PHYSICAL REVIEW VOLUME 122, NUMBER 6 JUNE 15, 1961

Spallation of Interstellar Matter: Cosmic-Ray Intensity in the Past*

S. N. MILFORD
Department of Physics, St. John's University, Jamaica, New York

AND

S. P. SHEN
Department of Physics, St. John's University, Jamaica, New York and State University of New York, Albany, New York

(Received February 2, 1961)

It is pointed out that spallation of interstellar matter by cosmic rays occurs, and that the lithium, beryllium, and boron thus produced can be used as rough indexes of the average interstellar cosmic-ray intensity. Using available data, this method gives an upper limit of the order of 10 $\text{cm}^{-2}\ \text{sec}^{-1}$ for the intensity of interstellar cosmic rays of kinetic energy $>\sim 50$ Mev, averaged temporally over the past few billion years and spatially over several cubic kiloparsecs in the solar neighborhood.

SPALLATION reactions have been studied in targets exposed to accelerator beams[1] as well as to cosmic rays (e.g., in meteorites[2]), and are believed to be important on the surface of certain stars.[3] Spallation reactions initiated by cosmic rays in condensing protostars have also been considered previously.[4]

Spallation reactions must also occur *in interstellar matter* bombarded by interstellar cosmic rays. (The "inverse" process, the fragmentation of heavy cosmic-ray nuclei by interstellar matter, is well known.[5]) In the spallation of interstellar matter by interstellar cosmic rays, the following relation holds:

$$n_{PD}=\int_{t=0}^{\tau}\int_{E=0}^{\infty} n_{TG}(t)\,j(E,t)\sigma(E)dEdt, \qquad (1)$$

where t is the time, E the kinetic energy of the bombarding particle in the laboratory system, σ the production cross section, τ the bombardment period, j the differential intensity of interstellar cosmic rays, and n_{TG} and n_{PD} the abundances of the target and product nuclei, respectively. j, n_{TG}, and n_{PD} are averages over some volume of space.

For the present application, Eq. (1) will be written in the approximate form,

$$(n_{PD}/n_{\text{Na}})=(n_{TG}/n_{\text{Na}})J\sigma\tau, \qquad (2)$$

where n_{TG} is now averaged also over the bombardment period τ, n_{Na} is the abundance of interstellar sodium, J is the integral intensity, averaged over time and space, of interstellar cosmic rays of kinetic energy above the "threshold" energy explained below, and σ is now the constant production cross section for energy above the "threshold".

Consider in particular the production of interstellar Li, Be, and B by cosmic-ray bombardment of interstellar C, N, and O. Nearly all of the Li, Be, and B produced appear as residual nuclei rather than as knock-on or evaporation particles from the high-energy reactions, and hence have kinetic energies of not more than several tens of Mev. These are eventually slowed, without destruction, by the interstellar medium. After acquiring electrons, they should become spectroscopically observable.

The origin of interstellar Li, Be, and B is at present not well known; nor are their abundances.[3,4,6,7] In studying the spectra of two stars about 300 and 1000 parsecs distant (1 parsec$\approx 3\times10^{18}$ cm), Spitzer and Field[6] found an upper limit of $\sim 5\times10^{-5}$ for the interstellar Be-to-Na abundance ratio. This is an upper limit for $n_{PD(\text{Be})}/n_{\text{Na}}$ in Eq. (2).

For $n_{TG(\text{C+N+O})}/n_{\text{Na}}$, the value 10^3 is adopted, assuming the interstellar ratio to be comparable to that given by Suess and Urey[8] for gross matter in the solar neighborhood.

The only extensively measured cross section, that for the production of 53-day Be^7 $[\sigma(\text{Be}^7)]$ by protons in C, remains nearly constant at about 10 mb from ~ 50 Mev up to 5.7 Bev (beyond which there is no data), and diminishes rapidly below ~ 50 Mev.[9] Hence, ~ 50 Mev is taken to be the "threshold" energy below which production is negligible. The excitation functions for the production of the neighboring nuclides are expected to have about the same "threshold" energy. $\sigma(\text{Be}^7)$ in N and in O are equal to that in C for energies

---

* Supported in part by the Air Force Office of Scientific Research and the Office of Naval Research, and by the Research Corporation.

[1] J. M. Miller and J. Hudis, in *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1959), Vol. 9, p. 159; G. Rudstam, *Spallation of Medium Weight Elements* (University of Uppsala, Uppsala, Sweden, 1956).

[2] S. F. Singer, Nature **170**, 728 (1952); Nuovo cimento **8**, 539 (1958); R. W. Stoenner, O. A. Schaeffer, and R. Davis, Jr., J. Geophys. Research **65**, 3025 (1960); P. Signer and A. O. Nier, *ibid.* **65**, 2947 (1960), and references therein.

[3] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Revs. Modern Phys. **29**, 547 (1957); A. G. W. Cameron, Chalk River Report CRL-41, 1957 (unpublished); S. Bashkin and D. C. Peaslee, Bull. Am. Phys. Soc. **6**, 7 (1961).

[4] W. K. Bonsack and J. L. Greenstein, Astrophys. J. **131**, 83 (1960).

[5] S. F. Singer, in *Progress in Elementary Particle and Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1958), Vol. 4, p. 203.

[6] L. Spitzer, Jr., and G. B. Field, Astrophys. J. **121**, 300 (1955).

[7] S. N. Milford and S. P. Shen (to be published).

[8] H. E. Suess and H. C. Urey, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 51, p. 296.

[9] M. Honda and D. Lal, Phys. Rev. **118**, 1618 (1960).

so far investigated (225 to 730 Mev).[9] Measured $\sigma(\mathrm{Li}^8)$ in C is ~ 1 mb.[10] Assuming that the maximum of the isobaric yield curve for mass number 7 occurs between Li^7 and Be^7, it can be estimated that $\sigma(\mathrm{Li}^7) \approx 20$ mb (this includes contributions from decay of other β-unstable isobars). $\sigma(\mathrm{Li}^6)$, $\sigma(\mathrm{Be}^9)$, and $\sigma(\mathrm{B}^{10})$ are expected to approximate $\sigma(\mathrm{Li}^7)$, while $\sigma(\mathrm{B}^{11})$ may be higher. Thus, rough estimates for the *elements* Li, Be, and B are: $\sigma(\mathrm{Li}) \approx \sigma(\mathrm{B}) \approx 40$ mb; $\sigma(\mathrm{Be}) \approx 20$ mb.[11]

The bombardment period τ is the average time elapsed since the interstellar matter under observation was last present in the interior of a star, since Li, Be, and B are completely destroyed by nuclear reactions whenever they enter a stellar interior.[3] Based on Schmidt's and Salpeter's detailed investigations[12] of the consumption and ejection of interstellar matter by stars in the solar neighborhood, it has been estimated[7] that $\tau \approx 2 \times 10^{17}$ sec (6 billion years).

On substituting now in Eq. (2) the several values adopted above, an approximate upper limit for J is obtained:

$$J < \sim 10 \text{ cm}^{-2} \text{ sec}^{-1}.$$

In studying the spectrum of the star T Tauri (distance: ~ 100 parsec), Bonsack and Greenstein have recently suggested a Li-to-Na ratio of less than $\sim 10^{-5}$ to $\sim 10^{-4}$ in the T-Tauri *nebula*, which is presumably the remainder of the interstellar matter from which the star condensed.[4] If this ratio is valid for the interstellar matter near T Tauri, then, using $\sigma(\mathrm{Li})$, Eq. (2) gives another upper limit for J:

$$J < \sim 1 \text{ to } 10 \text{ cm}^{-2} \text{ sec}^{-1}.$$

The meaning of J requires further comment. Above all, it must be emphasized that, due to the great uncertainties in our adopted values (especially in n_{PD}/n_{Na} and in τ), the upper limit obtained for J should not be taken literally, but should be regarded only as an order-of-magnitude estimate. However, in view of the present extremely limited knowledge of interstellar cosmic rays, even this rough estimate, based on available data, is of some interest. It is hoped that extra-atmospheric observations will soon greatly improve the interstellar nuclide abundance data.

J represents the cosmic-ray intensity averaged *temporally* over the past six billion years (τ), and *spatially* over the volume from which the observed interstellar Be or Li was collected. The combination of the random motion of interstellar matter and the motion of the product nuclei suggests that this volume is several cubic kiloparsecs in the solar neighborhood.

Furthermore, J includes interstellar cosmic rays of kinetic energy as low as ~ 50 Mev, if any. While the present order-of-magnitude upper limit for J is uncertain, it nevertheless suggests that the low-energy (50 Mev–1 Bev) interstellar cosmic-ray intensity does not exceed the integral intensity of interplanetary cosmic rays above 1 Bev by one order of magnitude. This method, if refined, may thus give some information on the question of the "low-energy cutoff"[5] in interstellar space and on cosmic-ray acceleration mechanisms in general.

Spitzer and Field[6] suggested that the unusually low interstellar Be-to-Na and Ca-to-Na ratios might be due to the preferential concentration of chemically similar Be and Ca in interstellar dust grains. If so, the upper limit for J based on the Be-to-Na ratio would be in error. This, however, now seems highly unlikely in view of the low Li-to-Na ratio obtained recently[4] in the T-Tauri nebula mentioned earlier, for Li is chemically similar, not to Be or Ca, but rather to Na itself.

Thus, interstellar Li, Be, and B can be used as upper-limit "integrating meters", albeit crude, for *interstellar* cosmic rays in much the same way as certain cosmic-ray-produced nuclides in meteorites have been successfully used, as first suggested by Singer,[2] as "integrating meters" for *interplanetary* cosmic rays.

Equation (2) can also be solved for lower limits of interstellar Li, Be, and B abundances, assuming a plausible lower limit for J; the possibility exists that interstellar spallation alone may account for a substantial portion of the interstellar abundances of these rare elements. Also, Eq. (2) can be solved for an upper limit of τ, a quantity closely related to the lifetime of interstellar matter. These and other points of astrophysical interest are discussed elsewhere.[7]

ACKNOWLEDGMENTS

We are grateful to Professor J. M. Miller for estimating the cross sections. We also wish to thank Professor S. A. Korff for helpful comments.

---

[10] S. C. Wright, Phys. Rev. **79**, 838 (1950).

[11] J. M. Miller (private communication).

[12] M. Schmidt, Astrophys. J. **129**, 243 (1959); E. E. Salpeter, *ibid.* **129**, 608 (1959).