PROPAGATION OF COSMIC RAYS AND NEW EVIDENCE FOR DISTRIBUTED ACCELERATION

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We explore the origin and propagation of cosmic rays in terms of conventional as well as supplementary newer assumptions. Cosmic rays are considered to be accelerated by supernova shock waves (possibly after injection by stellar flares) and to traverse clouds in the source region. After rigidity-dependent escape from these clouds into interstellar space, cosmic rays are further accelerated by the weakened shocks of old supernova remnants and then pass through additional material. The distributed acceleration hypothesis is discussed with emphasis on recent data on the abundances of cosmic-ray isotopes of N above 1 GeV/u and of He near 6 GeV/u. The isotopic abundance of He at 1 GeV/u would provide another test between this hypothesis and the scenario generally assumed hitherto. Measurement of the production cross sections, of the nuclides A = 14 and 15 from oxygen at E = 75 to 100 MeV per amu is also considered essential.

1. Introduction.

A theory of cosmic ray propagation must satisfy numerous experimental as well as theoretical constraints. We discuss some of these constraints in the next Section. Thereafter we describe a propagation scenario that takes into account these constraints. Finally we shall propose additional tests for distributed acceleration.

2. Experimental and Theoretical Constraints.

Acceleration and nuclear spallation do not occur at the same time, nor even intermittently in a series of equally strong acceleration processes, otherwise the secondary spectra would be flatter than those of the parent nuclei (Eichler, 1980, Cowsik, 1980, Fransson and Epstein, 1980). On the other hand, cosmic rays encounter a large number (about 100) shock waves during their galactic residence time (Axford, 1981). The seeming contradiction is resolved if cosmic rays are subject to a strong, early acceleration energized by a relatively young ($\gtrsim 10^4$ years) supernova remnant, e.g. by shock waves with a high compression ratio (3 to 4), and subsequent weak accelerations with a compression ratio $\lesssim 2.5$, which will not flatten the secondary energy spectra, (Axford 1981).

While the observed spectra of various cosmic-ray components (except at low energies) are similar in shape, the source spectra, after correction for rigidity-dependent depletion by fragmentation are flatter for protons and helium then for heavier nuclei (Engelmann et al. 1984). This is consistent with acceleration of protons and helium by very strong shock waves at even younger supernova remnants ($\lesssim 10^4$ years). The absence of heavier nuclei with such spectra is explicable by postulating confinement in clouds near these supernova remnants in which heavier nuclei break up while $\bar{p}$ and e^+ are produced, mainly in cosmic ray proton interactions.

Another observation that propagation models must satisfy is the near-constancy of the anisotropy below 10^5 GeV. From the review of Linsley (1983) we see that the amplitude of the anisotropy increases only a factor of about 3 between 10 and 10^5 GeV. The anisotropy is nearly constant also after correcting for the Compton-Getting anisotropy, since the latter is opposite in direction to the observed anisotropy. The effect of correction for the Compton-Getting anisotropy is shown in Fig. 4 of Hillas (1983). The small energy dependence of the anisotropy (much smaller than that of the secondary to primary abundance ratios) is readily explained in terms of the nested leaky box models of Cowsik and Wilson (1973, 1975), the multiple cloud model of Silberberg et al. (1983a) and the somewhat similar recent model of Morfill et al. (1985).

We shall now explore some constraints on the regions of cosmic ray acceleration and the injection process. Issa et al. (1981) explored the density of cosmic rays in various clouds and found that the density is about 4 times higher at O-B associations and about 4 times lower in other clouds such as those near T-Tauri associations. In O-B associations (with massive young stars) one can expect frequent supernovae; such regions were proposed as cosmic ray sources by Montmerle (1979).

The relationship between the cosmic ray abundances and the first ionization potential implies injection near 10^4 °K. Such injection conditions occur in solar and stellar flares (J.-P. Meyer, 1985). Also the warm, fluffy regions around interstellar clouds have such temperatures, but a large fraction of non-volatile material is in grains in these regions; while the contribution of material from grains at cosmic ray sources has been explored, quantitative predictions are still inadequate. J.-P. Meyer (1985) has also shown that due to electron attachment and reduced ionization losses of heavy nuclei, injection energies of $\geq$ 1 MeV are consistent with cosmic ray abundances. While H and He abundances in cosmic rays are low, they may be low already at the injection stage, just as in solar flares there are effects of heavy ion enhancement.

3. Origin and Propagation. The following scenario is consistent with the above constraints: Flare particles are injected and accelerated by supernova shock waves in O-B stellar associations with an energy gain by a factor of about 100. From the earliest phase, when the clouds are least broken up, only protons and helium and their secondaries survive; the source spectra of protons and helium are flatter due to acceleration during the young phase of supernova remnants ($\sim10^4$ years old) . Some time thereafter, when the clouds are broken up to some extent, heavy nuclei and their secondaries also survive after acceleration and propagation in clouds. The rigidity dependence of secondary-to-primary ratios is associated with rigidity-dependent leakage from the clouds of the source regions. Subsequent leakage from the galaxy has a small rigidity dependence-such as that of the anisotropy.

In interstellar space (Axford, 1981) cosmic rays encounter about a 100 weak shocks with small (< 2.5) compression ratios, which accelerate cosmic ray particles without flattening their spectra, consistent with our model of distributed acceleration (Silberberg et al. 1983b).

4. Further Tests for Distributed Acceleration. Jordan and P. Meyer (1984) have recently measured the ratio ^{3}He/^{4}He = 0.24 ± 0.05 at 6 GeV/u. This value is higher by a factor of two than those measured at 200 to 300 MeV per amu, 0.114 ± 0.015 at 200 MeV per amu (Badhwar et al. 1967 and Webber and Yushak 1983) and 0.11 ± 0.03 at 300 MeV per amu (O'Dell et al. 1965). J.-P. Meyer (1971, 1974) has calculated the energy dependence of the ^{3}He/^{4}He ratio, assuming an exponential path length distribution and a mean path of 7 g/cm^2. More recent data permit the calculation of the energy dependence of the mean path length traversed by cosmic rays (Ormes and Protheroe 1983). In Fig. 1 we display the above experimental data, and the calculated abundance ratio, including the energy dependence of the mean path length. The solid line represents the case of distributed acceleration, with an energy gain of 4 after fragmentation, and the dashed curve represents the standard propagation calculation. We note that with distributed acceleration, the peak value of the ratio ^{3}He/^{4}He is shifted to ~ 4 GeV/u, and agrees with the measured value within 1.4 standard deviations, or 1.0 standard deviations if a weaker rigidity dependence of the path length $\propto R^{-0.5}$, (that is also in common use), is adopted. The uncertainty in solar modulation does not permit an adequate determination of the path length for $E < 500$ MeV per amu. Fig. 1 is based on the cross sections used by J.-P. Meyer (1971, 1974) and the modulation parameters of Webber and Yushak (1983). A considerably longer path length fits the low-energy data, if one uses the modulation parameters of Jordan and P. Meyer (1984). Thus, with distributed acceleration, the ^{3}He/^{4}He data near 6 GeV/u are consistent with the standard path length of ~7 g/cm^2 at these energies. Without distributed acceleration, the dashed line of Fig. 1 shows the significant disagreement between the high energy measurement of ^{3}He/^{4}He and the standard propagation model.

Jordan and Meyer (1984) have interpreted the data in terms of a long path length, ~ 15 g/cm^2 possibly associated with regions where cosmic-ray $\bar{p}$ production takes place. In terms of this model, the ^{3}He/^{4}He ratio near 1 GeV/u should be high, probably near 0.3. With distributed acceleration, it is expected to be between 0.15 and 0.20.

Another test for distributed acceleration is provided by the ^{15}N/^{14}N ratio between 0.1 and 0.4 GeV/u, and the cross sections σ_1[O ($\Delta A = 1$)] and σ_2 [O ($\Delta A = 2$)] at energies between 75 and 100 MeV/u. The ratio σ_1/σ_2 at the latter energies should be smaller than the value at 225 MeV/u of Guzik et al. (1985) and at 700 to 900 MeV/u of Webber et al. (1983). This would account for the discrepancy between the data of ^{14}N/N at 2.5 GeV/u of 0.55 ± 0.04 (Byrnak et al. 1983 and Goret et al. 1983) and the lower value of 0.45 ± 0.04 at 100 to 400 MeV/u, (Mewaldt 1981 and references therein).

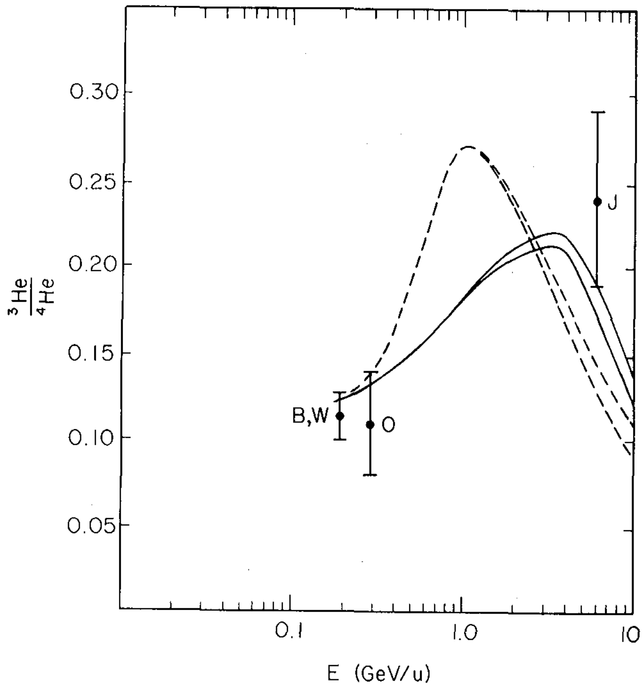

Figure 1: The experimental and calculated ratios of ^{3}He/^{4}He. The solid curve is based on distributed acceleration and the dashed curve on the standard propagation model.

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