A Comparison of Models of Cosmic-Ray Source Composition

R. Silberberg, C.H. Tsao and A.F. Barghouty[1]

Physics Department, Roanoke College, Salem, VA 24153, USA

Abstract

Several models for the origin of cosmic rays have been proposed to explain the relative differences of cosmic-ray source abundances and the general abundances of elements and isotopes. One model, for example, assumes injection at normal stars like the sun, using FIP-modified coronal rather than photospheric abundances. Another with acceleration and breakup of grains by supernova shock waves has been popular with several authors. On the basis of the known abundances of few elements, we demonstrate how a critical evaluation of one model's merits against the others can be made.

1   Source Composition and the Origin of Cosmic Rays:

The elemental and isotopic abundances of cosmic rays (CR), when corrected for spallation in the interstellar gas back to the source(s) tend to resemble the general abundances, e.g. Grevesse and Anders (1989), but also display some significant differences. The general abundances (GA) are based on solar spectra and carbonaceous chondrite meteorites. The elements H, He and N are underabundant in CR by a factor of 20-30 relative to GA. The nuclide ^{20}Ne is underabundant in CR by a factor of 6, the elements O, S, Ar and Kr by a factor of about 4, and C, Zn, Se, Xe and the nuclide ^{22}Ne by a factor of 2. Also, the r-process part of lanthanides and Pt is overabundant in CR by a factor of 2, and the r-process actinides (Th with U) are overabundant in CR by a factor of 4.

A number of models have been proposed to account for such differences, all in one form or another attempting to delineate the composition with the origin of cosmic rays. The observed cosmic-ray elemental and isotopic abundances can, in principle (i.e., with assumed high precision in the relevant cross sections and with realistic galactic propagation calculations), help discriminate among these models. Below, we illustrate how one can, on the basis of known abundances of few elements, critically evaluate such models.

1.1   Models Based on the Acceleration of Material from Supernovae: In this model, proposed by Yanagita et al. (1990) and more recently by Lingenfelter et al. (1998), cosmic rays are thought to originate in freshly formed material from supernovae, particularly grains in young supernova remnants. Here the "age" of cosmic rays after nucleosynthesis should be similar to the galactic confinement time deduced from, e.g., ^{10}Be. With such a relatively short age, about 1-2 $\times$ 10^7 years, trans-uranic nuclei like Pu and Cm should survive. From Blake and Schramm (1974) one can deduce that for an "age" of $\sim 10^7$ years the ratio (U+Pu+Cm)/Th should be ~ 7.

The observed ratio from LDEF (Long Duration Exposure Facility) from Thompson et al. (1993), Domingo et al. (1995) and Keane et al. (1997) is, however, only 0.7$\pm$0.3 with Cm $\sim$ Pu $\sim$ 0. Fig. 1 shows the time after nucleosynthesis that corresponds to the observed LDEF abundance ratio and that predicted by this model, i.e., $\sim 10^9$ and $\sim 10^7$, respectively. The LDEF ratio suggests an origin for cosmic rays in stars or interstellar medium derived mainly from supernovae over about 10^9 years ago.

1.2   Models Based on the Acceleration of Pre-Supernova Stellar Wind Particles: Silberberg et al. (1990) proposed that the initial phase of acceleration by the supernova shock waves boosts many of the pre-supernova stellar wind particles to cosmic ray energies. These wind particles, especially in the Wolf-Rayet stars, are enriched in products of He-burning, i.e., ^{12}C and ^{16}O, and of He+N burning that yields (in 2 steps) ^{22}Ne. In this model, there is an early yield in the history of the galaxy of an abundance of nuclei that, via spallation, yield Be and B.

---

[1]Present address: California Institute of Technology, MC 220-47, Pasadena, CA 91125, USA.
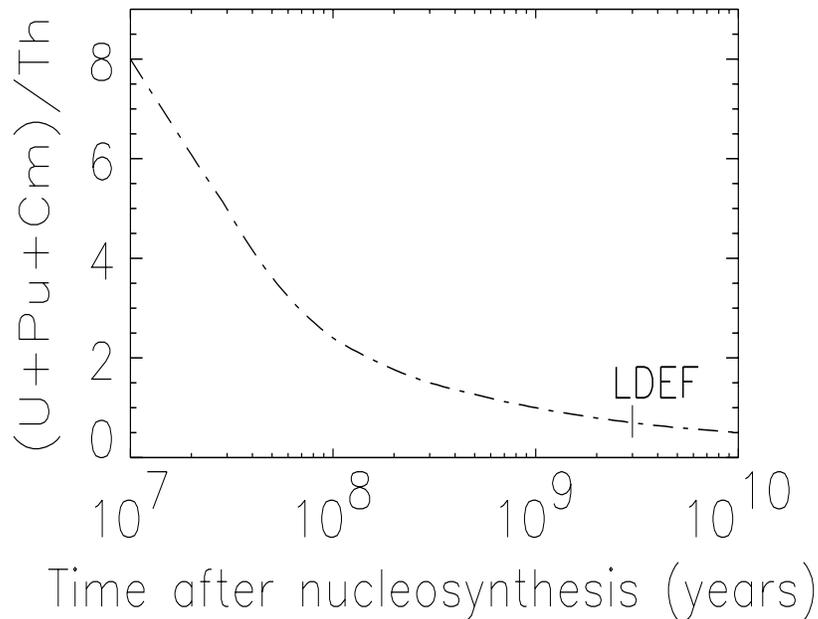
Figure 1: The ratio (U+Pu+Cm)/Th as a function of time after nucleosynthesis, based on Blake and Schramm (1974). The LDEF-observed ratio suggests a time on the order of 10^9 years, whereas model 1 implies a time on the order of only 10^7 years.

After the supernova shock wave has passed through the region of the pre-supernova wind particles, it proceeds to accelerate the stellar flare particles (see section 1.4) or gas with non-volatile grains (see section 1.5). While this model does account for the observed yields of B and Be, it needs to be combined with other acceleration models, e.g., 4 and/or 5, for it to be consistent with other observed composition.

1.3 Models Based on the Acceleration of Material in Bubbles with Multiple Supernova Remnants: Higdon et al. (1998) proposed this model in which, after nucleosynthesis, the acceleration takes place predominantly after 10^5 years and up to the bubbles' lifetime of 5×10^7 years, so as to allow ^{57}Ni to decay before acceleration (the half-life of ^{57}Ni is $\sim 10^5$ years). This model is not consistent with the observed U/Th abundance ratio and the corresponding time after nucleosynthesis depicted in Fig. 1.

1.4 Models Based on the Acceleration of Stellar Flare Particles: Here the initial injection is at normal stars like the sun, with photosphere-to-corona particle escape dependent on the first ionization potential (FIP). If FIP < 10 eV (which corresponds to a temperature of about 10^4 K), these elements have higher abundances. This stellar-injected component is supplemented by the Wolf-Rayet star component that contributes significantly to ^{12}C, ^{16}O and ^{22}Ne, and a fraction of ^{4}He. The FIP-dependent suppression of high-FIP elements was proposed by Havnes (1971), Casse, Goret, Cesarsky (1973) and Meyer (1985). Flare stars as injectors of cosmic-ray nuclei were proposed by Shapiro (1997). The Wolf-Rayet contribution was proposed by Meyer (1981).

An additional process is needed to fit the elements H, He, N, Na and the nuclide ^{20}Ne. Silberberg and Tsao (1990) proposed such a procedure wherein a rigidity-dependent suppression of ions near 1 MeV/nucleon, which is on the order of a flare-particle energy, takes place. Heavier nuclei, due to multiple electron pickup

have $Z_{eff}/Z < 1$, hence they have a relatively higher rigidity and undergo easier escape from the stellospheres. Equation (1) of Silberberg and Tsao (1990) relates CR source to GA. Fig. 2 below, based on that relation, compares the calculated and observed source abundances. The fit for the 18 elemental and isotopic abundances is about 20%.

The data of Binns et al. (1989) implies an enhancement of the r-process elements at and beyond the r-process peak at Z=52,54. For the elements Ge and Pb, the stellar flares model has to adopt the solar spectral abundances rather than the meteoritic abundances, as more representative of the general galactic abundances.
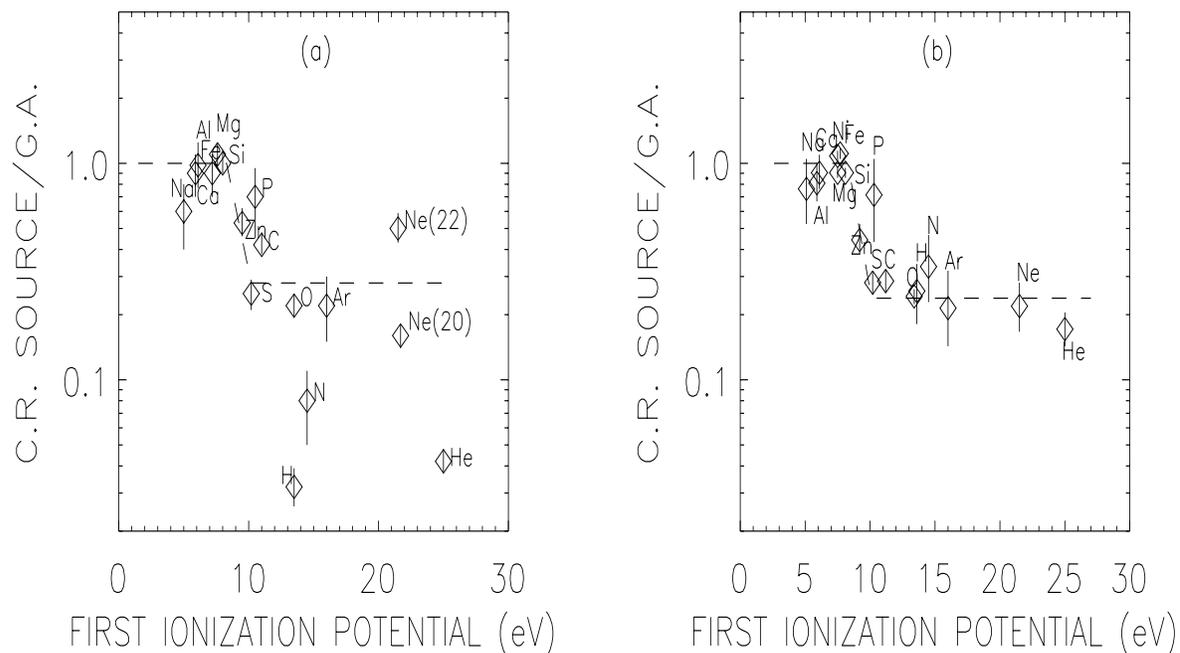
Figure 2: The ratio of cosmic-ray source abundances to general abundances for Z<29, and Zn, before (a) and after (b) correcting for light element suppression and Wolf-Rayet star contribution. (From Silberberg and Tsao, 1990.)

1.5 Models Based on the Acceleration of Grains and of Interstellar H and He:

In this model there is preferential acceleration of non-volatile or refractory elements whose condensation temperature is above 10^3 K. The grains are accelerated by supernova remnant shock waves, break up, and are again accelerated by the supernova shock waves together with the relatively less abundant volatile nuclei. This model was first proposed by Bibring and Cesarsky (1981), Sakurai (1990), and recently discussed in detail by Meyer, Drury and Ellison (1997).

The standard deviations of the FIP and grain models have been calculated. For P, the FIP model deviates by 2 standard deviations (s.d.). For Te, the grain model deviates by 2-3 s.d. and for Cu, Ga, Sn and (Th,U) by 1 s.d. Thus, the data appear to slightly favor the stellar flare (i.e., FIP-dependent) injection model over the grain acceleration model.

References

Bibring, J.P. and Cesarsky, C.S., 1981, Proc. 17th ICRC (Paris) 2, 289

Binns, W.R. et al., 1989, ApJ 346, 997

Blake, J.B. and Schramm, D.N., 1974, Ap. Space Sci. 30, 275

Casse, M., Goret, P. and Cesarsky, C.S. 1975, Proc. 14th ICRC (Munich) 2, 646

Domingo, C. et al., 1995, 24th ICRC (Rome) 2, 572

Grevesse, N. and Anders, E., 1989, in Cosmic Abundances of Matter, J.C. Waddington, ed., AIP Conf. Proc. 183, (New York: AIP)

Havnes, O., 1971, Nature 229, 548

Hayakawa, S., 1969, in Cosmic Ray Physics, (New York: Wiley)

Higdon, J.C., Lingenfelter, R.E. and Ramaty, R., 1998, ApJL, 509, L33

Keane, A.J. et al., 1997, 25th ICRC, (Durban) 3, 361

Knott, C.N. et al., 1997, Phys. Rev. C56, 398

Lingenfelter, R. E., Ramaty, R. and Kozlovsky, B., 1998, ApJL 500, 2153

Meyer, J.P., 1981, 17th ICRC (Paris) 2, 265

$---$, 1985, ApJ 57, 173

Meyer, J.P., O'C.Drury, L., and Ellison, C., 1997, ApJ 487, 182

Sakurai, K., 1990, in Cosmic Rays, Supernovae and the Interstellar Medium, M.M. Shapiro, R. Silberberg and J.P. Wefel, eds., (Dordrecht: Kluwer)

Shapiro, M.M., 1997, 25th ICRC (Durban) 4, 353

Silberberg, R. and Tsao, C.H., 1990, ApJL 352, L49

Silberberg, R., Tsao, C.H., Shapiro, M.M. and Biermann, P.L., 1990, ApJ 363, 265

Thompson, A. et al. 1993, 23rd ICRC (Calgary) 1, 601

Yanagita, S., Nomoto, K. and Hayakawa, S., 1990, 21st ICRC (Adelaide) 4, 44