ALFVEN WAVE SCATTERING AND THE SECONDARY TO PRIMARY RATIO

G. Larry Bretthorst and Steven H. Margolis
McDonnell Center for the Space Sciences
Washington University
St. Louis, Missouri 63130, U.S.A.

1. Introduction. The cosmic ray abundances have traditionally been used to determine the elemental and isotopic nature of the Galactic Ray Sources and average measures of propagation conditions (1). Detailed studies of the physics of propagation are usually paired with relatively straightforward estimates of the secondary-to-primary (S/P) ratios. In the work reported here, calculations of elemental abundances are paired with a more careful treatment of the propagation process. It is shown that the physics of propagation does indeed leave specific traces of Galactic structure in the Cosmic Ray abundances.

2. Theory. The increasing evidence for an energy-dependent truncation of the pathlength distribution (2,3) led Margolis (4) to suggest that such observations would be the natural result of the low bulk streaming speed of the cosmic rays interacting with self-generated Alfvén waves (5-8). In particular, Skilling (7) showed that the plasma processes could be modeled by a time-dependent, non-linear diffusion equation. Using that equation, Margolis and Bussard (9) demonstrated that the self-scattering phenomenon did lead, not only to an energy-dependent truncation, but also to variations in the S/P ratios consistent with those observed. In that paper, they solved for the pathlength distribution and used the analytic procedure of Margolis (10) to determine the abundances. In the work presented here, the steady-state, non-linear diffusion equation is solved simultaneously with the equations governing spallation to determine the observed cosmic ray abundances directly from the physics.

By neglecting the contribution of the less-abundant heavier nuclei to wave generation and by including fragmentation, the single species equation of Skilling (7) can be written

$$v_A \frac{\partial}{\partial z} \left\{ \frac{n_1 + \Gamma}{\left| \partial n_1 / \partial z \right| + T} \frac{\partial n_i}{\partial z} \right\} + \sum_{j=1}^{M} \sigma_{ij} n_j + S_i(z) = 0$$

where n_i is the steady-state number density of particles of species i (n_1 represents the protons), σ_{ij} is the net fragmentation/decay cross section for reactions taking species j into i (the diagonal term represents the total inelastic cross section), $S_i(z)$ is the source term for i as a function of position. The single coordinate z represents a relative position along a flux tube; the much smaller transverse diffusion term has been neglected. As will be discussed below, z should not be interpreted directly as either radial position or height in the Galaxy. The other quantities in this equation can be related to parameters describing the interstellar plasma and magnetic field. The Alfvén speed is v_A, Γ is related to the damping rate of the waves, and T is related to the external energy input to the waves. The spatial distribution of the source term in this equation is taken to be a Gaussian with a width subject to adjustment. Symmetry about the origin is assumed. The outer boundary condition is one suggested by Freedman (11) to account for the presence of a Galactic Wind.

In the limit of large Γ and T this model goes into the standard diffusion model. In the limit of small Γ and T this equation goes into a wave equation. In the region of physical interest neither extreme limit applies. This variation in behavior drives the observed features of the energy dependence. The variable truncation results from the changing bulk streaming speed, which forces the relativistic particles to accumulate grammage without the bulk of the particles moving at anywhere near relativistic speeds. This stands in sharp contrast to the image normally associated with, say, the nested leaky box (12), which pictures a source as surrounded by a specific shell of matter.

3. Results. There are seven unknown parameters to be determined from the observed abundances of the cosmic rays. They are: T , Γ, v_A , the source magnitude for hydrogen s_H , a reflection coefficient at the outer boundary r , the full width at half maximum of the source distribution function f_w, and the number density of the interstellar gas with which the cosmic rays interact n_0. These were constrained by matching the abundances from equation (1) to the observed abundances from the French-Danish experiment (13). The distance to the outer boundary z_{max} was fixed at 1.5 Kpc after initial testing showed it was constrained only approximately. The relative source magnitudes were fixed from a calculation by Margolis (14). The hydrogen to heavies ratio and observed spectrum were taken from Webber and Lezniak (15). The errors in the free parameters are estimated to be about 10%. The best values of the free parameters were found to be characteristic of the values given by Spitzer (16) for the cool diffuse clouds (HI regions).

Currently the interstellar medium (ISM) is believed to consist of three types of regions, molecular clouds, HI regions, and hot intercloud regions (17). Classically the cosmic rays were assumed to permeate all types of regions, such that the measured characteristics of the propagation medium were thought to be a weighted average over all regions. Of the three regions, only the HI clouds support significant wave densities. Resonant waves in any region will act to limit the particle bulk streaming velocity to values on the order of the Alfvén velocity. This velocity is low compared to the individual particle velocities; the particles spend a long time in such regions. In the hot intercloud medium, the damping is large (18) so that the waves do not exert a significant influence on the bulk streaming velocity. The molecular clouds seem to have left no imprint on the observed cosmic rays: the particles are either excluded from the clouds (19) or lost by interactions with the dense gas. Interpreting the measurements in terms of wave-particle interactions points only to the HI regions.

This unique signature can be understood simply. Assume that the clouds occupy 1% of the volume of the ISM and the intercloud medium 99% (these figures are estimates of lower and upper bounds, respectively). The cosmic rays will travel through these regions guided along the magnetic field, hence the non-correspondence of the coordinate z to a single direction in space. The Alfvén velocity within the clouds (where the electrons are supplied by the ionization of intersteller carbon) is about 1.9×10^7 cm sec^{-1}: the bulk velocity is held to about 10^{-3} the speed of light. The density within a cloud is about 0.2 atom cm^{-3}, but the density in the intercloud medium is 0.02 atom cm^{-3}. Thus, the cosmic rays accumulate 100 times as much grammage in the clouds as outside them, which explains the singular signature.

The threading of the magnetic field through the different regions does bring to mind the work of Parker (20). The calculations presented here are consistent with Parker's picture of the clouds anchoring the magnetic field in the Galaxy as the cosmic rays inflate the field lines above the plane. This dynamic interaction provides a means for cosmic ray escape from the Galaxy as well as a complicated topology for the coordinate z. The work presented here indicates that the cosmic rays are injected into the wandering field lines over relatively broad ($f_\omega = 600$ pc) regions (perhaps by interstellar shocks), and that these field lines carry the cosmic rays outside the Galaxy within a distance along the field of 1 or 2 Kpc. Further directions for study would be the understanding of electron propagation in the hope of using radio observations of Galactic halos.

4. Conclusion. The propagation of the cosmic rays and the energy dependence of the secondary to primary ratios can be understood from the interaction of the particles with waves in the interstellar magnetic field. The calculations presented here point to the cool HI clouds as the primary influence on cosmic ray abundances. This work suggests a clear reflection of the structure of the Galaxy in the measurements of Cosmic Rays.

5. Acknowledgements. This work was supported under NASA grant NAG8-448 and McDonnell Center Research funds. One of us (GLB) was supported by a Washington University Graduate Fellowship.

6. References

1. Simpson, J. A. (1983), *Ann. Rev. Nucl. Part. Sci.* **33,** 323.
2. Garcia-Munoz, M., Guzik, T. G., Margolis, S. H., Simpson, J. A., and Wefel, J. P. (1981), *Proc. 17th Int. Cosmic Ray Conf. (Paris)* **9,** 195.
3. Garcia-Munoz, M., Guzik, T. G., Simpson, J. A., and Wefel, J. P. (1984), *Astrophys. J. (Letters)* **280,** L13.
4. Margolis, S. H. (1981), *Proc. 17th Int. Cosmic Ray Conf. (Paris)* **9,** 215.
5. Wentzel, D. G. (1969), *Astrophys. J.* **156,** 303.
6. Kulsrud, R. and Pearce, W. (1969), *Astrophys. J.* **156,** 445.
7. Skilling, J. (1970), *Mon. Not. R. Astr. Soc.* **147,** 1.
8. Skilling, J. (1975), *Mon. Not. R. Astr. Soc.* **173,** 255.
9. Margolis, S. H. and Bussard, R. W. (1983) *Proc. 18th Int. Cosmic Ray Conf. (Bangalore)* **9,** 271.
10. Margolis, S. H. (1983), *Proc. 18th Int. Cosmic Ray Conf. (Bangalore)* **9,** 267.
11. Freedman, I., Giler, M., Kearsey, S., and Osborne, J. L. (1980), *Astron. and Astrophys.* **82** 110.
12. Cowsik, R. and Wilson, L. W. (1975), *Proc. 14th Int. Cosmic Ray Conf. (Munich)* **2,** 659.
13. Engelmann, J. J., Goret, P., Juliusson, E., Koch-Miramond, L., Masse, P., Soutoul, A., Byrnak, B., Lund, N., Peters, B., Rasmussen, I. L., Rotenberg, M., and Westergaard, N. J. (1983), *Proc. 18th Int. Cosmic Ray Conf. (Bangalore),* **2,** 17.
14. Margolis, S. H. (1985), *Astrophys. J.*, (in press).
15. Webber, W. R. and Lezniak, J. A. (1974), *Astrophys. Space Sci.* **30,** 361.
16. Spitzer, L. (1978), *Physical Processes in the Interstellar Medium,* (New York: Wiley-Interscience).
17. McKee, C. and Ostriker, J. P. (1977), *Astrophys. J.* **218,** 148.
18. McIvor, I. (1977), *Mon. Not. R. Astr. Soc.* **178,** 85.
19. Skilling, J. and Strong, A. W. (1976), *Astron. Astrophys.* **53,** 253.
20. Parker, E. N. (1966), *Astrophys. J.* **145,** 811.
21. Garcia-Munoz, Mason, G. M., and Simpson, J. A. (1977), *Astrophys. J.* **217** 859.