Final Report on the Astrophysics Theory Grant

"Cosmic Ray Propagation through the Magnetic Fields of the Galaxy with Extended Halo" (NAG 5-10888)

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In this project we perform theoretical studies of 3-dimensional cosmic ray propagation in magnetic field configurations of the Galaxy with an extended halo. We employ our newly developed Markov stochastic process methods to solve the diffusive cosmic ray transport equation. We seek to understand observations of cosmic ray spectra, composition under the constraints of the observations of diffuse gamma ray and radio emission from the Galaxy. The model parameters are directly are related to properties of our Galaxy, such as the size of the Galactic halo, particle transport in Galactic magnetic fields, distribution of interstellar gas, primary cosmic ray source distribution and their confinement in the Galaxy. The core of this investigation is the development of software for cosmic ray propagation models with the Markov stochastic process approach. Values of important model parameters for the halo diffusion model are examined in comparison with observations of cosmic ray spectra, composition and the diffuse gamma-ray background. This report summarizes our achievement in the grant period at the Florida Institute of Technology. Work at the co-investigator's institution, the University of New Hampshire, under a companion grant, will be covered in detail by a separate report.

As a preparation for developing a new computation code for the calculation of cosmic ray propagation in interstellar space, we first make a calculation of cosmic ray path length distribution, which is the distribution of particles as a function of total grammage of interstellar matter penetrated by cosmic rays during their propagation from their source to the solar system. When particle energy change during the interstellar propagation is small, the diffusion transport equation of cosmic ray transport can be broken into two parts: the calculation of the path length distribution from a diffusion-convention equation and the calculation of secondary cosmic ray production. The later part is commonly called the weighted slab model, which is being used extensively by researchers in the community to interpret cosmic ray composition data from space missions such as IMP-8, Ulysses and ACE. The path length distribution is a key input for the calculation of secondary comic ray production. In the first part of this funding period, we run various models of cosmic ray propagation to gain understanding of the behavior of the path length distribution. We vary the distribution of interstellar gases and other parameters charactering the structure of galactic magnetic fields. We find that the path length distribution can often be fitted by a single exponential law at long path lengths (typically > 3 gm/cm^2). This is consistent with what is chosen to use by most people in the weighted slab model calculation. Such a behavior is due to the diffusive nature of particle transport in interstellar space. However, the path length distribution at low path lengths crucially depends on the details of the model we run. For example, when we put in a interstellar gas distribution derived from the column densities of HI and H_2 for Galactocentric annuli based on 21cm and CO emissions surveys, the path length distribution function is slightly depleted at low path lengths $<\sim 1$ gm cm^2. However, if we introduce a local supper bubble of low gas density of ~200pc in diameter next to the solar system, we find that the path length distribution is enhanced at low path lengths, meaning that

higher percentage of cosmic rays arriving at the solar system traversed little interstellar gas. Similarly, if we put in a lumpy interstellar gas distribution to model interstellar gas cloud, the path length distribution became lumpy too at short path lengths but not at long path lengths. This work was published in the proceedings of the 28th International Cosmic Ray Conference held in Tsukuba, Japan.

With the result of calculated path length distribution from the above diffusion model, we proceed to calculate of secondary cosmic ray production with weighted slab model (we call it COSMO). The code was previously developed at the University of Chicago for the interpretation of IMP-8 and Ulysses cosmic ray composition data. It contains all the nuclear cross sections needed for the calculation of up to 96 nuclear elements and isotopes. At this stage, COSMO only takes path length distributions in either single or double exponential law. Our output of path length distribution calculation does not necessary follow an exponential function. We have to decompose it into a summation of multiple exponentials in order to run COSMO. This way of implementing the path length distribution into COSMO is very time consuming. This is because the path length distribution is a function of particle energy as well as path length. We have to run the path length distribution calculation for more than 20 energies in order to obtain the 7 parameters used by COSMO to characterize the mean path length as a function of energy. The results of cosmic ray spectra from several single exponential run are averaged according to their weights to total path length distribution to derive primary and secondary cosmic ray spectra. We have tested the result of our cosmic ray abundance calculation against the results by Andrew Strong's code with a different numerical approach with some relatively simple models. The benchmark B/C ratio comes out to be consistent. In addition, our calculation yields abundance of radioactive isotopes, such as ^{10}Be, ^{26}AL, ^{36}Cl etc. Recently we are investigating the effects of the local super bubble on the cosmic ray abundance. We find that the bubble makes little change to unstable nuclear elements such as B; however, the abundance of radioactive isotopes is significantly reduced. This is because these radioactive isotopes come mostly from local interstellar space, where the bubble makes a significant contribution. This work was also published in the proceedings of the 28th International Cosmic Ray Conference.

The above two steps have shown us that Markov stochastic integration is a viable approach to the problem. In the last part of the grant period, we concentrate on the development of a complete software for computing the propagation of cosmic ray nuclei in the Galaxy. We take 87 diffusive transport equations, each of which represents a nucleus type. The 87 equations all are nested together through nuclear decay and nuclear spallation with the interstellar gas. It is a huge task to solve so many partial differential equations in 3-d galactic structure, because one has to solve the 87 partial differential equations one by one. To overcome this difficult, we have invented a matrix stochastic integration method. In our approach, we write the 87 particle differential equations in a matrix format. If we assume that all the species in the nuclear reaction chain preserve their energy per nucleon, the transport behavior is the same for all the species. Then we can use one stochastic differential equation to represent the transport of cosmic rays in the Galaxy. The nuclear interaction of cosmic ray with the interstellar medium is expressed by a matrix. As cosmic rays propagate through the interstellar medium, we integrate the nuclear interaction matrix over time, resulting in a new matrix representing the nuclear transformation probability among all the nuclear species. The intensity of 87 cosmic ray species is the product of the transformation matrix and the cosmic ray source intensity. The computer code must

include all total and partial cross sections of comic ray nuclei and their decay times. Their energy dependence is also included. The cross sections data are taken from large number of experiment data sets. We have tested the code with some example runs. The results are consistent with previous calculation with simple models.

With the code, we have achieved a number of new results regarding the understanding of the physics of cosmic ray interstellar propagation:

(a) In our first model run, we use the average interstellar medium density derived from astronomical observations, set a halo height of 4 kpc, and choose a cosmic ray source distribution that is consistent with galactic diffuse gamma ray emission. With this model, we can produce an energy dependence of B/C ratio that is consistent with cosmic ray observations. The sub-iron to iron ratio is also consistent with observations.

(b) We have calculated the abundance ratio of a few radioactive isotopes, such as $^{26}Al/^{27}Al$, $^{10}Be/^{9}Be$ and $^{36}Cl/^{37}Cl$. Most of the ratios agree with observations. However, the $^{10}Be/^{9}Be$ ratio is about a factor of two smaller than the observations and its energy dependence deviates significantly. We attribute this discrepancy to uncertainty of partial cross section of ^{10}Be production. Another possible solution is introduce large enough reacceleration during interstellar propagation.

(c) Our code can allow us to handle small-scale inhomogeneity of the interstellar medium. As an example run, we have run a model that includes a super bubble of a radius of 200 pc centered at the solar system. The bubble has a much lower gas density than the average interstellar medium. We found that the bubble doesn't affect the abundance ratio of stable cosmic ray nuclei, but it affects that the abundance of radioactive nuclei with short lifetime. For example, the $^{10}Be/^{9}Be$ ratio from the super bubble model becomes even lower. So it cannot explain the discrepancy in (b)

(d) Because code can let us trace particle history, we can gain deeper understanding of the physics of cosmic ray propagation. This is the unique advantage of this code over other codes developed by researchers in the community.

(e) We have traced the history of secondary particle production process and found the contribution of primary cosmic rays to the resulting cosmic ray nucleus type we see at Earth. For example, of all the carbon cosmic ray nuclei we measured, only ~40% are from primary cosmic rays while ~60% are produced from heavier cosmic ray primaries such as oxygen, iron, etc. This is a significant new result that can help us to understand the cosmic ray measurements better. We have also looked at the production of other cosmic ray species. We found that many secondary cosmic rays are produced mainly from a few most abundant cosmic ray primaries. For example, Boron is mainly produced from carbon and oxygen and chlorine is mainly from iron. This result suggests that we simplify the calculation of secondary cosmic ray production. If a calculation of cosmic ray abundance suffers a large uncertainty due to uncertainty in cross section, we can actually search for solution which cross section in particle production chain needs improvement rather than the whole nuclear reaction network.

(f) We made a calculation of the spatial distribution of cosmic ray sources that contribute to cosmic ray we see at the Earth. We found that most cosmic rays come from within 5 kpc. Primary cosmic rays have a different distribution from that of secondary

cosmic rays. Sources are confined in the disk but particle transport is mainly through diffusion in the halo.

The above work has been submitted to Astrophysical Journal for publication. Attached is a copy of the paper. Because the work contains a number of new developments, we expect a positive response from referees. One of my students, Ashraf Farahat, based his Ph.D. dissertation entirely on this work. Ashraf Farahat received his degree in May 2005.

We look at the effect of anisotropic diffusion coefficient on cosmic ray distribution. The average magnetic field in the Galactic disk is considered to be either a spiral or circular. The diffusion coefficient parallel to the magnetic field varies from 1 to 10 times the diffusion coefficient perpendicular to the average magnetic field. We find that the anisotropy of the diffusion coefficient has little effect on the radial distribution of diffuse gamma-ray emission, but the main effect of the large-scale magnetic field is on the azimuth distribution. Currently, there are not enough data to decide whether the average field and anistropic diffusion play a role on cosmic ray interstellar propagation. We have not published this work, because we consider the results are still preliminary and the conclusions can change when different model parameters are inputted.

In addition, because solar modulation affects cosmic ray composition at energies below ~5 GeV/n, we have done a number of studies of cosmic ray modulation in the heliosphere. One of our studies find that the modulation parameter commonly cited in the paper is an ambiguous number if we use different modulation models. For example, the code using force-field approximation of 1-d modulation equation will produce different cosmic ray spectra and composition for the one that solve the modulation equation exactly with the same modulation parameter. However, if we first use measured cosmic ray proton spectrum to constrain the modulation parameter, the composition calculations from the two models are very close.

In summary, we have achieved our main goals outlined in our proposal. The major part of work, the development of a comprehensive code of cosmic ray propagation in interstellar space, has been completed. Results of model runs are new and encouraging. The code has opened up many new opportunities to look at galactic cosmic rays using various kinds of models. For future work, we will run models with different galactic magnetic field configurations and different interstellar medium distribution such as lumpy molecular clouds or random cosmic ray sources.

Papers produced under full or partial support of this grant

1. "Numerical Model for Cosmic Rays Species Production and Propagation in the Galaxy", A. Farahat, M. Zhang, H. Rassoul, H. and J.J. Connell, submitted to Astrophys. J., April 2005
2. "The Compton-Getting Effect of Energetic Particles with an Anisotropic Pitch-Angle Distribution: An Application to Voyager 1 Results at ~85 AU", Ming Zhang, Astrophys. J., 624, 1038, 2005.
3. "The Compton-Getting Effect of Energetic Particles with an Anisotropic Pitch-Angle Distribution", Ming Zhang, Adv. Space Res., in press, 2004.
4. "Perpendicular transport of solar energetic particles in heliospheric magnetic fields", Ming Zhang, J.R. Jokipii, and R.B. McKibben, Astrophys. J., 595, 493, 2003.
5. "Ulysses Observations of Solar Energetic Particles From the July 14 of 2000 Event at High Heliographic Latitudes", Ming Zhang, R. B. McKibben, and C. Lopate, J. R. Jokipii and J. Giacalone, M.-B. Kallenrode, H. K. Rassoul, J. Geophys. Res., 108, 1154, 2003.
6. "Modulation of galactic cosmic rays at solar maximum: observations", Ming Zhang, Adv. Space Res. 32, 603-614, 2003.
7. "Perpendicular Diffusion and Drift of Solar Energetic Particles in Heliospheric Magnetic Fields", M. Zhang, J.R. Jokipii and R.B. McKibben, Proc. 28th ICRC, 3495-3498, 2003
8. "Modulation of Galactic Cosmic Rays near and beyond the Termination Shock", B. Ball and M. Zhang, Proc. 28th ICRC, 3839-3842, 2003
9. "Calculation of Elemental and Isotopic Abundance of Cosmic Rays Using Markov Stochastic Theory: The Effect of Local Superbubble", A. Farahat, M. Zhang, H. Rassoul and J.J. Connell, Proc. 28th ICRC, 1957-1960, 2003