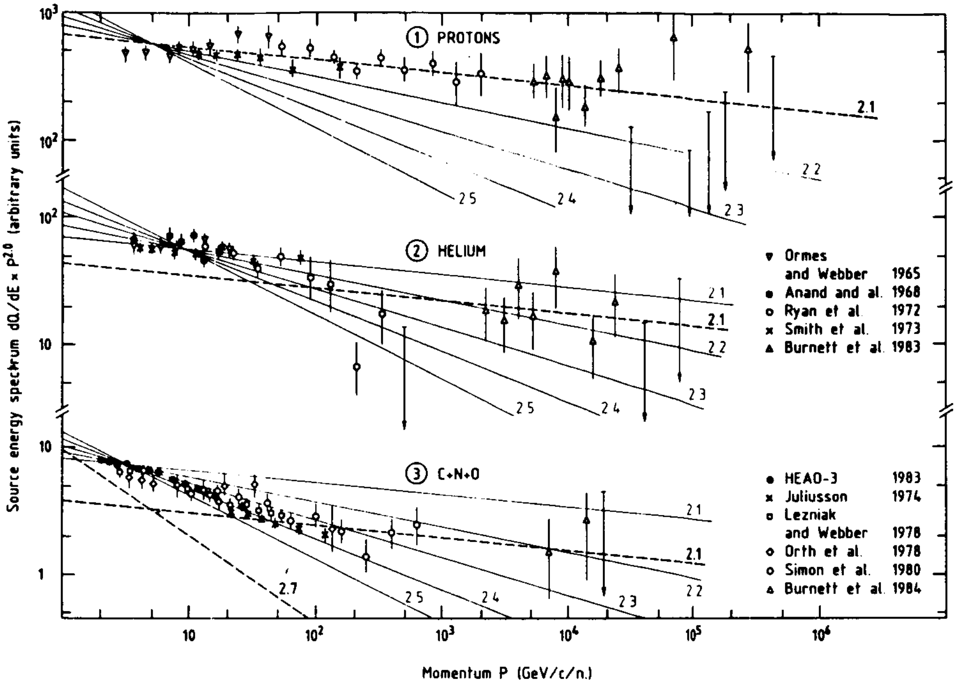

Figure 1. The observed anisotropy is shown as a function of energy. A Compton Getting anisotropy corresponding to a streaming velocity of 20 km/sec is indicated as is the anisotropy which would be expected from a diffusion coefficient varying as the square root of rigidity [from Ormes, 1983, adapted from Hillas, 1984].

diffuse throughout the galactic magnetic fields, thereby remaining trapped for times which are long compared to their straight line travel times across the galaxy. The low anisotropy led them to propose that the galaxy had a halo of turbulent plasma and magnetic fields which acted as the containment volume for cosmic rays. As a result, a steady-state picture arose in which cosmic rays are produced at a given rate and are lost at a given rate, leaving the galaxy

Figure 2. A radio continuum map of the edge on Spiral galaxy NGC891 from the Westerbork Synthesis Radio Telescope at 21.2 cm (1412 MHz) from Allen, Baldwin, and Sancisi, 1978. The contours are shown superposed on a photograph from the 200-inch Palomar telescope courtesy of Hale Observatories.

with a constant or nearly constant density (and intensity) of energetic particles over its lifetime. This led to the phenomenological model we refer to as the "leaky-box" model:

$$Q + \text{spallation} = \text{escape} + \text{interaction} + \text{decay}$$

where the steady injection of particles from sources and the spallation of heavier nuclei to lighter ones is balanced by the loss of particles from the galaxy or their loss due to interaction or decay.

a. The "Leaky-Box" Model

As cosmic ray nuclei spiral through interstellar space, they suffer inelastic collisions with interstellar gas and the "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 species expected to be rare in the source abundance spectrum. The most prominent of these are lithium, beryllium, and boron, created primarily by the fragmentation of carbon and oxygen nuclei, and the nuclei with atomic numbers 21 to 25, the so-called sub-iron nuclei.

At energies greater than a few GeV/amu, 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 nearly energy-independent.

Assuming the interstellar gas consists only of hydrogen, and that the energy is high enough (greater than ~ 10 GeV/amu) so ionization losses can be neglected, the flux f_i of a species i (where i is the atomic number) is simply related to the source term $Q_i(\mathrm{cm}^{-3}\mathrm{s}^{-1})$ and the mean escape length $\lambda_e(\mathrm{g\ cm}^{-2})$ through

$$\frac{f_i}{\lambda_{eff}} = \frac{Q_i}{mn_H} + \sum_j \delta_{i,j} \frac{f_j}{m} \qquad (1)$$

$$\text{where } \frac{1}{\lambda_{eff}} = \frac{1}{\lambda_i} + \frac{1}{\lambda_e} + \frac{1}{\rho\beta C\tau_i}.$$

λ_i are the nuclear destruction lengths for species i due to interactions on interstellar material, τ_i is the decay lifetime for radioactive species ($=\infty$ for stable nuclei), ρ is the mean density in the storage column, and $\delta_{i,j}$ is the cross-section for producing nucleus i from nucleus j (λ_i decreases when i increases, e.g., $\lambda_{He} = 17$ g cm^{-2}, $\lambda_C = 7$ g cm^{-2}, $\lambda_{Fe} = 2.5$ g cm^{-2}).

For purely secondary species, such as the light elements lithium, beryllium, and boron, $Q_i = 0$ and the knowledge of the flux f_i and of the nuclear cross-sections involved is sufficient to determine the mean escape length λ_e; it is found to decrease as energy, or rigidity, increases: $\lambda_e \propto R^{-0.6\pm0.1}$, as we will detail later. [Juliusson, Meyer, and Muller, 1972; Smith et al., 1973; Ormes and Protheroe, 1983; and Koch-Miramond et al., 1983]. (Rigidity is defined as the momentum per unit charge: $R = pc/eZ$).

As discrepancies are found between this simple picture and data, additional parameters are added to the phenomenological models to maintain agreement and improve understanding. One of the more widely used of these is the nested leaky-box model, really a two parameter leaky-box. In the original version of the nested leaky-box model [Cowsik and Wilson, 1973; Meneguzzi, 1973], cosmic rays are trapped both near their sources and at the boundaries of the galaxy, with a finite probability of escape from each. The assumption made by these authors is that λ_s, the pathlength traversed in the sources, but not that near the galactic boundary, is rigidity-dependent. 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, no matter what form $\lambda_s(R)$ has.

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. At high energy (E>1.5 GeV/amu), results of the HEAO3-C2 experiment, together with earlier results, can be accounted for with an exponential distribution of pathlengths [Protheroe, Ormes, and Comstock, 1981; Koch-Miramond et al., 1983]; however, lower energy data may require a truncation of the path length distribution [Garcia-Munoz et al., 1984].

b. Cosmic Ray Diffusion and Interstellar Turbulence Spectrum

It can be shown that the leaky-box model is equivalent to a diffusion model with a halo, provided the characteristic dimension of the storage volume is significantly larger than the galactic disk where the particles are presumably accelerated.

In most diffusion models, the elemental composition of cosmic rays is 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 κ (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_0 and of height h; cosmic rays of velocity v diffuse outward through a halo of height H >> h [Ginzburg, Khazan, and Ptuskin, 1980]. The diffusion coefficient κ is assumed (probably incorrectly) to be constant in space. Then κ is related to the mean escape length λ_e, calculated with the leaky-box Formula (1) by:

$$\kappa = (n_0 Hhvm)/\lambda_e. \tag{2}$$

In terms of diffusion models, variations of the elemental composition of cosmic rays could be interpreted as implying that either κ or the size of the confinement region varies with particle energy (rigidity).

The biggest uncertainty is what to assume for one size of the halo. Using H = 6 kpc and taking n = 0.5 atoms/cm^3 and λ_e = 7 g/cm^2 (the value at about 1 GeV/amu) gives a diffusion coefficient $\kappa = 10^{28}$ cm^2/sec. Assuming that the particle transport is diffusive, what is responsible for the interactions which scatter the particles so effectively? Fermi [1949] has pointed out that moving inhomogeneities with a scale larger than the particles gyroradius in the magnetic field reflect particles of large pitch angle. This scattering process can lead to both diffusion and acceleration of cosmic rays. But the Fermi acceleration mechanism 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 [Wentzel, 1974, and references therein]. This scattering leads to cosmic ray diffusion along the magnetic field lines; there is some energy exchange between cosmic rays and the hydromagnetic waves, but only to higher order in v_A/c, where $v_A = (B^2 4\pi\rho^*)^{1/2} \sim$ is the Alfvén velocity, where ρ^* is the density of ionized matter. The Alfvén velocity is in the range of tens of km/sec.

Let us define F(k) as 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 $F << 1$), the diffusion coefficient along field lines of particles of rigidity R and velocity v is given by:

$$\kappa\,(R) = \frac{4}{3\pi}\,\frac{v\,R/Bc}{F(k = r_e^{-1})}, \text{ where } r_e = \frac{R}{Bc}. \qquad (3)$$

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, Cordes, and Rickett, [1981]. These authors conclude that the data are consistent with a power law spectrum of fluctuations, with an index of -3.6 ± 0.2. If the hydromagnetic wave spectrum had the same slope, this would be equivalent to:

$$F(k)\ \alpha\ k^{-0.6 \pm 0.2}. \qquad (4)$$

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 [1965] has argued that a cascade in an incompressible, weakly turbulent magnetized fluid, leads to a spectrum F(k)

$\alpha\ k^{-0.5}$. 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. If $F\ \alpha\ k^{-0.5}$ there, then we see from the Formula (3) that the cosmic ray diffusion coefficient is $\kappa\ \alpha\ vR^{0.5}$; this is very close to the dependence required to account for the observed variations of the ratio of secondary to primary nuclei with energy. Thus, the present observations of elements heavier than He, at energies lower than ~ 1000 GeV/amu, are well accounted for by a model where cosmic rays are scattered by resonant hydromagnetic waves related to the general interstellar turbulence [Cesarsky, 1975, 1980].

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., Fransson and Epstein, 1980; Silberberg et al., 1983; and Simon, Heinrich, and Mathis, 1986]. The fact that the data at rigidities above a few GV are well explained by a variety of models indicates that new discriminators must be found to determine whether re-acceleration or deceleration is an important effect.

3. OBSERVATIONS OF COSMIC RAYS

With this theoretical picture in mind, let us turn to the observations made at Earth on the cosmic rays themselves.

Calorimetric and emulsion chamber devices have now measured [Grigorov, et al., 1971; Ryan, Ormes, and Balasubrahmanyan, 1972; and Burnett et al., 1983] the proton spectrum up to 100 TeV directly, and find that it obeys a power law $dN/dE = kE^{-\gamma}$ with $\gamma = 2.7 \pm 0.1$. There is no evidence of, but rather poor limits on, possible structure in the form of bumps, wiggles, or bends in the spectrum. This data is summarized in Figure 3. The proton differential spectrum does not appear to suffer any drastic change of slope between 10 and 10^6 GeV. The significance of these proton observations—the most abundant species of cosmic ray—is that the lack of structure implies

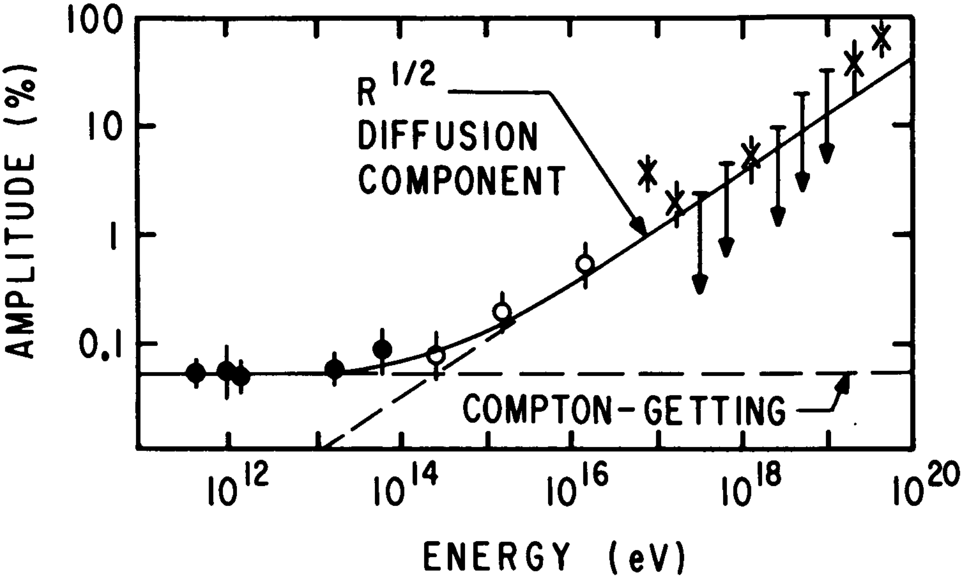

Figure 3. Direct measurements of cosmic ray spectra between 10 – 10^6 GeV as a function of total energy per nucleus. Measurements of the primary proton and helium spectrum are shown. The total particle spectrum is also shown [from Webber, 1983].

the mechanism(s) responsible for determining the shape of the proton spectrum is (are) continuous over this very large energy range.

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 f is related to the source term Q through $f_i = Q\tau_e$. 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 ~ 10^6 GV. This is a severe constraint on acceleration and propagation models as these two processes are presumably responsible for determining this spectral shape.

Several balloon measurements of cosmic ray composition at energies up to 150 GeV/amu have shown that the ratio of secondary to primary abundances decreases as the energy increases [Juliusson, Meyer, and Muller, 1972; Ormes and Freier, 1978, and references therein]; also, the observed spectra of heavy primary species are flatter than those of lighter ones. More recently, the French-Danish spectrometer (C2) on the satellite HEAO-3 has provided extremely accurate data on the cosmic ray elemental composition from boron to zinc in the energy range 0.8-25 GeV/amu [Koch-Miramond, 1981].

Using these data, Formula (1) makes it possible to calculate λ_e as a function of R, at least in the context of the leaky-box model. Koch-Miramond et al. [1983] have corrected the low energy part of their data for the effects of solar modulation, assuming a modulation parameter $\phi = 600$ MV, which is appropriate for the time in the solar cycle at which the measurements were made. They find that, at R>5.5 GV, and escape length $\lambda_e = 22\ R^{-0.6}$g/cm^2 of pure hydrogen accounts for the secondaries of C, O, and Fe. Ormes and Protheroe [1983] obtained a similar result. These analyses are limited by knowledge of cross-sections rather than by statistical uncertainties.

Many of the cross-sections have now been (or are currently being) measured and the resulting escape length is shown in Figure 4. Note its decrease with increasing energy, implying that the higher the energy, the more easily particles can escape the storage region. We now have confirmation that this decrease continues beyond a hundred GeV/amu. The data from the HEAO-C ultraheavy experiment were presented recently [Jones et al., 1985]. This experiment contained a complement of large area detectors designed to identify trans-iron nuclei. It had excellent statistics and could study nuclei heavier than calcium. Taking advantage of the relativistic rise of signals in the ionization chambers of their instrument, they obtained results on the abundances of several elements from 10 GeV/amu up to an energy > 100 GeV/amu. Their results are consistent with those of the French-Danish group in the range (10-25 GeV/amu) where both experiments apply; at higher energies, the HEAO3-C3 data indicate that the power law dependence with energy of the ratios (iron secondaries/iron) derived by the HEAO3-C2 data extends to about 100 GeV/amu, or rigidities of about 200 GV.

Streitmatter et al. [1985] reported that the iron spectrum itself has a slope of 2.65 in the energy range beyond 50 GeV/amu as expected in the leaky-box

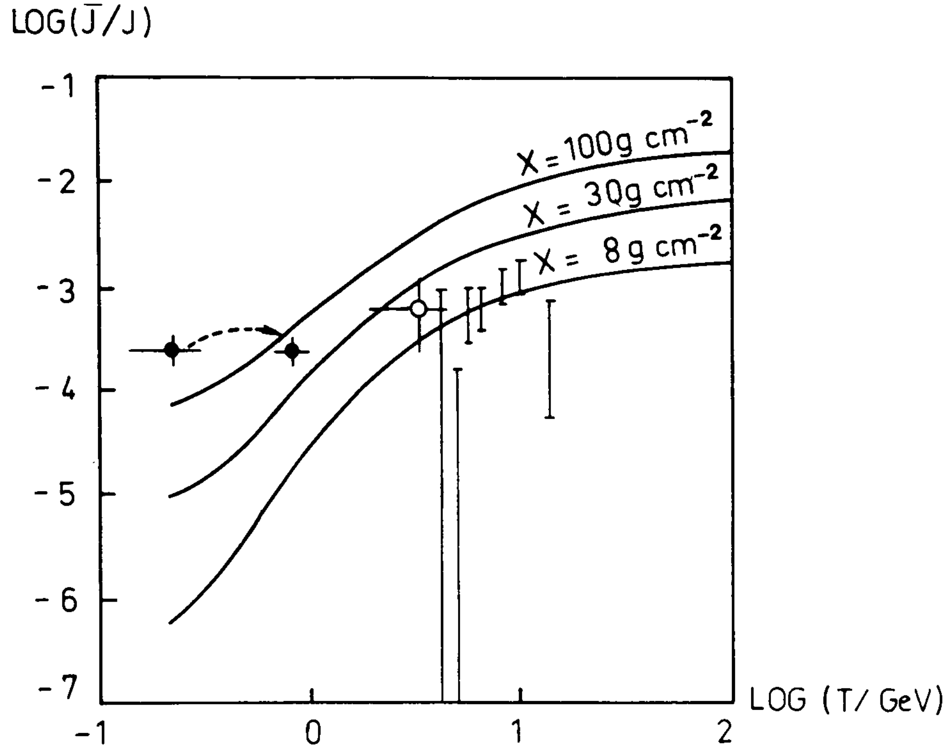

Figure 4. The mean escape length as a function of rigidity for a modulation parameter $\phi = 600$ MV [from Koch-Miramond et al., 1983].

model. What happens at even higher energies, or rigidities, such as R > 1000 GV? The ratio of secondary to primary element abundances have not yet been measured at such rigidities. Soon, results from the flight of the University of Chicago's Spacelab 2 experiment [L'Heureux et al., 1985] should solidify and extend these results. At still higher energies, in the decades on either side of 10^{15} eV or 10^{6} GV, the only method for learning about the spectrum and composition is through ground-based air shower studies. Hillas [1981] reviewed the situation of these energies a few years ago, and Linsley [1983] reviewed it more recently. Alternative points of view have been discussed in recent papers by Balasubrahmanyan et al. [1987] and Streitmatter et al. [1985]. The situation is confusing. Some experiments indicate a gradual enrichment in the abundances of heavy nuclei, others do not. Some experiments indicate a hardening in the all particle spectrum above 10^{14} eV, others do not. New direct measurements in this energy range are surely needed.

a. Radioactive Secondary Nuclei

Measurements of the abundances of unstable secondary nuclei, such as ^{10}Be (with a mean lifetime for decay at rest of $\tau_d = 2.2 \times 10^6$ yr), ^{26}Al($\tau_d = 0.85 \times 10^6$ yr), and ^{35}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 mean density in the storage volume, thus characterizing the different models.

In the framework of the leaky-box model, such measurements, combined with the determination of λ_e from the elemental composition, permit us in principle to estimate the mean escape time of cosmic rays and hence 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, Wiedenbeck and Greiner [1980] deduce from their satellite data on ^{10}Be at 60-185 MeV/amu a confinement time of 8.4 (+4.0, −2.4) Myr, and a mean density $n_H = 0.33$ (+0.13, −0.11) cm^{-3}. The mean age from ^{26}Al is 9 (+20, −6.5) Myr [Wiedenbeck, 1983], and ^{36}Cl leads to a lower limit to this age of 1 Myr [Wiedenbeck, 1985]. 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 thicker than the disk. However, they could also indicate that cosmic rays are preferentially trapped in low density regions of the disk between the clouds.

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" [Ginzburg, Khazan, and Ptuskin, 1980]. For instance, in the one-dimensional model described earlier, the abundances of secondary radioactive elements of decay period τ_d are determined by two combinations of parameters: $(n_o\tau_d)$ 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/amu, should help constrain these parameters [e.g., Cesarsky et al., 1981].

b. 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 > 50 GeV, the spectrum steepens, but electrons are still present at least up to 2000 GeV [Tang, 1984; Nishimura et al., 1980; Prince, 1979 and references therein]. 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 high energy 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.

4. ORIGIN AND PROPAGATION OF DIFFERENT COSMIC RAY SPECIES

a. Source Spectral Index, Composition and Energetics

After so many years of active research, there is not yet a firm answer to the question: where do cosmic rays come from? The main problem is, of course, that the arrival direction brings little or no information on the source. Astrophysicists are then left with a less direct set of clues: spectrum, composition, energetics, anisotropy.

Observations must first be corrected for propagation effects; this is usually done in the framework of the galactic leaky-box model. Once λ_e is derived, at various rigidities, by applying Formula (1) (or its equivalent, including ionization losses, at energies < a few GeV/amu) to secondary species, it becomes possible to derive the source abundances Q_i by applying the same formula to primary species. In this way, Engelmann et al. [1985] have derived source spectra of primary species with $Z > 5$ from the HEAO3-C2 data. Assuming H and He nuclei behave like the other species, the observed spectrum must be divided by $\lambda_e(R)$ in order to correct for propagation. The source spectra thus obtained are displayed in Figure 5. Data from other experiments are also represented. In the range $R \simeq 2 - 20$ GV, Engelmann et al. [1985] found that the spectra are generally steeper than previously thought. This leads to a rather surprising conclusion that the source spectra of the heavy nuclei are steeper (index 2.4) than those of the more abundant protons (index 2.1). Unfortunately, this is based on an experiment which only covers a narrow band of energy—the lower end of which may be complicated by solar modulation effects—and the experiment itself may be subject to systematic effects at the high energy end. Therefore, the results need confirmation. However, they are suggestive that there may be more than one "source" or mechanism operating to produce the locally observed cosmic rays.

The implications of this result have not yet been studied in full detail. Essentially all of the published work on cosmic ray origin continues to assume that protons and alpha particles originate and propagate as the other species, and that the λ_e derived from studies of heavy nuclei can be used to estimate the energetics. For the local Kpc^2 in the galactic plane, cosmic ray energetics is derived using the fact that, on the average, cosmic rays escape at a rate $c\lambda_{gal}/\lambda_e$, where λ_{gal} is the column density of matter across the galactic disk. The energy requirement to maintain the cosmic ray pool is then $\sim 10^{38}$ erg/Kpc^2 sec. (Alternative derivations, using the cosmic ray "age" derived from secondary radioactive isotopes, yield similar results). If we retain the same leaky-box model for all species, the results of Engelmann et al. [1985]

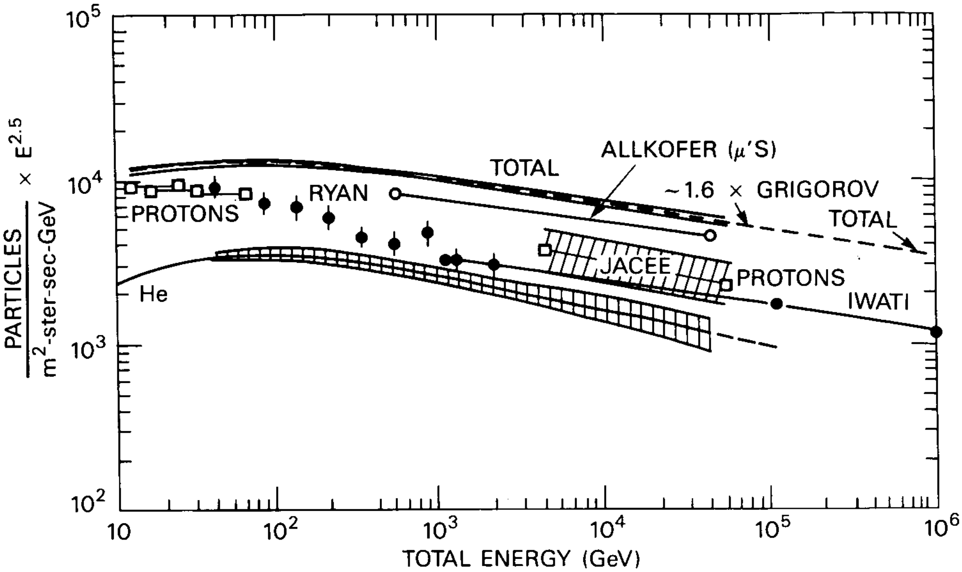

Figure 5. Observed spectra compared with various source spectra. Proton and possibly helium are consistent with source spectra with indices 2.1. Heavier nuclei, on the other hand, may require steeper source spectra. [This figure is from Engelmann et al., 1985. Original references can be found therein.]

imply that the local cosmic rays consist of two components: a flat component, with source index ~ 2.1, and a steep component, with source index ≃ 2.4. At rigidities below ~ 100 GV, most of the nuclei heavier than He would belong to the steep component, while at all energies the flat component would be dominant in the proton flux.

The leaky-box formalism, as we have seen, accounts well for the observations relating to the steep component which is rich in heavy nuclei. But there is no compelling reason to believe that the flat component, which is relatively proton-rich, has the same history. The steep component may be just local, and transient; the determinations of λ_e and of age from radioactive isotopes only relate to this component. But the proton-rich component is the only one that counts when discussing energetics, constancy in time of the cosmic ray flux, and isotropy. The abundances of secondary elements with $Z > 2$, at energies < 100 GeV, may simply not be relevant when studying it!

Some light can be focused on this problem by refining the spectra of hydrogen and helium, and studying carefully their secondaries ^3He, D, and antiprotons.

b. Antiprotons

The general picture of cosmic ray storage and propagation in the galactic magnetic fields described above has been based largely on the abundances of heavy nuclei. However, recent observation of the antiprotons has thrown this unified picture into disarray.

Secondary antiprotons are generated in the inelastic collisions between high energy nuclear cosmic rays and interstellar medium particles. The flux of galactic antiprotons has been measured recently by Golden et al. [1979 and 1984], by Bogomolov et al. [1979] and by Buffington, Schindler, and Pennypacker [1981] at various energies (Figure 6). The data of Golden et al. seem to be on solid ground and to be confirmed by the lower statistics observation of Bogomolov et al. The low energy point of Buffington et al. is more startling and unfortunately on less stable ground experimentally [Stephens, 1981].

Buffington, Schindler, and Pennypacker [1981] measured the flux of cosmic ray antiprotons in the range 130-320 MeV, which corresponds after demodulation to a mean interstellar energy of $\sim$ 800 MeV. The data are compared with the calculation based on the leaky-box model where antiprotons are assumed to be secondaries produced by collisions of protons and heavier nuclei with interstellar matter. The Buffington et al. point falls well below the kinematic cutoff but indicates that there is a high flux of low energy antiprotons present [Buffington and Schindler, 1981]. Even ignoring this data, the mean target thickness to produce the intensity observed by Golden et al. must be three or four times that of the heavier cosmic rays. This is discussed at length in the paper by Balasubrahmanyan, Ormes, and Streitmatter (this volume) where the various models which have been advanced as an explanation have been presented. Combined with the finding that the source spectra of heavier

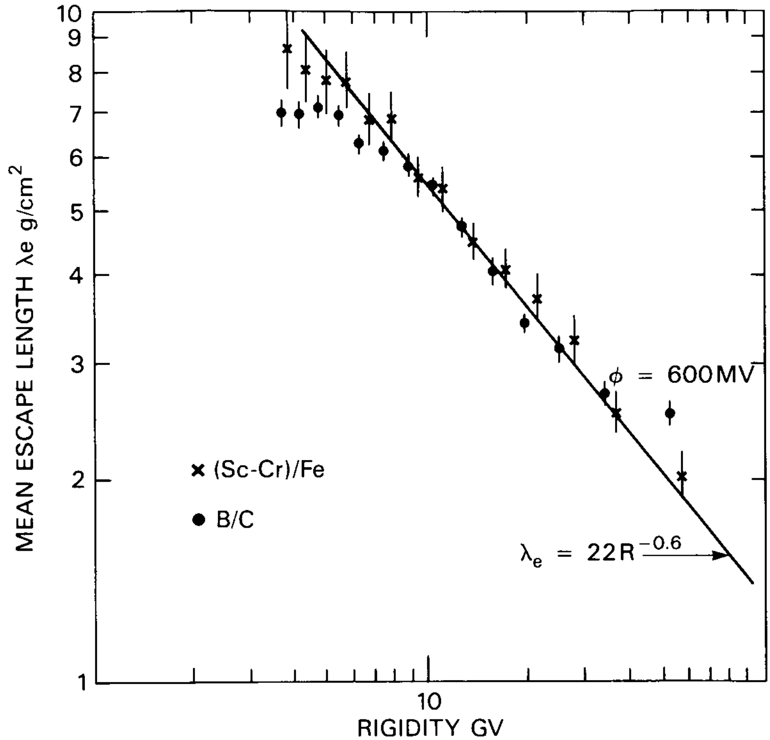

Figure 6. The observed antiproton to proton flux ratios [Golden et al., 1984, vertical bars; Bogomolov et al., 1979, open circle; and Buffington, Schindler, and Pennypacker et al., 1981, solid circle] compared with the antiprotons produced by a shell of matter surrounding a strong shock acceleration region [from Lagage and Cesarsky, 1985].

nuclei may be different from protons and helium, these data may indicate that the origin of the protons and/or their history after acceleration is different from that of heavier nuclei.

It may be that this unexpectedly high abundance of antiprotons is an additional indication that the history of all cosmic rays does not follow from the abundances of secondary nuclei alone. Golden et. al. [1984], showed that within the framework of an energy independent leaky-box model (source spectral index = 2.6), $21 g/cm^2$ of material is required. Alternately, Lagage and Cesarsky [1985] showed that the high energy observations of antiprotons could be accounted for if all cosmic ray protons had a source spectrum of index 2.1 and traversed $7 g/cm^2$ in their sources before escaping into the galaxy, or if a fraction x of the cosmic rays traversed a slab of width X at the source, with $xX = 7 g/cm^2$ [Lagage and Cesarsky, 1985]. (This $7 g/cm^2$ is energy-independent and should not be confused with the $7 g/cm^2$ traversed by heavy nuclei at 1 GeV/nucleon.) As noted by these authors, a problem with this "thick-source" model is that, in addition to the antiprotons, neutral pions are produced, which decay into gamma rays. The total galactic gamma ray flux predicted by this model exceeds that observed by COS-B by a factor ~ 3.

If protons have a different history from heavier nuclei, what about helium nuclei? There are data from a balloon experiment indicating that at high energy the helium nuclei may have traversed a target intermediate between that of protons ($21 g/cm^2$) and heavier nuclei ($7 g/cm^2$). This result [Jordan and Meyer, 1984] is sensitive to the assumed shape of the helium spectrum and remains controversial. Further data on the ^3He and deuterium abundances at high energy are needed to resolve this issue: is the matter traversed a continuous function of atomic number, or is there a discrete difference between protons and all heavier nuclei? If the latter, to which camp do the helium abundances belong?

c. Anisotropy

We have been taking the point of view that abundances of the elements are indicative of cosmic ray propagation. An alternative point of view has been taken by Hillas [1984], who uses the anisotropy as the main indicator on the propagation. This can only be done at energies above a few 100 GeV, since at lower energies the trajectories of the cosmic rays are perturbed by the solar wind. Hillas notes that, at energies > 10^3 GeV, the amplitude of the first harmonic of the cosmic ray anisotropy is, very roughly proportional to the product (cosmic ray differential flux . $E^{2.47}$) (reference Figure 1). Now, if τ_e is the confinement time, the anisotropy is expected to be ~ t/τ_e, where t is the time for escape in a straight line. Hillas proposes a simple interpretation of Figure 1: that the source spectrum is a power law of index 2.47 over the whole energy range, and that all the features in the spectrum are due to propagation effects. At 10^3 GeV, the amplitude of intensity variation is of ~ 0.06%. If the boundary of the cosmic ray confinement region is at y kpcs, $\tau_e(10^3 \text{ GeV}) \simeq$ 5y Myr. Since the spectrum of protons does not appear to change significantly between 5 and 10^3 GeV (see Figure 3), the mean age at 5 GeV would be ~ $(1000/5)^{2.7-2.47}\ \tau_e\ (10^3 \text{ GeV}) \simeq 17$ Myr (where 2.7 is the observed index of the proton spectrum at these energies). This is comparable to the age derived from radioactive secondary isotopes, so the global energetics of galactic cosmic rays is not very much changed in this picture.

d. Cosmic Ray Sources

We summarize by listing the requirements on cosmic ray sources.

i) Energetics: the order of magnitude of the power required to replenish cosmic rays "within" a cylinder of base 1 Kpc^2 within the galactic disk, of height 1 to ~ several Kpc, is ~ 10^{38} ergs/sec.

ii) Source spectrum: most probably a power law, at least in the range from a few GeV/amu to ~ 10^6 GeV/amu, perhaps up to 10^8 or even 10^9 GeV! Spectral index: 2.1? 2.4? or 2.7? Or somewhere in this range.

iii) Source composition: well determined now, for most elements, in the GeV/amu range. May give clues to the origin of the cosmic radiation or at least, as we have seen, to a component of it.

Within a radius of 3 kpc from the Sun, the average energy input from supernovae is estimated to be ~ 10^{39} erg s^{-1} kpc^{-2}; supernovae are widely believed to be the main accelerators of cosmic rays. Stellar winds expend ~ 10^{38} erg s^{-1} kpc^{-2} in the interstellar medium, and they may also contribute to cosmic ray acceleration. [Cesarsky and Montmerle, 1983]. Composition arguments have often been invoked to eliminate pulsars as a candidate source, but the debate on the role of pulsars in cosmic ray acceleration is not closed.

5. ACCELERATION MECHANISM

We require (probably) an acceleration mechanism capable of producing a power law spectrum.

a. Fermi Acceleration

The basic concept of acceleration of particles via encounters with "moving magnetic walls" was introduced by Fermi as early as 1949. Fast particles of velocity v that encounter magnetic walls are separated by a mean distance moving at a velocity V. The walls reflect the particles and enhance their energies.

$$\frac{dE}{dt} = \frac{2V^2}{c\lambda} E = \alpha E \tag{4}$$

This process has enjoyed an enduring popularity among astrophysicists because it predicts that the energy spectrum of the colliding particles should be a power law: $N(E) \alpha E^{-\gamma}$, $\gamma = (1 - \frac{1}{\alpha\tau_e})$, where τ_e is the mean time spent by a particle in the accelerating region.

b. Particle Acceleration by Parallel Shocks in a Scattering Medium

This attractive mechanism must have been in the air several years ago, as it has been discovered simultaneously by astrophysicists all over the world [Krimsky, 1977; Axford, Leer, and Skadron, 1977; Blandford and Ostriker, 1978; and Bell, 1978]. This is somewhat surprising, as the tools used in the various derivations, and the motivation, have been around for a much longer time.

Let us consider a strong shock, propagating at a velocity V in the direction of the magnetic field lines. We assume that $V = v_A$, where v_A is the Alfvén velocity. In the shock frame, the gas is flowing in at a velocity $u_1 = V$. At the shock, the gas is compressed by a factor r, so that the velocity downstream, relative to the shock, is $u_2 = V/r$.

The presence of scattering centers of cosmic rays is postulated, so that cosmic rays diffuse on both sides of the shock; the diffusion coefficient is, in general, a function of space, particle momentum, and time. In any case, the scattering centers act as cosmic ray traps, ensuring that the particles will be reflected back and forth across the shock a large number of times. Every passage through the shock is equivalent to running head-on into a "magnetic wall" of velocity $V = u_1 - u_2 = V(1 - 1/r)$; averaged over all incidence angles, there is a mean energy gain per traversal of the shock given by

$$\Delta E = (4/3)\,(V/c)\,(1-1/r)E \qquad (5)$$

Taking proper account of the probability of particles escaping the system leads to the time-independent spectrum:

$$N(E) \propto E^{-\mu},\ \mu = (2+r)/(r-1) \qquad (6)$$

For strong adiabatic shocks, $r = 4$ and $u = 2$. Weaker shocks generate steeper spectra.

The remarkable property of this mechanism is that, in the time-independent limit, the slope of the power law it generates depends only on the shock strength, and not at all on the diffusion coefficient (assumed "small enough") or the dimensions of the scattering region (assumed "large enough").

The study of shock acceleration of cosmic rays is now an active area of research. A fundamental review of the subject has been written by Drury [1983]. A detailed application of the mechanism to the acceleration of galactic cosmic rays is given in Blandford and Ostriker [1980]; see also Axford [1981].

Many aspects of this mechanism have been studied since, and it is impossible to review this rich field here. Let us just emphasize some of the main problem areas:

i) This problem has always been treated in the framework of the quasi-linear theory, which assumes that the turbulent energy in the hydrodynamic waves acting as particle scatterers is much less than the energy density of the magnetic field. However, the anisotropies induced by supernova shocks in the pre-existing population of galactic cosmic rays are sufficient to render these waves extremely unstable; the wave amplitudes predicted by the qausi-linear theory are too high to be fully consistent with this theory.

ii) If cosmic rays extract so much energy from the shock, their pressure can become the dominant one. For instance, this will inevitably occur if cosmic rays are getting accelerated by a strong shock, to a spectrum E^{-2}, for a sufficiently long time. Even if the shock is not so strong ($r < 4$), the cosmic ray pressure can become dominant if the rate of injection of particles in the system is sufficiently rapid. The expectation is that, eventually, the cosmic rays broaden the shock, making it a less efficient particle accelerator. If the shock becomes wider than the particle mean free path λ, all particles of a given energy obtain the same amount of adiabatic acceleration as they cross the shock region. Ellison and Eichler [1985] have studied these problems and find that this mechanism still produces a universal spectrum which is very similar to a power law of index ~ 2. The efficiency of cosmic ray acceleration by this mechanism is very high, of order 25%.

iii) An important problem of the theories of shock wave acceleration is that the maximum energy that can be attained is limited, either by the lifetime of the shock itself or by its curvature radius. This problem was treated in detail by Lagage and Cesarsky [1983, 1985]. In the case of supernova shocks, the limiting factor is the shock lifetime; under most optimistic assumptions, the maximum energy E_{max}, for particles of charge Z, is only ~ 10^5 Z(B/10^{-6} gauss) GeV, where B is the strength of the magnetic field in the most diffuse phase of the interstellar medium.

This result holds whether the shock is linear or cosmic ray dominated. Taking into account the nonlinearity introduced by the fact that, upstream, the Alfvén waves are generated by the cosmic rays, so that the diffusion coefficient is space- and time-dependent, E_{max} is limited to values which may be as low as 2000 Z (B/10^{-6} gauss) GeV. Invoking supernova shocks propagating in the galactic halo does not alleviate the problem [Lagage and Cesarsky, 1987].

The possible acceleration of high energy cosmic rays by stellar wind terminal shocks is still controversial. If shock acceleration is operating there over long times, stellar winds have the advantage that the shock is a standing shock, which remains strong for longer times than supernova shocks. The maximum energy is then determined by the shock curvature, and the strength of the magnetic field: $E_{max} \sim 5.10^5 Z(B/10^{-5}G)$ (D/5 pc) GeV, where D is the shock radius. In a recent paper Kazanas and Ellison [1986] attempt to model the binary X-ray source Cygnus X-3, which may be emitting ultrahigh energy gamma rays [Samorski and Stamm, 1983; Lloyd-Evans et al., 1983; Watson, 1985 and references therein], and thus be a source of cosmic rays of energy up to 10^7-10^8 GeV. Assuming the presence of a collisionless, spherical accretion shock around the compact object in Cygnus X-3, and assuming that the magnetic field strength is in equipartition with the accretion flow, Kazanas and Ellison argue that protons of energy as high as 7.10^6 GeV may be accelerated by the shock in this system.

While these problems are serious and are being worked theoretically, it is clear that shocks in the interstellar medium do accelerate particles. Shock acceleration remains the most promising mechanism for producing the power law spectra observed in the galactic cosmic rays, at least in the energy range from 1 to 10^6 GeV.

6. SUMMARY

The study of systematic trends in elemental abundances is important for unfolding the nuclear and/or atomic effects that should govern the shaping of source abundances and in constraining the parameters of cosmic ray acceleration models [for reviews see Casse, 1984; Simpson, 1983]. These issues were discussed in the rapporteur paper by J. P. Meyer [1985]. The isotopic composition and elemental abundances of trans-iron nuclei have much to contribute about the nucleosynthesis, sites, and timescales for the origin of cosmic rays. [See Binns et al., 1987, this volume.]

In principle, we can also learn much about the large-scale distributions of cosmic rays in the galaxy from all-sky gamma ray surveys such as COS-B and SAS-2. Gamma ray intensities are proportional to the line integral along the line of sight of the product of the cosmic ray flux and the matter density. However, because of the uncertainties in the matter distribution which come from the inability to measure the abundance of molecular hydrogen, the results are somewhat controversial. A debate exists as to whether on a scale of 0.5 to 1 kpc there are more cosmic rays where there is more matter. [See paper by Fichtel, 1987, this volume.] Questions exist about whether the cosmic ray intensity falls off in the outer galaxy or remains about the same. Because around 100 MeV there are almost as many gamma rays from the bremsstrahlung process as from π^{0} decay, resolution of these issues will await the improved energetic gamma ray experiment telescope (EGRET) on GRO. Very high energy ground-based cosmic ray telescopes will help in understanding the role that sources like Cygnus X-3 play in accelerating cosmic rays. High resolution radio observations of external galaxies [e.g., Duric et al., 1986] may provide clues about the role of shocks and spiral density waves in particle acceleration.

As we have seen, the leaky-box model accounts for a surprising amount of the data on heavy nuclei. However, a growing body of data indicates that this simple picture may have to be abandoned in favor of more complex models which contain additional parameters. For example, an energy-dependent modification of the exponential path length distribution, natural to the simple leaky-box model, has long been invoked to explain differences between the escape length derived from sub-iron secondaries and the Li, Be, and B components [Guzik et al., 1985]. The shape of the high energy electron spectrum led Tang and Muller [1983] to favor the nested leaky-box model. The spectral differences at the source and the antiproton observations lead us to postulate a separate origin for protons and heavier nuclei. Acceleration by weak shocks may lead to a reinterpretation of the observed element ratios in terms of material traversed. Observations of anisotropy, the consistency of the flux in time, and the gamma ray distribution tell us primarily about properties of protons, and nothing about those same quantities for heavier nuclei. Age measurements have been made for low energy nuclei and possibly for electrons, but their interpretations are model-dependent. In short, the observations still leave us in some confusion and greatly in need of further observations.

Future experiments on the Spacelab and Space Station will hopefully be made of the spectra of individual nuclei at high energy. Antiprotons must be studied in the background free environment above the atmosphere with much higher reliability and precision (the world's observed antiprotons number of order 60) to obtain spectral information.

Isotopic composition needs to be measured over more elements and over an extended energy range. Ultraheavy abundances beyond tin in the periodic table must be measured with single element resolution and the abundances of actinides determined.

The future for these observations includes the Heavy Nuclei Collector currently being constructed for an exposure on NASA's Long Duration Exposure Facility and the Particle Astrophysics Superconducting Magnet Facility (Astromag) being planned for NASA's Space Station. The Gamma Ray Observatory is scheduled for launch in 1990. If all these plans are brought to fruition, the next two decades should see tremendous progress made in unraveling the problem of the origin of cosmic rays.

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