SPALLOGENIC ORIGIN OF NUCLEI IN METEORITES

B.ZANDA[1] AND J.AUDOUZE[1,2]

1 Institut d'Astrophysique du CNRS,
98 bis, boulevard Arago
75014 Paris, FRANCE

2 Laboratoire René Bernas,
91405 Orsay, FRANCE

1. Introduction

The study of the cosmic ray fluxes propagation inside meteorites is a way to improve our knowledge both on these objects (exposure ages, size of irradiated parent bodies, location of samples within these bodies...) and on these fluxes (spectral index, total intensity, time variation...).

In this communication, we present some preliminary results obtained from a model built to evaluate the different interactions between cosmic rays and meteorites. With this model, we are able to compute fluxes as a function of depth inside the meteorite, taking into account energy losses by ionization and spallation reactions which induce both particle destruction and production. This procedure, in which particle fluxes and cross sections are treated independently from each other, differs significantly from the thick target approach (see Kohman & Bender-1967, Trivedi & Goel-1973) based on the measurement of spallation products generated in accelerator experiments.

2. Cosmic rays propagation inside meteorites

The basic equation describing the independent of time variation with depth of the flux Φ_i ($cm^{-2}\ s^{-1}\ MeV^{-1}$) can be written as :

$$\Omega\nabla\ \Phi_i + \sigma\ n\ \Phi_i = Q_i + \frac{\partial(\omega_i\ \Phi_i)}{\partial E} \qquad (1)$$

where
- σ is the total destruction cross section of nuclear species i
- n is the number of target nuclei per unit volume,
- Q_i is the production term of secondary particles,
- ω_i is the energy loss of nucleus i due to excitation and ionization of the target medium ($\omega_i = -dE/dx$)
- The streaming factor $\Omega\nabla$ depends on the geometry of the meteorite :
  If θ is the propagation angle,

- $\Omega\,\nabla = \cos\theta \frac{\partial}{\partial x}$ in plane parallel geometry

  x being the depth inside the meteorite
- $\Omega\,\nabla = \cos\theta \frac{\partial}{\partial r} + \frac{\sin^2\theta}{r} \frac{\partial}{\partial(\cos\theta)}$ in spherical geometry,

  r being the distance from the center.

3. Asymptotical behaviour of the transport equation at high energy

Above 1 GeV N^{-1}, energy losses and secondary particles production become negligible. Therefore, equation (1) reduces to :

$$\Omega\,\nabla\,\Phi_i + \sigma\,n\,\Phi_i \simeq 0 \qquad (2)$$

The boundary conditions are :

$$\phi\,(0,\cos\theta) = \Phi_{i,o} \qquad (0<\theta<\frac{\pi}{2}) \text{ in slab geometry}$$

$$\phi\,(R,\cos\theta) = \Phi_{i,o} \qquad (-\frac{\pi}{2}<\theta<\pi) \text{ in spherical geometry}$$

(we assume here that the incoming cosmic ray flux $\Phi_{i,o}$ is isotropic).

With such conditions, the solutions of equations (2) are :

$$\Phi_{slab}\,(x,\cos\theta) = \Phi_0 \exp(-\frac{\sigma n x}{\cos\theta})$$

$$\Phi_{spherical}\,(r,\cos\theta) = \Phi_0 \exp[-\sigma\,n(r\cos\theta + \sqrt{R^2-r^2\sin^2\theta}]$$

In figure 1, we compare the integrated flux ϕ over all directions calculated as a function of depth inside a meteorite in the case (i) of a plane parallel shape and (ii) of a spherical shape with R= 40 cm. It can be seen that the flux is always lower if calculated in the plane parallel assumption than in spherical geometry. The error made in treating a spherical 40 cm radius meteorite as an infinite slab would only be of a factor 1.2 at the surface but it would become as high as a factor 8 in the center.

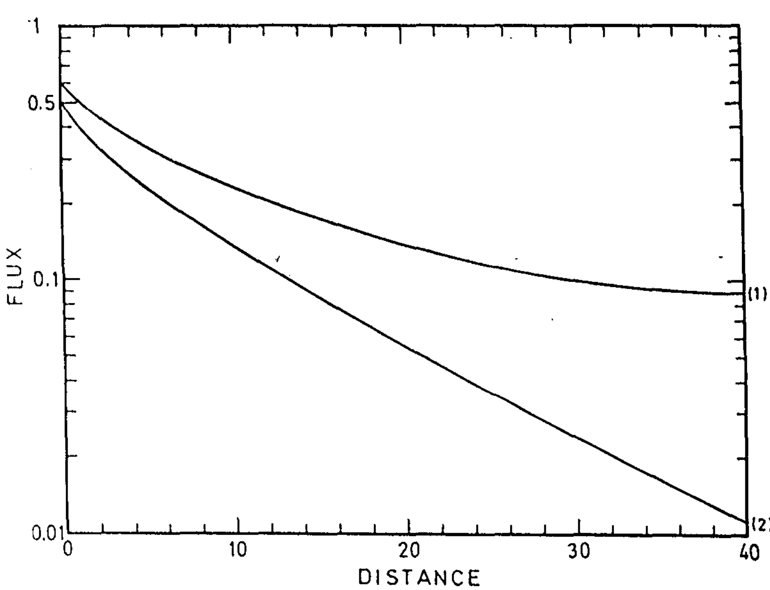

Figure 1

Comparison of depth dependent integrated fluxes (1) in spherical geometry and (2) in slab geometry. Note that the surface flux (1) is higher than (2) because of outgoing particles.

4. Solution of the complete equation including secondary particles production and energy losses

We have adopted the following procedure and assumptions:
(i) the ionization energy loss dE/dx was calculated from the Gloeckler formula (1970),
(ii) the secondary particles production can be written as :

$$Q(E,\cos\theta,r) = \int_E^\infty \sigma(E')\, P(E'\to E)\, \Phi(E',\cos\theta,r)\,dE'$$

where $P(E'\to E)$ is the probability to produce a secondary particle of energy E from a primary particle of energy E'.

In this preliminary approach, we used $P(E'\to E)= \frac{P}{E'}$,
where P, the average number of outgoing secondaries per spallation reaction is an ajustable parameter of our calculation, and the secondary spectrum is assumed to be flat.

The presence of an integral term in the second member of (1) requires the use of iterative computations.
This can be described as follows :

$$(\Omega\,\nabla + \sigma\, n - \frac{\partial\omega i}{\partial E})\, \phi^{(n)} = \int_E^\infty P\, \frac{\phi^{(n-1)}}{E'}\, dE'.$$

Details of the flux computations will be described in Zanda (1985).

The spallation cross-sections used to deduce nuclei production are derived from Silberberg and Tsao (1972a, 1972b, 1977, 1979).

The energetic particles may have two origins :
(i) the galactic cosmic rays which are modulated by the solar activity (we derived our modulated spectrum out of Proteroe, Ormes and Comstock -1981),
(ii) the solar cosmic ays. Since this solar source consists in particles with E<100 MeV, it only affects the first few centimeters of the meteorite and will not be considered here.

5. Preliminary results

Because of the existing experimental data, we chose to first test our model on the iron meteorite Grant. Computations were made for a meteorite having the same chemical composition and various radius (40 cm, 35 cm and 30 cm) admiting a secondary particle yield per interaction p=0.75. Figure 2 shows a comparison of our results with measurements by Signer and Nier (1960) for Ne21. It can be seen that there is a good agreement between calculation results and experimental datas for a radius of 35 cm which is a little less than the pre-atmospheric radius that these authors derived of their calculation.

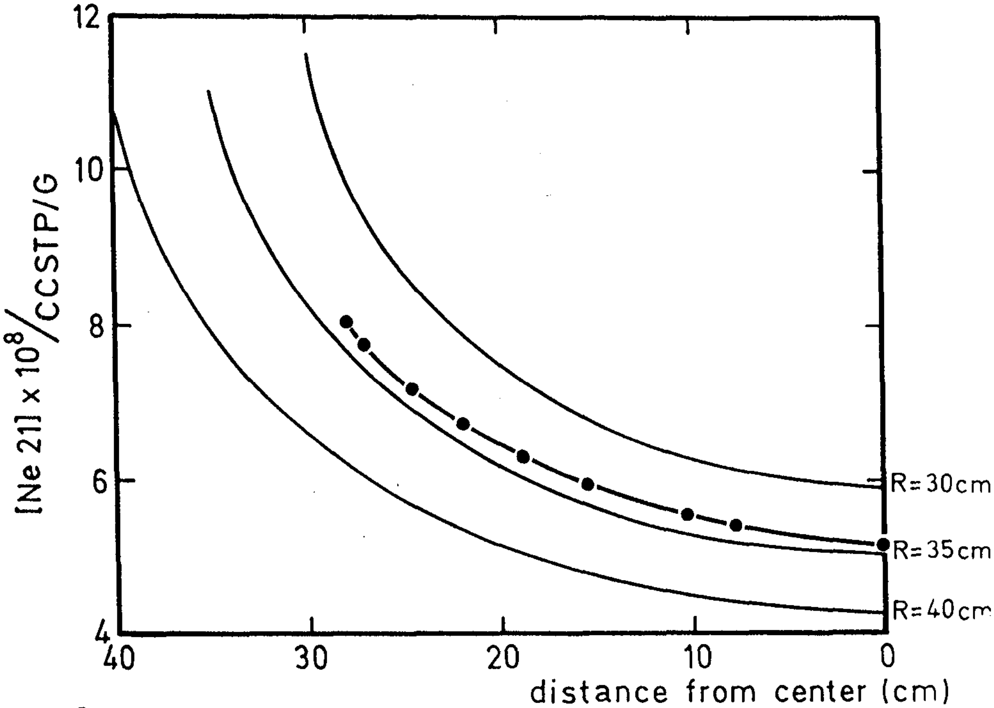

Figure 2
Comparison of computations results for various radius (single curves) and experimental datas from Signer and Nier (dotted curve).

6. Conclusion

The results obtained with the model presented here are sufficiently encouraging to pursue and improve that type of studies, in particular by finding a proper treatment for the outstanding problem of secondary particles production. Unfortunately, taking into account the actual geometry of a meteoritical sample at the time it suffers the bulk of the cosmic ray irradiation will still remind a difficulty.

We wish to thank G. Malinie for helpful discussions throughout the preparation of this paper.

7. References

1. Gloekler, G., (1970), in "Introduction to Experimental Techniques of High Energy Astrophysics" p.1, Ogelman H. and Wayland J.R. Ed. NASA SP-243
2. Kohman, J.P., and Bender, M.L., (1963) in "High Energy Nuclear Reactions in Astrophysics" p.169, B.S.P. Shen Ed. Benjamin, New York
3. Proteroe, R.J., Ormes, J.F. and Comstock, G.M., (1981) Ap.J., 247, p.362
4. Signer, P., and Nier, A.O., (1960), J.G.R., 65, p.2947
5. Silberberg, R., and Tsao, C.H., (1972a&b), Ap.J.Suppl. series, 220, p.315 & p.335
6. Silberberg, R., and Tsao, C.H., (1977), in 15th I.C.R.C., Plovdiv, 2, p.84
7. Trivedi, B.M.P., and Goel, P.S., (1973), J.G.R., 78, p.4845
8. Tsao, C.H., and Silberberg, R., (1979) in 16th I.C.R.C., Kyoto, 2, p.202.