MODELLING COSMIC-RAY EFFECTS IN THE PROTOSOLAR DISK.

T. L. Wilson, NASA, Johnson Space Center, Houston, TX 77058, thomas.l.wilson@nasa.gov.

Introduction: The role that Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) play in the dynamic evolution of protosolar disks and the origin of our Solar System is a fundamental one. The GCRs are an important component of the interstellar medium (ISM), and even play a role in correcting the age determinations of some irons versus CAIs (calcium-aluminum inclusions) in meteoroids [1]. Because CRs also are one of the energy transport mechanisms in a planetary nebula, the question of modelling their effect upon this broad subject is a serious topic for planetary science. The problem is addressed here.

Relevance of the Modelling Problem: CRs are energetic nuclei that interact with Solar System matter, the physical nature and depth of collisional interaction being a function of energy. Chondrites, for example, are extraordinary mixtures of presolar and solar nebular materials and asteroidal debris [1] that have undergone numerous changes, some of which include nuclear transmutation and heating induced by CRs. The original chemical and physical state of such material has thus been extensively obscured by complex processes and isotopic change [2], some of which is reflected in CR exposure histories [3]. The physics and chemistry are basically understood but the ambient CR environment is highly variable and usually unknown. This can be seen in the X-wind model of Shu et al. [4, 5] and the bipolar jet model of Liffman & Brown [6].

Modelling the effect of CRs during the formation of the Solar System is thus a daunting task. For example, one hypothesis is that ^{26}Al may have been produced in the presolar molecular cloud due to irradiation by CRs [7, 2]. Another is the complex nature of the proto-Sun's journey through the local ISM (LISM), both past and present [8-22]. Hence, CRs serve at least two roles during the origin of solar systems, both as a radionuclide transmutation mechanism as well as for the transport of energy. These obscure the entire process of formation of what actually happened, yet is analyzed in present-day meteorites and extraterrestrial samples.

Misconceptions: An additional problem regarding CR effects involves a serious misconception in the literature. A number of authors [e.g. 23-24] have made claims that the astrophysical interaction of particles such as CRs in the ISM can be simulated using accelerated-ion beams from Earth-based particle accelerators. It is true that the latter have been used for CR calorimeter calibrations [25] but this is not the same thing. The notion that accelerator beams can simulate a CR flux is false, and that fact has been demonstrated experimentally at CERN using CERF (CERN-EU High-Energy Reference Field) [26] embedded in the SPS (Super Proton Synchroton) beamline there. CERF attempted to moderate accelerator beams in an effort to simulate radiation fluxes and spectra at aircraft and space altitudes where neutrons and muons dominate. When CERF was adjusted to produce the neutron spectra, it failed for the muons – and vice versa.

The reason is quite simple. GCRs and SEPs are single-event phenomena whereas accelerator beams have astronomical luminosities (comparatively speaking) and do not represent the same physics as CR interactions. CERF showed that the resultant muon fluxes during intranuclear cascades were wrong in comparison to CR-induced events.

In summary, a comprehensive strategy for analyzing CRs in the protosolar disk is necessary and must involve satisfactory computational models using Monte Carlos, ISM transport codes, and dynamic modelling of the proto-Sun and heliosphere.

CRs and Protoplanetary Disks: When the embedded young Sun appeared in a solar nebula forming from dense molecular clouds that made up the LISM of our Galaxy, a basic structure for the Solar System emerged. A solar wind appeared that created a bowshock in the LISM as the proto-Sun rotated about our Galactic Center, and a heliosphere formed. The heliosphere and its interaction with the LISM are the principal regulatory mechanisms defining the ambient CR environment. Analytical studies are usually comprised of a hydrodynamic or magnetohydrodynamic (MHD) adaptation of two counterflowing fluids [18], the solar wind and the interstellar plasmas in a three-phase ISM [27]. Some energetic neutral particles are unaffected by the bowshock but later become photoionized CRs known as anomalous CRs (ACRs) [8, 10, 11, 15].

The solar wind consists of energetic plasma with an embedded magnetic field that modulates the GCR flux. The modulation involved is usually based upon a time-dependent transport equation originating with Parker [28] that is derived from Fokker-Planck theory

$$\frac{\partial f}{\partial t} = -(\boldsymbol{V} + \langle v_d \rangle)\cdot\nabla f + \nabla\cdot(\boldsymbol{K}\cdot\nabla f) + \frac{1}{3}(\nabla\cdot\boldsymbol{V})\frac{\partial f}{\partial \ln P} + Q \qquad (1)$$

where $f(\boldsymbol{r}, P, t)$ is the CR distribution function, P is rigidity, $\boldsymbol{r}$ is position, $\boldsymbol{V}$ is solar wind velocity, Q is some source function, and t is time. $\boldsymbol{K}$ represents the symmetric diffusion tensor, and one of the most relevant assumptions in CR modulation studies [8-22] is its component diffusion coefficients.

The subject such as Eq. (1) has a long history involving MHD plasma theory (for what is known as the Navier-Stokes-MHD regime, K_n<<1) or the kinetic Boltzmann transport equation (known as the kinetic regime, K_n>>1). Because MHD is a *fluid* theory (nonlinear Navier-Stokes), it cannot be used for *kinetic* phenomena (Boltzmann equation). The difference is determined by the Knudsen number K_n, with the transition between being defined as $K_n = 1$.

Using these fluid and kinematic transport codes one can attempt to simulate the CR environment about the protosun for the X-wind [4, 5], the bipolar jet model [6], or any other as appropriate. At the present time, in contrast, our heliosphere is basically a low-density cavity carved out of the LISM by the solar wind [12]. It is embedded in a warm, low-density interstellar cloud flowing through a local rest frame at ~18 km s^{-1}.

Galactic Propagation Models: Clearly the CR flux varies not only due to modulation by solar activity via the solar wind, but it also changes due to a variable heliosphere in response to its interaction with the dynamic LISM.

How can one address the basic question of CR-induced properties observed in cosmochronic archives such as ice cores or chondrites? The computational tools all exist, consisting of three basic categories: the plasma transport codes, the dynamic solar modulation codes, and the Monte Carlo interaction codes. The first two have been discussed above, while the third takes the modulated CR plasma flux as an input to induce changes in cosmogenic materials such as chondrites, primitive meteorites, interplanetary dust, asteroids, comets, and lunar rock or regolith. One of the best Monte Carlos is FLUKA used at CERN [29, 30].

To the blend above must be added a newcomer that is seeing a number of important applications such as the Fermi Gamma-Ray Large-Area Telescope (GLAST). This is the existing Galactic Propagation (GALPROP) code available through Stanford University and partially funded by NASA [31-34]. The interpretation of current data from today's CR and γ-ray detecting satellites requires something beyond previous transport codes - which is one of GALPROP's primary goals. It is essential to upgrade many of the older existing codes using measurements being made today in both astrophysics and CR physics [31, 35-37].

Hence GALPROP represents an effort to incorporate some of the latest spacecraft measurements such as EGRET [31] and other astrophysical data from BESS [35], ATIC [36], and Pamela [37] into the numerical propagation codes that deal with LISM and heliospheric variations that influence CR flux. Similar modifications can prove useful in the study of CR contributions to the protosolar disk and our own Solar System when the three basic code categories are adequately addressed.

References: [1] Scott E. (2007), *Ann. Rev. Earth Plan. Sci., 35,* 577–620. [2] Reedy R.C., Arnold J.R., Lal D. (1983), *Science, 219,* 127-135. [3] Marti K., Graf T. (1992), *Ann. Rev. Earth Planet. Planet. Sci., 20,* 221-243. [4] Shu F. Et al. (2001), *Ap. J., 548,* 1029-1050. [5] Shu F., Shang H., Lee T. (1996), *Science, 271,* 1545-1552. [6] Liffman K., Brown M. (1996), in Hewins R. et al., eds., *Chondrules and the Protoplanetary Disk* (Cambridge Univ. Press), 285-302. [7] Morfill G.E., Hartquist T.W. (1985), *Ap. J., 297,* 194-198. [8] Ferreira S., Scherer K. (2004), *Ap. J., 642,* 1256-1266. [9] Ferreira S., Pogieter M.S. (2004), *Ap. J., 603,* 744-752. [10] Florinski V. et al. (2004), *Ap. J., 610,* 1169-1181. [11] Le Roux J., Fichtner H. (1997), *Ap. J., 477,* L115-L118. [12] Müller H.-R. et al. (2006), *Ap. J., 647,* 1491-1505. [13] Pogorelov N., Zank G., Ogino T. (2006), *Ap. J., 644,* 1299-1316. [14] Zank G., Frisch P. (1999), *Ap. J., 518,* 965-973. [15] Scherer K. et al. (2008), *Ap. J., 680,* L105-L108. [16] Scherer K. et al. (2008), *Adv. Spa. Res., 41,* 1171-1176. [17] Borrmann T., Fichtner H. (2005), *Adv. Spa. Res., 35,* 2091-2101. [18] Fahr H., Kausch T., Scherer H. (2000), *Astron. Ap., 357,* 268-282. [19] Büsching I., Potgieter M.S. (2008), *Adv. Spa. Sci., 44,* 504-509. [20] Fichtner H. (2005), *Adv. Spa. Sci., 35,* 512-517. [21] Frisch P., Slavin J. (2006), *Astrophys. Spa. Sci. Trans., 2,* 53-61. [22] Scherer K., Ferreira S. (2005), *Astrophys. Spa. Sci. Trans., 1,* 17-27. [23] Tombrello T.A. (1983), *IEEE Trans Nucl. Sci., NS-30,* 1169-1172, Fig. 7. [24] Mocchizuki K. et al. (1993), *Meteoritics, 28,* 405. [25] Ganel O. et al. (2001), *Adv. Spa. Res., 27,* 819-824. [26] Mitaroff A., Salari M. (2002), *Rad. Protection Dosimetry, 102,* 7-22. [27] Cox D. (2005), *Ann. Rev. Astron. Astrophys., 43,* 337-385. [28] Parker E.N. (1965), *Plan. Spa. Sci., 13,* 9-49. [29] Ballarini F. et al. (2007), *Adv. Spa. Sci., 40,* 1339-1349. [30] Wilson T. (2007), *Proc. 30th International Cosmic Ray Conf., 4,* 655-658. [31] Ptuskin V.S. et al. (2006), *Ap. J., 642,* 902-916. [32] Strong A., Moskalenko I., Reimer O. (2004), *Ap. J., 613,* 962-976. [33] Moskalenko I. et al. (2002), *Ap. J., 565,* 280-296. [34] Strong A., Moskalenko I. (2001), *Adv. Spa. Res., 27,* 717-726. [35] Wang J. et al. (2002), *Ap. J., 564,* 244-259. [36] Chang J. (2008), *Nature, 456*, 362-363. [37] Donato F. et al. (2009), *Phys. Rev. Lett., 102*, 071301.