Astron. & Astrophys. 15, 337–359 (1971)

The Production of the Elements Li, Be, B by Galactic Cosmic Rays in Space and its Relation with Stellar Observations

M. Meneguzzi*, J. Audouze* and H. Reeves*
Service d'Electronique Physique, Saclay, and Institut d'Astrophysique de Paris

Received May 28, 1971

The L-element (Li, Be, B) contamination rate of the interstellar gas by nuclear reactions induced by the Galactic Cosmic Rays (G.C.R.) is calculated using a diffusion model of fast moving particles in the Galaxy. The presence of helium in the G.C.R. flux and in the interstellar gas is taken into account.

It is found that most of the stellar and meteoritic data is in agreement with a model which otherwise gives a reasonable account of the G.C.R. observations. This model assumes an injection spectrum in total energy power ($W^{-2.6}$) diffusing in a leaking galaxy with an escape range of 6.3 g cm^{-2}. The intensity, the composition at the source and the spectral shape have remained the same for the last 10^{10} years.

However a large part of the ^{7}Li must come from another source. Two possibilities are discussed: a) thermonuclear ^{7}Li ejected from Giant Stars in "dirty" regions of our Galaxy, b) spallative ^{7}Li generated from an intense low energy component of the G.C.R.

The relative merits of both hypotheses are discussed.

Key words: galactic cosmic rays — Li, Be and B abundances — interstellar gas.

I. Introduction

The presence of the L elements (lithium, beryllium, boron) in our Galaxy (observed in stars and in the solar system) is best explained in terms of the continuous bombardment of interstellar atoms by Galactic Cosmic Rays (G.C.R.). Through spallation reactions, the L-atoms are generated and later decelerated to the thermal energies of the interstellar gas. The process is one of the slowest in nature: one gram of beryllium is the crop of more than 10^5 years in a volume of one cubic astronomical unit ($= 3 \times 10^{39}$ cm^3): New stars are eventually formed out of this gas, which reveal by their absorption features the presence of these atoms in their surface layers.

This so-called "galactogenetic" hypothesis has been presented by Reeves *et al.* (1970) (hereafter called RFH) after it was realized by Ryter *et al.* (1970) that the "autogenetic" hypothesis (L elements formed by stellar flares at the surface of young stars) meets with many difficulties. Some implications of the galactogenetic hypothesis were also studied by Fowler *et al.* (1970) (called FRS) and by Mitler (1970).

One interesting feature of this hypothesis is that it brings together a lot of data which previously appeared unrelated: a consistent model of the origin and propagation of the G.C.R. must not only explain the observed flux of all nuclear species at all energies; it must also account for the abundances of the L-elements in stellar surfaces and in the meteorites (taking, of course, into consideration the possibility of ulterior alterations by realistic physical processes).

Indeed, while the observed flux of the G.C.R. gives information on the present high energy portion of the interstellar spectrum (below several hundred of MeV, our information is blurred by solar modulation effects), the stellar abundances give an integrated rate over all energies and over periods which are comparable to the age of the Galaxy. For instance, to anticipate over the following sections, let us consider the element Be. In stars its abundance is usually found to be in the range $5 \times 10^{-12} <$ Be/H $< 5 \times 10^{-11}$ (Table 3) with 2×10^{-11} as a mean value. Its present rate of formation by G.C.R. in space (using a reasonable demodulation factor) is $= 7 \times 10^{-29}$ H^{-1} s^{-1}. The ratio of these two quantities gives the duration of the process: i.e. 2×10^9 to 2×10^{10} years (10^{10} years for the mean value).

* Contribution du groupe «Astrophysique à Haute Energie et Milieu Interstellaire».

This order-of-magnitude analysis confirms the view that

A) The L elements are made mostly by the action of the G.C.R. in space.

B) The mean flux over the life of the Galaxy is comparable to the present flux in the vicinity of the sun [radioactive isotopes in meteorites confirm the constancy of the flux over the last 10^9 years (Lal and Peters, 1967; Lal, 1969)].

In this paper we plan to consider the problem of the L-elements in the G.C.R. anew and discuss it with respect to all these observable parameters (G.C.R. and stellar data).

The diffusion problem is treated according to the formalism described by Gloeckler and Jokipii (1969) (Section IV) while the solar modulation effects are estimated according to Goldstein *et al.* (1970) (hereafter GFR) which imply in particular that the very low energy interstellar particles ($E < 100$ MeV N^{-1}) are decelerated by the expansion of the solar wind and never reach the vicinity of the earth.

A source composition (or more exactly an injection composition at the sources) is calculated and an energy spectral shape (applicable to all the constituents at the injection) is searched for which would at the same time reproduce:

a) the interstellar flux intensity (and flux ratios) of the various components of the G.C.R. as a function of energy (after appropriate demodulation from solar effects);

b) the abundance of the five L isotopes (^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B) wherever they have been observed (assuming that the G.C.R. has remained constant over the last 10^{10} years);

c) and (if possible) the ionization and the heating of the H I regions in the interstellar gas.

The general plan of this paper is as follows: in section II and III all the relevant data is discussed; in section IV the diffusion model is briefly described; in sections V and VI the high energy component ($E > 2$ GeV N^{-1}) of the observed flux is used to fix the injection composition and leakage range (both assumed to be energy independent); the effect of a G.C.R. flux with an injection spectrum in power law of total energy is computed: the interstellar fluxes give reasonable account of the observations and the total amount of L-elements generated after 10^{10} years is consistent with stellar and solar data on ^{6}Li, ^{9}Be, ^{10}B and ^{11}B.

The data on lithium appears to require another source of ^{7}Li. This may be due to high fluxes at low energy ("carrots") (Section VII) or to a stellar source of thermonuclear ^{7}Li.

Problems related to the interstellar He ratio, to the G.C.R. Be ratios and to the CNO fluxes are discussed in the Appendices.

II. Nuclear Parameters

The measurements of the spallation cross-sections of astrophysical interest are steadily improving in number and in accuracy (Gradsztajn, 1965; Davids *et al.*, 1969; Yiou *et al.*, 1969; Regnier, 1971 and other references to follow). A general compilation is in preparation in our laboratory at Saclay (Tobailem *et al.*, 1971) which has been of great use to us.

One major improvement of the last few years has been the measurement of alpha-induced spallation cross-sections (Crandall, 1956; Pape 1966; Fontes, 1970; Radin, 1970; Mullié and Gauvin, 1971). The high energy cross-sections are usually two or three times larger than for the equivalent proton-induced reaction (from the same target to the same final product). Since the helium to hydrogen ratio is ≈ 0.1 the alpha induced contribution to spallation

Table 1. *Proton induced reaction cross-sections (in* mb*) for the production of* L *elements at high energy (*$E > 2$ GeV*)* *(italicised numbers are experimental)*

Product \ Target	^{56}Fe	^{28}Si	^{24}Mg	^{20}Ne	^{16}O	^{15}N	^{14}N	^{13}C	^{12}C	^{11}B	^{10}B	^{9}Be	^{7}Li ^{7}Be
Mass 11	7	12	12	18	*25*	25	45	20	50				
Mass 10	5	5	5	14	*15*	15	12	16	15	20			
^{10}Be	4	2	2	2	*1*	1	2	3.5	3.5	34			
Mass 9	6	4	4	4	*3.5*	4	6	10	*6*	6.5	25		
^{7}Be	*10*	*4*	*12*	10	*10*	10	*12*	10	*9*	*5.5*	6	7	
^{7}Li	8	6	12	10	*14*	14	10	6	6	18	6	6.5	
Mass 6	10	6	12	10	*14*	14	7	7.5	*7.5*	12	20	10	40

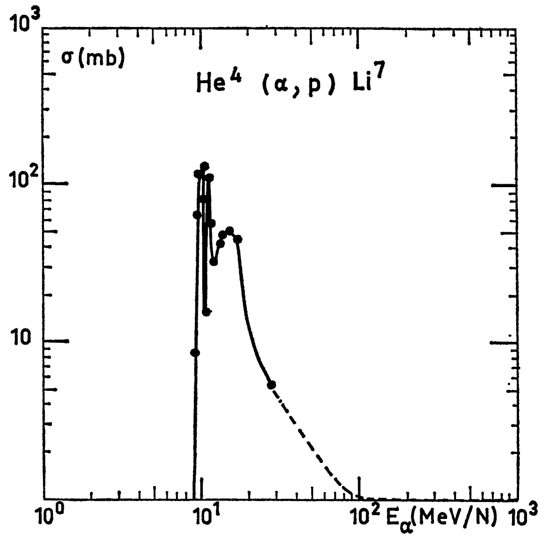

Fig. 1. Excitation curve of ^{4}He (α, p) ^{7}Li. The dots are experimental points. The dashed line is our estimate for the high energy values (see text). The same numerical values were used for the ^{4}He (α, n) ^{7}Be

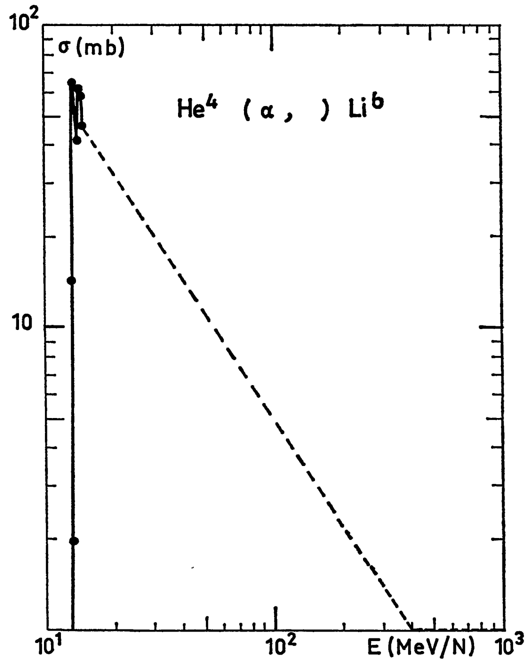

Fig. 2. Excitation curve of ^{4}He (α,) ^{6}Li. The dots are experimental points. The dashed line is our estimate for the high energy values

at high energy is generally 20% of the proton induced contribution. For product nuclei which have a very small proton induced cross-section (such as ^{10}Be) the ratio is appreciably larger.

In the low energy range the situation is quite different. As seen in Fig. 4 the G.C.R. fluxes have about the same energy spectral shape in a scale of energy per nucleon (MeV N^{-1}). In this scale the threshold energies for given alpha-induced reactions are some three to four times lower than for the proton-induced equivalent reactions. Furthermore a fair number of alpha-induced reactions exhibit an important "compound nucleus" peak a few MeV above the threshold. Thus alpha-induced reactions become the dominant processes in the range $E < 20$ MeV N^{-1} range of the G.C.R.

Actual experimental measurements of spallation cross-sections are also useful as basic elements for studies of the spallation systematic behaviour, and for the derivation of empirical relationships. Such studies have been made by Rudstam (1966) (for $A > 40$), Audouze *et al.* (1967) by Lavrukhina *et al.* (1969), and by Silberberg and Tsao (1971).

We have drawn full excitation functions (from measured and estimated points) which have been used in this work. In Table 1 the high energy values of the cross-sections which were used in our computation net-work are given for proton-induced reactions. Some of these values differ slightly, but never very significantly, from the numbers estimated independently by Shapiro and Silberberg (1970). This coherence shows that the nuclear physics aspect of the G.C.R. problem is no more a cause of major uncertainties (at least in the low mass range) except perhaps for the $\alpha + \alpha$ reaction to be discussed next.

The $\alpha + \alpha \rightarrow$ Li, Be *Reactions*

Experimental data is available only in the very low energy range ($E < 30$ MeV/nucleon). Following Hayakawa (1968) and Fowler, Caughlan and Zimmerman (1967) we have used the theory of the detailed balance to calculate the low energy part of the excitation function. Our estimate of the higher energy part of the excitation is based on the fact that similar reactions (at least for larger mass target) are expected to proceed via compound-nucleus formation, and to present a highly peaked cross-section in the corresponding energy range (few tens of MeV). At higher energies they would decrease rapidly (steeper than E^{-1}) and probably level off to a rather low value above 100 MeV[1]).

[1]) Experimental results on ^{16}O and ^{28}Si show that the (α, *pn*) reaction cross-section falls as E^{-2} from the peak till at least 150 MeV in total energy (Mullié, thesis, 1971).

Discussions with nuclear physicists (in particular with Turkevitch) has led us to estimate that no one of the three processes $^4He + ^4He \to ^7Li$, ^7Be, ^6Li should have a cross-section of more than a few mb above a few hundred MeV N^{-1}.

In Figures 1 and 2 the excitation function for $\alpha + \alpha \to ^7Li$ and ^6Li used in this work are displayed. We have taken the same values for $\alpha + \alpha \to ^7Be$ than for $\alpha + \alpha \to ^7Li$.

III. Astrophysical Parameters

a) *Observed* G.C.R. *Fluxes*

The results from many groups were used in this work: Webber *et al.*, 1971; Fan *et al.*, 1968; Garcia-Munoz *et al.*, 1969; Lezniak *et al.*, 1969; 1970; O'Dell *et al.*, 1969; Von Rovenvinge *et al.*, 1969; Comstock *et al.*, 1969; Cassé *et al.*, 1970. Our selection has been heavily influenced by the recent review article of Shapiro and Silberberg (1970).

In Table 2, the high energy fluxes composition for those species which are relevant to our calculation are tabulated (normalized to 100 for carbon). Other observational results will appear in Figs. 3—8, 14, 19.

b) *Interstellar Abundances*

For the interstellar abundances we have used the "universal" abundances (Cameron, 1968). For the still unsettled case of the helium abundance (Danziger, 1970) (Burbidge, 1969) we have taken $n_{He}/n_H = 0.1$. In the appendix A we have let n_{He}/n_H vary from 0.05 to 0.15 to study the importance of this parameter (after a suggestion by Jones).

Table 2

Z	G.C.R. observed composition	Interstellar G.C.R. flux calculated (this work)	Source G.C.R. flux calculated	Source G.C.R. flux used (this work)
1	5.8×10^4	5.8×10^4	4.2×10^4	4.2×10^4
2	3.4×10^3	3.4×10^3	3.0×10^3	3.0×10^3
3	16 ± 2 (*a*)	16	0	0
4	11 ± 3 (*a*)	12	0	0
5	27 ± 3 (*a*)	25	0	0
6	100	100	100	100
7	27 ± 2 (*a*)	26	(see text)	11 (see text)
8	86 ± 4 (*a*)	88	105 (*a*)	110
10	20 ± 2 (*a*)	19	20 (*a*)	25
12	21 ± 2 (*a*)	20	23 (*a*)	29
14	15 ± 2 (*a*)	17	20 (*a*)	26
26	11.3 ± 1.4 (*a*)	12	23 (*a*)	25

High energy ($E > 2$ GeV) G.C.R. fluxes. The values denoted by (*a*) are from Shapiro and Silberberg (1970). The slightly larger values used here (fifth column) are expected to compensate our neglecting the production of secondary $A > 15$.

c) *Observations of* Li, Be, B *in Stars*

The relevant observations have been summarized and discussed by Wallerstein and Conti (1969). We shall only give a review of the pertinent data.

The T Tauri stars (young stars, $\tau = 10^7$ years) in gravitational contraction show large abundances of lithium, with Li/H ranging from 8×10^{-10} to 4×10^{-9}. No data is available on $^7Li/^6Li$ or on Be.

Early type stars (with very shallow surface convective zone) of young clusters (Pleiades $= 5 \times 10^7$ years; Hyades 5×10^8 years) have lithium abundances in the range 3×10^{-10} to 2×10^{-9}. Since very little destruction is expected to have taken place by thermonuclear reactions in the surface of these stars, the abundances reported are most likely those of the interstellar gas from which they were formed (spallation in the stellar atmosphere is assumed here to be negligible).

Later type stars of the same clusters show smaller Li abundance, decreasing with spectral class for a given cluster and with age when stars of the same spectral class are considered. This effect can reasonably be assigned to nuclear reactions at the bottom of the convective zone (the mean temperature of this zone increases with spectral type in the sense $F \to G \to K$). This effect has been discussed by Greenstein and Richardson (1951) and also by Herbig and his collaborators (see for instance Herbig, 1965).

The combined abundances of ^7Li, ^6Li and ^9Be can only be measured for slowly rotating bright F and G stars. In Table 3 we present a stellar "pedigree" of those stars for which Li and Be values (or upper limits) are reported in the literature. Together with the name and the spectral classes, the visual magnitude, the $B - V$ index, the luminosity in solar units, the surface effective temperature are estimated from the correspondence between the spectral type (Morton and Anders, 1968) the luminosity and the evolutionary tracks of Iben, 1967. (For this task we have been greatly helped by Mrs. Claude Chevalier.)

The rotation velocities (or their limits) were obtained from Herbig and Spalding (1955) and from Sletteback (1955).

In the last four columns the Li, Be and the Li/Be and $^7Li/^6Li$ values are listed. The Be/H ratios range from 5×10^{-12} to 5×10^{-11} in stars, which show no sign of peculiar effects. There seems to be an increase of Be with spectral class (from F to G) or with stellar age. In the present work we do not attempt to explain this correlation; we estimate a mean value

$$\mathrm{Be/H} = 2 \times 10^{-11}, \text{ mean stellar value}$$

which we shall use in the future discussion.

The Li/Be ratio ranges from more than one hundred (mostly F0 to F5 stars) to a few units (in late F and early G stars). As discussed before, this correlation can qualitatively be related to the increasing depth of the surface convective zone. However some difficulties will appear shortly.

About fifteen stars have been searched for all three isotopes ^{6}Li, ^{7}Li, ^{9}Be. The ^{7}Li/^{6}Li ratio range from 2 to more than 10 (^{6}Li unobservable). Six stars do show ^{6}Li(^{7}Li/^{6}Li < 4). Five of them (ν And, 10 Tau, β Com, ι Per, ξ Uma A) have rather similar values of Li and Be (see table). We shall name them the "G.C.R." stars for reasons which will soon become apparent.

The average ratios of L elements in these stars is

Li/H	$= 2 \times 10^{-10}$	G.C.R. Stars
Be/H	$= 3 \times 10^{-11}$	
Li/Be	$= 7$	
^{7}Li/^{6}Li	$= 2.5$	

We recall that the lifetimes τ against thermonuclear destruction are in the following order:

$$\tau(^6\mathrm{Li}) \ll \tau(^7\mathrm{Li}) \ll \tau(^9\mathrm{Be}) .$$

Hence (unless more complicated effects have taken place) we expect that the stars with the lowest ^{7}Li/^{6}Li should have suffered the least thermonuclear destruction. Conversely, quoting Wallerstein and Conti: "It will be noticed that the earliest F stars, those containing the most Li, and which should not have had their initial light element content modified by mixing, contain no evidence for ^{6}Li".

d) The Solar System

During the last I.A.U. meeting in Brighton (Aug. 1970) a panel of experts on the spectroscopic determination of Li and Be gathered to discuss the solar observations.

The values given below were generally accepted. For boron one has only an upper limit (Engvold, 1970)

Li/H	$= 10^{-11}$	Solar values
Be/H	$= 10^{-11}$	
B/H	$< 3 \times 10^{-10}$	

In the planetary system more accurate data is available but chemical fractionation may have blurred the initial picture. We shall, at any rate, put greater weight on the interpretation of isotopic ratios (Li and B) than on element ratios. The remarkable constancy of isotopic ratios in the various spots in which they have been measured (for lithium the constancy is better than 3% for lunar, terrestrial and meteoritic samples) certainly excludes important chemical isotopic separation. The values are (Krankovsky and Muller, 1967; Bernas *et al.*, 1969; Shima, 1962)

^{7}Li/^{6}Li	$= 12.5 \pm 0.3$	Planets
^{11}B/^{10}B	$= 4 \pm 0.4$	

For comparison with stellar data the planetary element abundances are normalized by taking their abundances with respect to silicon abundances and then the solar ratio of H/Si (Sill and Willis, 1962; Grevesse, 1968, 1969; Quijano-Rico and Wänke, 1969).

Li/H	$= 1.2 \times 10^{-9}$ (^{6}Li $= 10^{-10}$, ^{7}Li $= 1.1 \times 10^{-9}$)	
Be/H	$= 2 \times 10^{-11}$	Planets
B/H	from 2×10^{-10} to 8×10^{-9}	

The range of B/H is correlated with petrographical properties, hence implies important chemical fractionation.

We note that the planetary lithium is quite comparable to the T Tauri or young clusters value ($=10^{-9}$). In the same manner the planetary beryllium value agrees with our "mean stellar value" ($=2 \times 10^{-11}$).

The solar value of Li and the upper limit on ^{7}Li/^{6}Li shows that heavy destruction of solar lithium must have taken place (most likely by thermonuclear destruction in the surface convective zone). The agreement between solar and planetary beryllium

Table 3. *In this table are listed the stars for which* Li *and/or* Be *have been measured. For each object we give the spectral type* Sp, *the visual magnitude Mv, the spectral index B−V, the luminosity compared to the solar luminosity* (log $L/L_\odot$), *the effective temperature* log T_e; *the mass and the age obtained from Iben's tracks the rotational velocity or its upper limit, the observed abundance of* Li *and* Be *and the ratios* Li/Be *and* ^{7}Li/^{6}Li. *Finally in a column labelled "remarks" the specific features of the object are given* (V.B. = *visual binary* — S.B = *spectroscopical binary).*

Star	Sp.	Mv	$B-V$	log $L/L_\odot$	log T_e	$M/M_\odot$	Years
ξ Serp	F0 IV	1.9	0.27	1.16	3.89	1.7	4.0×10^8
η Lep	F0 V	2.4	0.32	0.96	3.872	1.8	1.0×10^9
χ Leo	F2 III IV	1.5	0.33	1.32	3.87	2.0	1×10^9
γ Vir N	F0 V	3.3	0.35	0.60	3.864	1.35	1×10^8
γ Vir S	F0 V	3.3	0.35	0.60	3.864	1.35	1×10^8
45 Tau	F2 V	2.7	0.36	0.84	3.86	1.5	1×10^9
σ Boo	F2 V	3.5	0.38	0.52	3.85	1.35	5×10^9
α Cmi	F5 IV V	2.6	0.40	0.88	3.845	1.75	1×10^9
HR 5110	F2 IV	1.4	0.40	1.36	3.845	2.0	1×10^9
θ Cyg	F4 V	3.6	0.40	0.48	3.845	1.50	5×10^7
ι Leo	F2 IV	2.3	0.41	1.0	3.84	1.60	1×10^9
η Ari	F5 V	3.2	0.44	0.64	3.83	1.20	2×10^9
ι Peg	F5 V	3.1	0.44	0.68	3.83	1.25	2.5×10^9
π^3 Ori	F6 V	3.7	0.45	0.44	3.825	1.25	1.5×10^9
40 Leo	F6 IV	3.2	0.45	0.64	3.825	1.25	2.5×10^9
θ Uma	F6 IV	1.8	0.46	1.20	3.82	1.8	1.3×10^9
110 Her	F6 V	2.6	0.46	0.88	3.82	1.4	2×10^9
γ Lep A	F6 V	4.0	0.47	0.32	3.818	1.2	5×10^7
χ Cnc	F6 V	4.1	0.47	0.28	3.818	1.2	5×10^7
ν Serp	F6 V	3.0	0.47	0.72	3.818	1.25	3×10^9
θ Per	F7 V	3.5	0.48	0.52	3.815	1.25	2×10^9
τ Boo	F7 V	3.3	0.48	0.60	3.815	1.3	2×10^9
ξ Peg	F7 V	3.1	0.50	0.68	3.810	1.3	2.5×10^9
ι Psc	F7 V	3.1	0.51	0.68	3.804	1.15	2.5×10^9
ν And	F8 V	3.1	0.54	0.68	3.793	1.20	2.5×10^9
β Vir	F8 V	3.6	0.55	0.48	3.79	1.15	3×10^9
10 Tau	F8 V	3.0	0.57	0.72	3.79	1.20	4×10^9
β Com	G0 V	4.7	0.58	0.04	3.78	1.0	1×10^8
η Boo	G0 IV	2.7	0.58	0.84	3.78	1.3	3×10^9
χ Her	F9 V	3.3	0.58	0.60	3.78	1.1	4×10^9
ι Per	G0 V	3.2	0.59	0.64	3.777	1.15	4.5×10^9
ξ Uma A	G0 V	4.3	0.59	0.20	3.777	1.0	5×10^9
χ' Ori	G0 V	4.4	0.60	0.16	3.773	1.0	4×10^9
β Cvn	G0 V	4.1	0.61	0.28	3.77	1.0	6×10^9
λ Ser	G0 V	4.2	0.61	0.24	3.77	1.0	4.5×10^9
ζ Her	G0 IV	2.6	0.66	0.88	3.75	1.3	3×10^9
Sun	G2	4.8	0.62	0.0	3.762	1.0	4.5×10^9
δ Eri	K0 IV	3.7	0.93	0.44	3.70	1.0	7×10^9

shows that the mean temperature at the bottom of the convective zone has not been hot enough to destroy the Be nuclei.

It is tempting to assume that the partial destruction of ^{6}Li in the planetary material is also due to nuclear effects *before* the formation of the planets. For a number of reasons to be developed in Reeves (1971) (amongst others the presence of the much more fragile deuterium atoms in the planetary material), this assumption appears untenable.

e) The Properties of the Interstellar Medium

The mechanism responsible for the heating and ionization of H I regions in the interstellar medium is not yet identified (Bergeron and Souffrin, 1971). Several workers have considered the low energy component of the G.C.R. as a possible candidate (Hayakawa, 1961; Spitzer and Tomasko, 1968; Pikelner, 1968; Balasubrahmanian *et al.*, 1968; Goldsmith *et al.*, 1969; Hjellming, 1969; Hjellming *et al.*, 1969; Pacheco, 1969).

Table 3 (continued)

Star	$v \sin i$ (km/s)	Li/H	Be/H	Li/Be	^{7}Li/^{6}Li	Remarks
ξ Serp	—	5×10^{-10}	2×10^{-12}	2.5×10^{2}	—	
η Lep	< 25	4×10^{-10}	5×10^{-12}	8×10^{1}	> 10	
χ Leo	< 25	$< 4 \times 10^{-10}$	$< 2 \times 10^{-11}$	—	—	
γ Vir N	25	2×10^{-9}	4×10^{-12}	5×10^{2}	> 10	} V.B.
γ Vir S	40	8×10^{-10}	3.3×10^{-12}	2.5×10^{2}	—	} V.B.
45 Tau	—	6.4×10^{-10}	4×10^{-12}	1.6×10^{2}	> 10	belongs to Hyades
σ Boo	< 15	$< 6 \times 10^{-10}$	$< 1.3 \times 10^{-12}$	—	—	
α Cmi	< 15	$< 6.4 \times 10^{-11}$	$< 0.25 \times 10^{-12}$	—	—	V.B.
HR 5110	< 25	$< 2.8 \times 10^{-10}$	$< 2.5 \times 10^{-12}$	—	—	S B
θ Cyg	—	$< 2 \times 10^{-10}$	$< 0.6 \times 10^{-12}$	—	—	
ι Leo	< 25	8×10^{-10}	8×10^{-12}	1.0×10^{2}	> 10	double
η Ari	< 20	5.2×10^{-10}	8×10^{-12}	6.5×10^{1}	—	
ι Peg	< 25	8×10^{-10}	1×10^{-11}	8×10^{1}	2	S B period 10.2 d
π^3 Ori	20	1.3×10^{-10}	3.2×10^{-12}	4×10^{1}	—	
40 Leo	20	$< 1.7 \times 10^{-10}$	$< 1.3 \times 10^{-12}$	—	—	
θ Uma	< 15	6.2×10^{-10}	8×10^{-12}	8×10^{1}	—	
110 Her	< 25	$< 5 \times 10^{-11}$	3.2×10^{-12}	$< 1.6 \times 10^{1}$	—	
γ Lep A	—	4×10^{-10}	1.0×10^{-11}	4×10^{1}	> 10	double (?)
χ Cnc	< 20	8×10^{-10}	8×10^{-12}	1×10^{2}	—	
ν Serp	< 25	1.7×10^{-10}	1.3×10^{-11}	1.3×10^{1}	—	
θ Per	< 25	4×10^{-10}	3.2×10^{-11}	1.3×10^{1}	10	double
τ Boo	< 15	$< 1.3 \times 10^{-10}$	3.2×10^{-12}	$< 4 \times 10^{1}$	—	companion M2
ξ Peg	< 25	1.3×10^{-10}	1.0×10^{-11}	1.3×10^{1}	> 10	
ι Psc	< 25	$< 3.3 \times 10^{-11}$	8×10^{-12}	< 4	—	
ν And	< 15	8×10^{-11}	1.3×10^{-11}	6	2	
β Vir	< 25	$< 5 \times 10^{-11}$	1.3×10^{-11}	< 4	—	
10 Tau	—	2×10^{-10}	5×10^{-11}	4	2	
β Com	< 20	2.5×10^{-10}	3.2×10^{-11}	8	2.5	
η Boo	20	$< 3.3 \times 10^{-11}$	$< 3.3 \times 10^{-12}$	—	—	S.B. subgiant
χ Her	< 15	5.2×10^{-10}	1.2×10^{-11}	4×10^{1}	> 10	
ι Per	< 15	1.6×10^{-10}	5.0×10^{-11}	3	3	
ξ Uma A	< 25	2.5×10^{-10}	4.0×10^{-11}	6	4	close V.B.
χ' Ori	< 20	3.2×10^{-10}	1.6×10^{-11}	2×10^{1}	> 10	
β Cvn	< 15	$< 5 \times 10^{-11}$	2.5×10^{-11}	< 2	—	
λ Ser	< 20	$< 6.6 \times 10^{-11}$	2×10^{-11}	< 3.3	—	V.V. (?) variable
ζ Her	< 15	$< 3.3 \times 10^{-11}$	$< 2.1 \times 10^{-11}$	—	—	close V.B. subgiant
Sun	< 15	$\cong 10^{-11}$	1.2×10^{-11}	$\cong 1.2$	> 10	
δ Eri	< 15	3×10^{-11}	2×10^{-11}	1.5	> 10	

The main parameter is $\zeta_{\rm H}$, the probability of ionization of one interstellar hydrogen atom per second. The total ionization rate per sec per nucleon is then (Eq. (10))

$$\zeta_n = \frac{n_{\rm H}\,\zeta_{\rm H} + n_{\rm He}\,\zeta_{\rm He}}{n_{\rm H} + 4 n_{\rm He}} = \frac{\zeta_{\rm H} + (n_{\rm He}/n_{\rm H})\,\zeta_{\rm He}}{1 + 4 n_{\rm He}/n_{\rm H}} \cong 0.79\,\zeta_{\rm H}\,.$$

According to various authors (Spitzer and Scott, 1969) the present state of the theory of interstellar matter requires

$$\boxed{\zeta_{\rm H} = 5 \times 10^{-16}\,{\rm s}^{-1}\,.}$$

Also Field, Goldsmith and Habing (1969) and Pacheco (1970) have estimated:

$$\boxed{\zeta_{\rm H} < 10^{-15}\,{\rm s}^{-1}\,.}$$

IV. The Diffusion Model

The general problem of the diffusion of fast particles in the Galaxy has been treated by many authors, in particular by Ginzburg and Syrovatsky (1964). In its most realistic form, one should consider the following physical conditions: a number of point-source objects distributed throughout a large but finite volume (the Galaxy) emit, in a time varying fashion, a flux of fast particles with a broad energy spectrum. The particles propagate in a diffusion-like motion within the Galaxy and have a certain probability of escaping the Galaxy when they reach the outer surface. The model considered here simplifies the calculation by the following assumptions.

The sources are distributed homogeneously throughout the Galaxy (the particles are emitted from everywhere) and emit continuously a time independent spectrum of high energy particles. Since we are mainly interested in the production of L-atoms and since these atoms, absent from the sources, are created *in fact* during the space journey of the parent nuclei, this approximation appears to be justified. However, at very low energy, the situation may be different since the particles do not reach very far from the sources. This problem is under study (Pacheco, 1971; Cesarsky to be published).

Instead of treating a diffusion process in a finite volume with a partially leaking surface we consider an infinite volume but add in the diffusion equation an extra term which represents the escape by a "castastrophic" loss. In other words a geometrical property becomes an intrinsic property of each particle. Jones (1970) has discussed the value of the approximation. The mean free path against escape $\Lambda_e = \varrho v \tau_e$ is assumed to be independent of energy, which implies that τ_e, the lifetime against escape, increases with decreasing energy, quite a reasonable assumption. We assume also that Λ_e is the same for all nuclear species at all energies.

Local fluxes are assumed to have reached equilibrium between injection, deceleration and catastrophic loss terms (steady-state). The transport equation, which gives the steady-state density for nuclei i in the G.C.R. is

$$\begin{aligned}\frac{\partial N_i(E)}{\partial t} = 0 = &- \frac{N_i(E)}{\tau_e} - \frac{N_i(E)}{\gamma \tau_i} + Q_i(E)\\ &+ \frac{\partial}{\partial E}(b_i(E)\, N_i(E))\\ &- [\sigma_{\alpha i}(E)\, n_{\mathrm{He}} + \sigma_{p i}(E)\, n_{\mathrm{H}}]\, v_i\, N_i(E)\\ &+ \sum_j \int_0^\infty N_j(E')\, [n_{\mathrm{He}}\, \sigma_{\alpha j i}(E, E')\\ &+ n_{\mathrm{H}}\, \sigma_{p j i}(E, E')]\, v_j\, dE' \qquad (1)\end{aligned}$$

where $N_i(E)$ is the cosmic ray number density of species i at energy per nucleon E, τ_i is the decay lifetime for unstable nuclei (such as ^{10}Be) and γ the Lorentz factor for time dilation; $Q_i(E)$ is the source term of primary particles (assumed to be constant in time and space); $b_i(E) = -\left(\frac{\partial E}{\partial t}\right)_i$ the energy loss per nucleon per sec by ionization, $\sigma_{\alpha j}$ and $\sigma_{p i}$ are total destruction cross-sections of the nuclei by alphas and protons respectively; n_{He} and n_{H} are the (mean) number densities of helium and hydrogen in the interstellar gas; $\sigma_{\alpha j i}$ and $\sigma_{p j i}$ are the spallation cross-sections for the production of the nucleus i by bombardement of the target j by alpha or protons; E and E' are the kinetic energy per nucleon of the product (i) and the parent (j) and v_i is the velocity of the particle i.

Unless otherwise noted, energies are always in energy per nucleon. From (1) the following equation is derived for the omnidirectional flux $\phi_i = N_i v_i$:

$$\begin{aligned}\frac{\partial \phi_i}{\partial X} = 0 = &- \frac{\phi_i}{\Lambda_i} + \frac{\partial}{\partial E}(w_i\, \phi_i) + q_i\\ &+ \int_0^\infty \sum_{j \neq i} \phi_j(E') \left[\frac{\sigma_{pji}(E, E') + \frac{n_{\mathrm{He}}}{n_{\mathrm{H}}}\sigma_{\alpha ji}(E, E')}{M_p + (n_{\mathrm{He}}/n_{\mathrm{H}})\, M_\alpha}\right] dE' \qquad (2)\end{aligned}$$

where X is the amount of the matter traversed (path length) in g cm^{-2}, Λ_i is the loss range of energetic particles against the combined effect of decay, nuclear destruction by interstellar particle or leakage from the Galaxy:

$$\frac{1}{\Lambda_i} = \frac{1}{\varrho v \tau_i \gamma_i} + \frac{\sigma_{p i} + \frac{n_\alpha}{n_p}\sigma_{\alpha i}}{M_p + \frac{n_\alpha}{n_p} M_p} + \frac{1}{\Lambda_e} \qquad (3)$$

where $\varrho = n_{\mathrm{H}}\, M_{\mathrm{H}} + n_{\mathrm{He}}\, M_{\mathrm{He}}$ is the density of the interstellar gas (the contribution of heavier elements is negligible); w_i is the rate of energy loss per g cm^{-2} ($w_i = b_i/\varrho\, v_i$) (both interstellar hydrogen and helium are considered) and $q_i = Q_i/(n_{\mathrm{H}}\, M_{\mathrm{H}} + n_{\mathrm{He}}\, M_{\mathrm{He}})$. The solution of (2) is then:

$$\begin{aligned}\phi_i(E) = \frac{1}{w_i(E)} \int_E^\infty dE'\\ \cdot \left[q_i(E') + \sum_j \int_0^\infty dE''\, \phi_j(E'')\, \frac{\frac{n_\alpha}{n_p}\sigma_{\alpha j i} + \sigma_{p j i}}{M_p + M_\alpha \frac{n_\alpha}{n_p}}\right.\\ \left. \times \exp\left(-\frac{R_i(E') - R_i(E)}{\Lambda_i}\right)\right] \qquad (4)\end{aligned}$$

where $R_i(E) = \int_0^E dE'/w_i(E')$ is the ionization range of the particle i at energy E per nucleon (in g cm^{-2}).

The exponential function in the integral[2]) represents, in effect, the probability that a particle injected or nuclearly produced at energy E' will survive and be counted in the flux at energy E. Throughout this calculation we have set

$$\sigma(E, E') = \sigma(E')\,\delta(E - E') \quad (5)$$

for proton and alpha induced cross-sections except for the $[\alpha + \alpha \rightarrow {}^6\mathrm{Li}, {}^7\mathrm{Li}, \mathrm{Be}^7]$, for which we use: (the final nuclei move at about one half of the velocity of the incident α)

$$\sigma(E, E') = \sigma(E')\,\delta(E - E'/4) \quad (6)$$

the Eq. (4) gives the interstellar flux $\phi_i(E)$ for each nuclear species i. It is worth recalling that the steady state hypothesis considered here is equivalent to the assumption of an exponential path length distribution $p(X)$:

$$p(X) \sim \exp[-X/\Lambda]\,. \quad (7)$$

Such a distribution was used with much success by Shapiro and Silberberg (1970) to fit the observed fluxes.

In a recent work (hereafter LRF) Lingenfelter *et al.* (1971) give reasons to believe that the path length distributions may be flatter than the exponential distribution. The effect of this distribution (LRF) will be discussed later on.

Each of the fast nuclei of the G.C.R. flux is faced with three possible fates: a) nuclear destruction (or decay); b) escape from the Galaxy (for our purpose they are lost) and c) deceleration to thermal interstellar energies and incorporation into the gas.

The number of thermalized nuclei added to the interstellar medium $\frac{d n_i}{d t}$ (in $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$) is, in fact, the sum of two contributions:

a) spallation of interstellar heavy nuclei by fast protons and alphas. In this case, the recoil energy of the L elements is low (a few MeV N^{-1}) and the rate of thermalisation is equal to the rate of production.

b) spallation of fast heavy nuclei by interstellar hydrogen and helium. In this case we must calculate the "current" of particles in energy space $[N_i(E)\,b_i(E)]$ and compute its value at an appropriately low energy. Below one MeV N^{-1} all nuclear processes are inoperant and the ionization range $R_i(E)$ (Eq. (4)) becomes much smaller than the loss range Λ_i (Eq. (3)). Hence, for secondary particles (for which $q_i = 0$), Eq. (1) reduces to

$$\frac{\partial}{\partial E}(N_i b_i) = 0\,, E \leqq 1\ \mathrm{MeV}\,. \quad (8)$$

In other words, the current in energy space remains constant all the way down to the thermalization energies. As the function $b_i(E)$ is rather poorly known below a few hundred of keV, it will be convenient to compute this current at one MeV.

Summing the two contributions (a) and (b) we get:

$$\frac{\partial n_i}{\partial t} = N_i(E) b_i(E) + \sum_j \int_0^\infty [\sigma_{pji}(E')\,\phi_p(E') + \sigma_{\alpha ji}(E')\,\phi_\alpha(E')]\,n_j\,dE'\,. \quad (9)$$

The mean ionization rate ζ_n per nucleon in the gas[3]) can be written as

$$\zeta_n = \frac{\sum_i A_i \int_0^\infty N_i(E) \frac{b_i(E)}{\Delta_i(E)} dE}{\sum_k n_k A_k} \cong \frac{\sum_k n_k Z_k \sum_i Z_i^2 \int \phi_i(E) \frac{\varepsilon_{\mathrm{HH}}(E)}{\Delta E} M_{\mathrm{H}}}{\sum_k n_k A_k}$$

$$\cong 1.7 \int \phi_p(E) \frac{\varepsilon_{\mathrm{HH}}(E)}{\Delta E} M_{\mathrm{H}}\, dE \cong 0.79\,\zeta_{\mathrm{H}} \quad (10)$$

where $\Delta_i(E)$ is the energy loss per ionization and ΔE its mean value ($\cong 36$ eV); $\varepsilon_{\mathrm{HH}}$ is the standard energy loss ($\mathrm{g}^{-1}\,\mathrm{cm}^2$) of protons in hydrogen $\left(\varepsilon_{\mathrm{HH}} = \frac{\sigma_{\mathrm{ion}}\,\Delta E}{M_{\mathrm{H}}}\right)$ σ_{ion} is the ionization cross-section.

For neutral hydrogen the expression (the Bethe's formula)

$$\varepsilon_{\mathrm{HH}} = 3.05 \times 10^{-4}\,\beta^{-2}\left[11.06 + \ln\frac{\beta^2}{1-\beta^2} - \beta^2\right] \quad \mathrm{GeV\,g^{-1}\,cm^2} \quad (12)$$

fits the best calculated curve from 0.5 MeV to several GeV ($\beta = v/c$).

[2]) For radioactive isotopes, Λ_i is energy dependent, and one must replace the exponential in Eq. (4) by:

$$\exp\left[-\int_E^{E'} \frac{dE''}{w_i(E'')\,\Lambda_i(E'')}\right].$$

[3]) The quantity J used in Salpeter and Wickramasinghe (1969) and in F.R.S. ($J \equiv 1.3 \times 10^{16}\,\xi_{\mathrm{H}}$) takes for a non-relativistic energy spectrum the approximate but very useful form

$$J = \sum_k n_k Z_k \sum_i Z_i^2 \int \phi_i \left(\frac{1\ \mathrm{MeV}}{E}\right) dE \cong 2.5 \int \phi_i \left(\frac{1\ \mathrm{MeV}}{E}\right) dE \quad (13)$$

In these units the observations mentioned in section III d require $J \cong 6$ but $J < 10$.

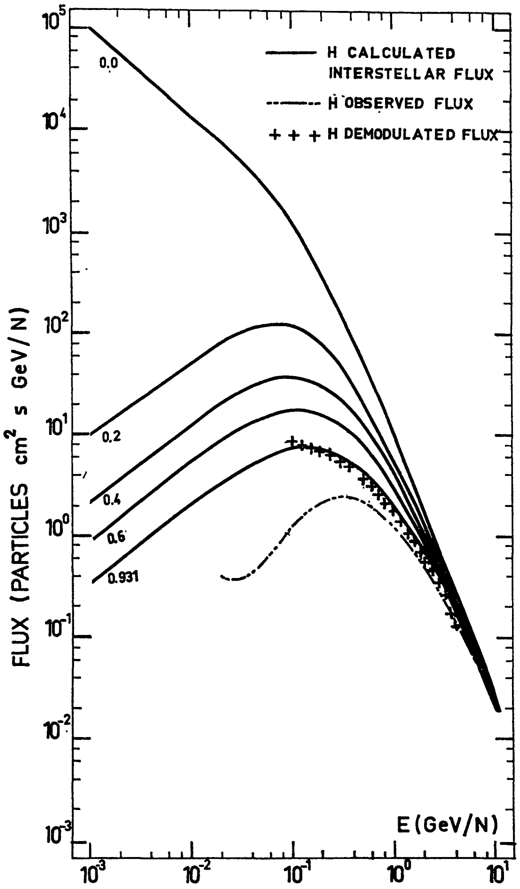

Fig. 3. Interstellar H energy spectra from an injection spectrum proportional to $(E_0 + E)^{-2.6}$ where E is the kinetic energy (GeV N^{-1}) and E_0 a parameter varying from 0 to 0.931 GeV N^{-1}. The curves are labelled by the corresponding E_0. Also shown is the observed H energy spectrum at solar minimum and the demodulated H spectrum as calculated by G.F.R.. The injection flux in total energy power ($E_0 = 0.931$ GeV) appears to fit very well the spectrum demodulated from solar effect

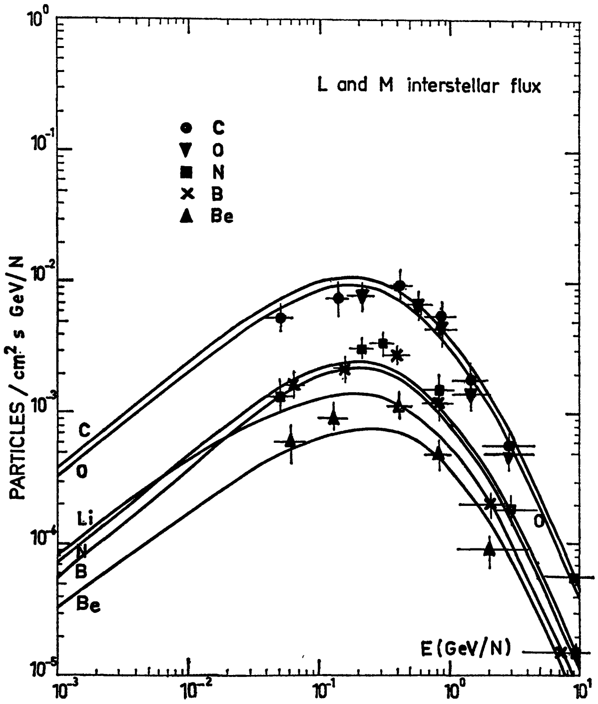

Fig. 4. Interstellar fluxes of Li, Be, B, C, N, O, from an injection spectrum in the total energy power. ($E_0 = 0.931$ GeV in Eq. (15) compared with undemodulated observations (Von Rosenvinge, 1969)). The flattening of the Li and Be curves at low energy is due to the effect of the $(\alpha + \alpha)$ reaction. The beta decay of ^{7}Be in ^{7}Li at low energy ($E < 20$ MeV N^{-1}) has not been incorporated in this figure

The Calculation

The computation is made in the following way:

a) The sources are assumed to emit fluxes with given injection chemical composition and given injection energy spectrum. These are represented by the term $q_i(E')$ in Eq. (4).

b) Starting from iron one computes Eq. (4) for each stable isotope (and Be^{10}) and includes in the calculation the spallation reactions leading to each stable isotopes (and ^{10}Be). However in the present calculations we have neglected the spallative formation of nuclei with $A > 15$ in space. The small error which results from this simplification has been estimated and compensated by increasing slightly the assumed abundances of these nuclei at the sources (Table 2).

c) the escape range Λ_e is left as a free parameter to be discussed in the next section.

V. The Escape Range

Since the L elements in the G.C.R. are most certainly of secondary origin (absent from the source), it has been customary to determine the leakage range Λ_e from the ratio of the L to M (CNO) nuclei at high energy in space.

This procedure neglects the possible contribution of the $(\alpha + \alpha)$ process to ^{6}Li, ^{7}Li, ^{7}Be which at low energies 10–20 MeV N^{-1} at least, where nuclear measurements exist, is dominant. It would be preferable then to compute Λ_e from the B/M ratio (since $\alpha + \alpha$ does not contribute to B). But the experimental value of this ratio is still controversial (see Fig. 8).

As we have assumed Λ_e to be energy independent we shall compute its value at high energies ($E > 2$ GeV) where (i) the ionization losses are unimportant (consequently the problem can be treated analytically) and where (ii) the contribution of the ($\alpha + \alpha$) reaction to the Li Be flux certainly becomes negligible since L nuclei of energy E are generated by α of energy ($4E$), and since the flux intensity decreases very rapidly above two GeV N^{-1}.

From Eq. (4) we have simply

$$\frac{1}{\Lambda_e} = \frac{\sum_i \frac{\phi_i}{\phi_L}\left(\sigma_{piL} + \sigma_{\alpha iL}\frac{n_{He}}{n_H}\right) - \left(\sigma_{pL} + \sigma_{\alpha L}\frac{n_{He}}{n_H}\right)}{M_p + \frac{n_{He}}{n_H} M_\alpha} \tag{14}$$

when L is one product nucleus (absent from the source) and the $\sum_j \phi_j$ represent all possible parents.

This formula can be adapted to the sum of all L isotopes (Li, Be, B). The observed value of L/M at high energy outside of the magnetosphere is 0.23 ± 0.02 (Webber, private communication 1971; Von Rosenvinge *et al.*, 1969; Shapiro and Silberberg, 1970). We obtain:

$$\Lambda_e = 6.3 \text{ g cm}^{-2} \text{ — including effects of He}$$

VI. Chemical Composition at Injection

The observed flux intensity (above 2 GeV N^{-1}) of the most abundant particles together with the value

Table 4

Element \ E (MeV N^{-1})	1	3	10	30	100	300	1000	3000	10000
Fe	3.6×10^{-5}	8.7×10^{-5}	2.3×10^{-4}	5.3×10^{-4}	1.0×10^{-3}	1.1×10^{-3}	4.6×10^{-4}	8.5×10^{-5}	6.0×10^{-6}
^{16}O	3.7×10^{-4}	8.9×10^{-4}	2.3×10^{-3}	5.2×10^{-3}	9.4×10^{-3}	9.2×10^{-3}	3.5×10^{-3}	6.0×10^{-4}	4.2×10^{-5}
N	7.7×10^{-5}	1.9×10^{-4}	5.0×10^{-4}	1.2×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	9.3×10^{-4}	1.7×10^{-4}	1.2×10^{-5}
^{15}N	2.6×10^{-5}	6.5×10^{-5}	1.8×10^{-4}	4.5×10^{-4}	8.3×10^{-4}	8.7×10^{-4}	3.6×10^{-4}	6.6×10^{-5}	4.6×10^{-6}
^{14}N	5.0×10^{-5}	1.2×10^{-4}	3.2×10^{-4}	7.4×10^{-4}	1.4×10^{-3}	1.5×10^{-3}	5.7×10^{-4}	1.0×10^{-4}	7.1×10^{-6}
$^{15}N/N$	0.34	0.35	0.36	0.38	0.37	0.37	0.38	0.39	0.39
C	4.2×10^{-4}	1.0×10^{-3}	2.7×10^{-3}	5.9×10^{-3}	1.1×10^{-2}	1.0×10^{-2}	3.9×10^{-3}	6.7×10^{-4}	4.7×10^{-5}
^{13}C	9.8×10^{-6}	2.4×10^{-5}	6.6×10^{-5}	1.6×10^{-4}	3.8×10^{-4}	5.0×10^{-4}	2.4×10^{-4}	4.6×10^{-5}	3.2×10^{-6}
^{12}C	4.1×10^{-4}	1.0×10^{-3}	2.6×10^{-3}	5.8×10^{-3}	1.0×10^{-2}	9.9×10^{-3}	3.7×10^{-3}	6.2×10^{-4}	4.4×10^{-5}
C^{13}/C	0.023	0.024	0.025	0.027	0.035	0.048	0.062	0.069	0.069
CNO/Fe	24	24	24	23	23	20	18	16	16
B	5.7×10^{-5}	1.4×10^{-4}	3.8×10^{-4}	9.7×10^{-4}	2.0×10^{-3}	2.2×10^{-3}	8.7×10^{-4}	1.6×10^{-4}	1.1×10^{-5}
^{11}B	4.2×10^{-5}	1.0×10^{-4}	2.8×10^{-4}	7.2×10^{-4}	1.4×10^{-3}	1.6×10^{-3}	6.1×10^{-4}	1.1×10^{-4}	7.7×10^{-6}
^{10}B	1.5×10^{-5}	3.7×10^{-5}	1.0×10^{-4}	2.6×10^{-4}	5.5×10^{-4}	6.2×10^{-4}	2.7×10^{-4}	4.9×10^{-5}	3.4×10^{-6}
$^{11}B/^{10}B$	2.8	2.8	2.8	2.8	2.6	2.5	2.3	2.3	2.3
Be	2.5×10^{-5}	5.9×10^{-5}	1.4×10^{-4}	3.4×10^{-4}	6.7×10^{-4}	7.8×10^{-4}	3.7×10^{-4}	6.9×10^{-5}	4.9×10^{-6}
^{10}Be	1.2×10^{-6}	3.0×10^{-6}	8.7×10^{-6}	2.3×10^{-5}	5.3×10^{-5}	9.8×10^{-5}	6.0×10^{-5}	1.3×10^{-5}	9.5×10^{-7}
^{9}Be	4.2×10^{-6}	1.0×10^{-5}	2.9×10^{-5}	7.2×10^{-5}	1.6×10^{-4}	2.2×10^{-4}	1.1×10^{-4}	2.1×10^{-5}	1.5×10^{-6}
^{7}Be	1.9×10^{-5}	4.3×10^{-5}	1.1×10^{-4}	2.5×10^{-4}	4.6×10^{-4}	4.7×10^{-4}	2.0×10^{-4}	3.6×10^{-5}	2.5×10^{-5}
$^{7}Be/Be$	0.78	0.77	0.74	0.73	0.69	0.60	0.54	0.52	0.51
Li	7.0×10^{-5}	1.7×10^{-4}	3.8×10^{-4}	7.6×10^{-4}	1.2×10^{-3}	1.2×10^{-3}	5.1×10^{-4}	9.1×10^{-5}	6.4×10^{-6}
^{7}Li	2.6×10^{-5}	6.1×10^{-5}	1.4×10^{-4}	3.2×10^{-4}	5.7×10^{-4}	5.5×10^{-4}	2.3×10^{-4}	4.0×10^{-5}	2.8×10^{-6}
^{6}Li	4.4×10^{-5}	1.1×10^{-4}	2.4×10^{-4}	4.3×10^{-4}	6.8×10^{-4}	6.9×10^{-4}	2.9×10^{-4}	5.1×10^{-5}	3.6×10^{-6}
L/M	0.18	0.18	0.17	0.17	0.18	0.20	0.22	0.23	0.23
He^4	2.4×10^{-2}	5.8×10^{-2}	1.5×10^{-1}	3.1×10^{-1}	4.8×10^{-1}	4.0×10^{-1}	1.4×10^{-1}	2.2×10^{-2}	1.5×10^{-3}
He/Fe	670	670	650	590	480	360	300	260	250
He/CNO	28	28	27	25	22	18	17	15	15
H	3.7×10^{-1}	8.7×10^{-1}	2.2	4.7	7.6	6.4	2.2	3.6×10^{-1}	2.5×10^{-2}

Calculated interstellar G.C.R. fluxes in $cm^{-2}s^{-1}$ (GeV N^{-1}) from a power law in total energy ($W^{-2.6}$) spectrum and source composition given in Table 2 with an escape length of 6.3 g cm^{-2}. The value of 1 particle cm^{-3} is chosen for the hydrogen number density and $n_{He}/n_H = 0.1$. The Be^7 is considered as a stable isotope, but the partial decay of Be^{10} at this density is computed. At much lower densities all the Be^{10} atoms would decay to B^{10} (see appendix B).

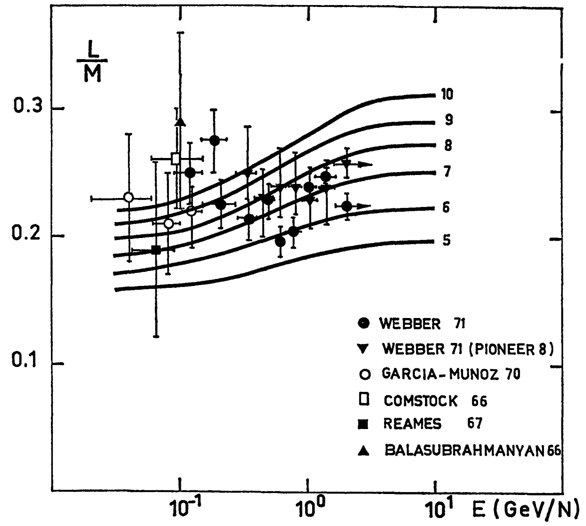

Fig. 5. Computed L/M ratio for various values of the escape range Λ_e in g cm^{-2} and corresponding observations. A choice of $\Lambda_e \cong 6.3$ g cm^{-2} appears reasonable

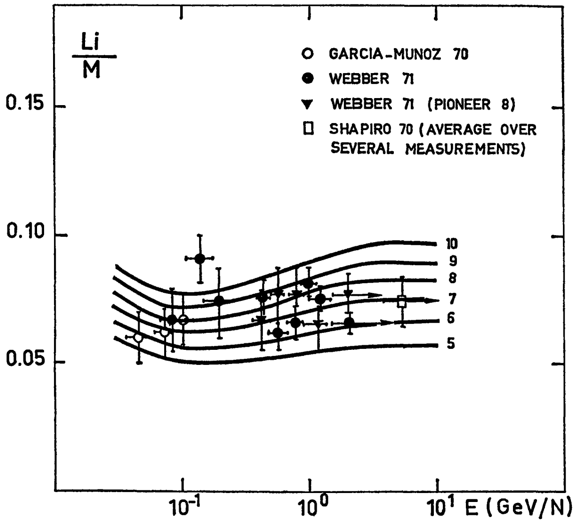

Fig. 6. Computed Li/M ratio for various values of the escape range Λ_e in g cm^{-2} and corresponding observations. Again the data fits $\Lambda_e \cong 6.3$ g cm^{-2}

of Λ_e obtained before are used to calculate the (high energy) chemical composition at injection. The results are given in Table 2 normalized to C = 100. The agreement with Shapiro and Silberberg is good.

The problem of the abundance of N at the source will be discussed in the Appendix C.

VII A. The Energy Spectrum at the Sources

We have tested a wide variety of source energy spectra ($q_i(E)$ in Eq. (4)). We have first considered a total energy power law spectrum: as discussed by Gloeckler and Jokipii (1969) the spectral shape

$$q_p(E) = K(E_0 + E)^{-2.6} \text{ cm}^{-2}\text{ s}^{-1}\text{ GeV}^{-1} \quad (15)$$

with $E_0 = M_p C^2 = 0.931$ GeV, E the kinetic energy in GeV and $K \cong 12.5$ for protons, is a very good choice in many respects.

The interstellar fluxes of primary and secondary particles, computed with $\Lambda_e = 6.3$ g cm^{-2} are in fair agreement with the demodulated fluxes of G.F.R. (1970) (Fig. 3 with $E_0 = 0.931$ and Fig. 4). Table 4.

The flatter slope of the Li and Be curve at low energy in Fig. 4 is due to the contribution of the $(\alpha + \alpha)$ reaction (Figs. 1 and 2). It should be reminded that the cross-section for this reaction is most uncertain above a few tens of MeV for α particles, hence above ten MeV for Li Be. In particular the crossover of Li and B in Fig. 4, may take place anywhere between 10 and 100 MeV N^{-1}.

In Figs. 5–8 are shown the various ratios of L/M Li/M, Be/M, B/M as a function of energy.

However the choice $\Lambda_e = 6.3$ g cm^{-2} determined at *high* energy appears to underestimate slightly the *low* energy ratios.

In Fig. 8 (B/M) we find a rather confusing situation. The (B/M) ratio should (as discussed before) be the best test of the value of Λ_e since it is free of any assumption on the $(\alpha + \alpha)$ reaction. Nevertheless it does seem to require a *higher* Λ_e around a few hundred of MeV than the Li/M or Be/M ratio (any contribution from the $(\alpha + \alpha)$ reaction would have lead to the *inverse* situation . . .).

Should the present experimental result (and, in particular, the apparent *increase* of the B/M ratio as the energy decreases) be confirmed, we may find it necessary to alter the present diffusion model of G.C.R.

The ratio of He/CNO in our calculations vary from 16 at 3 GeV N^{-1} to 19 at 300 MeV N^{-1}, and to 22 at 100 MeV N^{-1}; such a slow rise is compatible with the observations (Garcia Munoz *et al.*, 1968).

In Figs. 9 and 10 we have tried to obtain an upper limit to the $(\alpha + \alpha)$ cross-section at high energy from the observed Li/B and Be/B ratio in the G.C.R. (this ratio is practically independent of Λ_e and of the spectral shape assumed). The solid curves are labelled with the value of the $\sigma(\alpha + \alpha)$ cross-

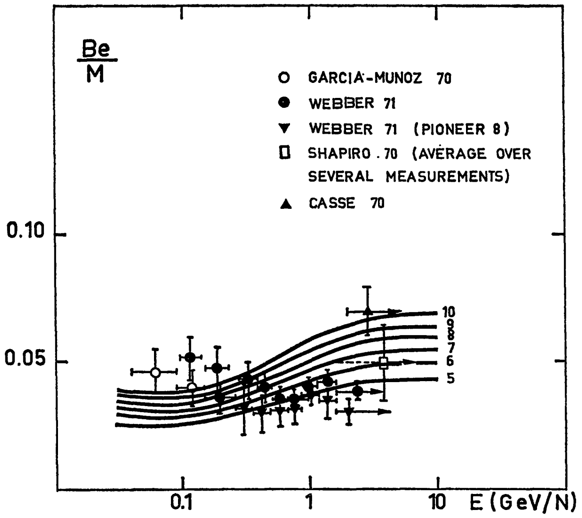

Fig. 7. Computed Be/M ratio for various values of the escape range Λ_e in g cm^{-2} and corresponding observations. Again $\Lambda_e \cong 6.3$ g cm^{-2}

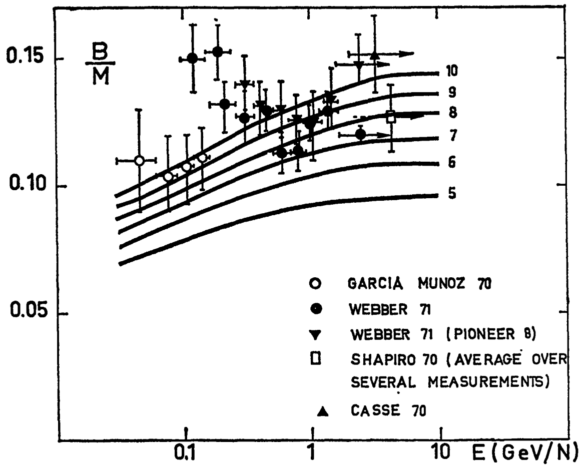

Fig. 8. Computed B/M ratio for various values of the escape range Λ_e in g cm^{-2} and corresponding observations. There is apparently a discrepancy between the 6.3 g cm^{-2} curve and the data at low energy

section (in mb) chosen for each of the three reactions leading to ^{6}Li, ^{7}Li, ^{7}Be, at all energies above 400 MeV N^{-1}. (E(Li or Be) > 100 MeV/N^{-1}.) Clearly the cross-section cannot be as large as 10 mb and probably not even as large as 3 mb as, otherwise, a turnover of the ratio would already have been observed around 100 MeV N^{-1}. This result is consistent with our choice of one mb from purely nuclear physics arguments but again we plea for actual measurements.

The rate of thermalization of the G.C.R. particles (and consequent enrichment of the interstellar gas) is obtained from Eq. (9). We find

$$\frac{d(n(\mathrm{Be})/n(\mathrm{H}))}{dt} = 7 \times 10^{-29}\ \mathrm{s}^{-1}\,. \qquad (16)$$

To estimate the stellar abundances of the L isotopes we have multiplied the formation rates computed here by an age of 10^{10} years, to account for the mean stellar Be/H. According the model of Schmidt (1963)

Table 5. *Calculated abundances after 10^{10} years. The injection spectrum Eq. (15) with various values of E_0 and a spectrum in power law of rigidity are considered separately in the various columns. The observed flux at 10* GeV *is used for the normalization of the different spectral shapes. The last column shows the effect of adding an intense low energy flux (described in the text) to a power law spectrum in total energy*

E_0 (GeV)	0.931	0.8	0.6	0.4	0.2	0.0	$R^{-2.6}$	Model C
^{6}Li/H	8.2×10^{-11}	1.0×10^{-10}	1.6×10^{-10}	3.1×10^{-10}	8.5×10^{-10}	2.3×10^{-8}	7.1×10^{-10}	1.5×10^{-9}
^{7}Li/H	1.2×10^{-10}	1.5×10^{-10}	2.3×10^{-10}	4.2×10^{-10}	1.1×10^{-9}	4.2×10^{-8}	1.0×10^{-9}	2.6×10^{-9}
^{9}Be/H	2.0×10^{-11}	2.4×10^{-11}	3.5×10^{-11}	5.8×10^{-11}	1.3×10^{-10}	1.4×10^{-9}	7.8×10^{-11}	6.6×10^{-11}
^{10}B/H	8.6×10^{-11}	1.1×10^{-10}	1.6×10^{-10}	2.8×10^{-10}	6.7×10^{-10}	6.7×10^{-9}	3.8×10^{-10}	2.0×10^{-10}
^{11}B/H	2.1×10^{-10}	2.6×10^{-10}	3.9×10^{-10}	7.0×10^{-10}	1.8×10^{-9}	2.4×10^{-8}	1.1×10^{-9}	9.1×10^{-10}
Li/H	2.0×10^{-10}	2.5×10^{-10}	3.9×10^{-10}	7.3×10^{-10}	1.9×10^{-9}	6.5×10^{-8}	1.7×10^{-9}	4.1×10^{-9}
B/H	3.0×10^{-10}	3.7×10^{-10}	5.5×10^{-10}	9.8×10^{-10}	2.5×10^{-9}	3.1×10^{-8}	1.5×10^{-9}	1.1×10^{-9}
^{11}B/^{10}B	2.4	2.4	2.4	2.5	2.7	3.6	2.9	4.5
^{7}Li/^{6}Li	1.5	1.5	1.4	1.4	1.3	1.8	1.4	1.7
B/Be	15	15	16	17	19	22	19	17
Li/B	0.66	0.68	0.71	0.71	1.1	2.1	1.1	3.7
Li/Be	10	10	11	13	15	46	22	62
ζ_H	6.8×10^{-18}	8.2×10^{-18}	1.3×10^{-17}	2.4×10^{-17}	6.8×10^{-17}	2.0×10^{-14}	1.0×10^{-16}	2.0×10^{-16}

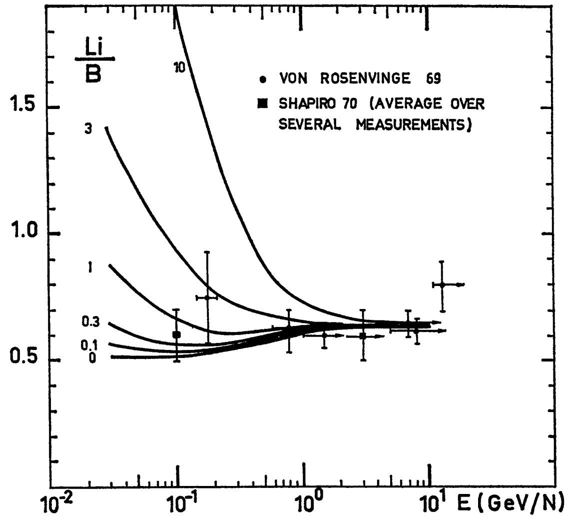

Fig. 9. Predicted Li/B flux ratio for various choices of the $(\alpha + \alpha) \rightarrow Li^7$, Be^7, Li^6 cross-sections at $E_\alpha > 400$ MeV N^{-1} (Fig. 2). The number 3 on one of the curve, for instance, means that a value of three mb has been assigned to each of these three processes. The experimental data is consistent with $\sigma \leqq 1$ mb

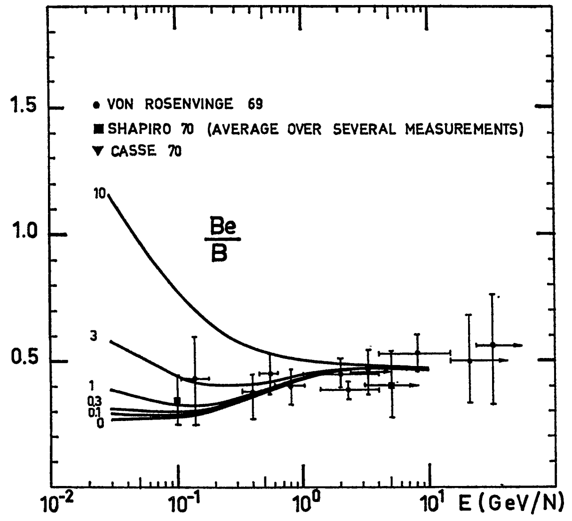

Fig. 10. Predicted Be/B flux ratio for various choice of the $(\alpha + \alpha)$ Li^7, Be^7, Li^6 cross-sections at $E_\alpha < 400$ MeV N^{-1} (Fig. 2); the number 3 on one of the curves for instance, means that a value of three mb has been assigned to each of these three processes. The experimental data is consistent with $\sigma \leqq 3$ mb

the age of the galactic gas against stellar formation (τ_{sf}) (and consequent Be destruction) is $\simeq 10^{10}$ years, suggesting that G.C.R. flux has not changed very much over this period. However τ_{sf} is in fact very poorly known and may well turn out to be appreciably shorter than 10^{10} years.

For our purpose it is better to pretend that the Be abundance is used to fix one free parameter: the average exposure time of the gas.

In Table 5 the abundance ratios of the L isotopes are tabulated (present rate of G.C.R. and 10^{10} years). Within the framework of the model, the uncertainties (mostly due to nuclear parameters) should not be larger than a factor of two for the element ratios and probably even smaller for the isotopic ratios.

A comparison with section IIIc and IIId shows that the predictions from the spectral shape of Eq. (15) ($E_0 = 0.931$ GeV N^{-1}) are in fair agreement (i) with the mean stellar, or solar-planetary Be/H abundance; (ii) with the lowest observed $^7Li/^6Li$ ratio in stars when further thermonuclear depletion is taken into account (iii) with the $^{11}B/^{10}B$ ratio in the solar system (however slightly underestimated), and (iv) with the upper limit of the B/H in the sun. Also well reproduced are the $^9Be/^7Li/^6Li$ data in the five "G.C.R." stars described in section IIIc. However this spectral shape will not explain the large Li/Be ratios observed in many F stars (Table 4) (since thermonuclear reaction will only decrease the ratio from its initial value), nor the large lithium abundance observed in T Tauri or early Pleiades or Hyades stars. The rate of ionization of interstellar medium by such a flux is of course far too small to account for the observations (see section IIIc).

VIIB. A Family of Spectra in $(E_0 + E)^{-2.6}$

Next we have varied the parameter E_0 in Eq. (15) from 0.931 GeV (power law in total energy) to $E_0 = 0$ (power law in kinetic energy). We have also considered the spectrum in power law of rigidity ($R = pc/Z$): the results resemble in many respects those of Eq. (15) with $E_0 \simeq 0.2-0.3$ GeV.

The calculated values appear in Figs. 3, 11, 12 and in Table 5 and 6. The interstellar flux of H (Fig. 3), within the frame work of the demodulation theory of GFR limits us to rather large values of E_0 ($E_0 > 0.5$). The flatness of the L/M curves (Figs. 5 to 7) suggests the same conclusion (lowering the value of E_0 leads to a decrease of the L/M ratio at low energy).

Within the present model (constant flux for 10^{10} y) the stellar values of Be/H and the solar upper limit of boron (Fig. 11) are again consistent with E_0

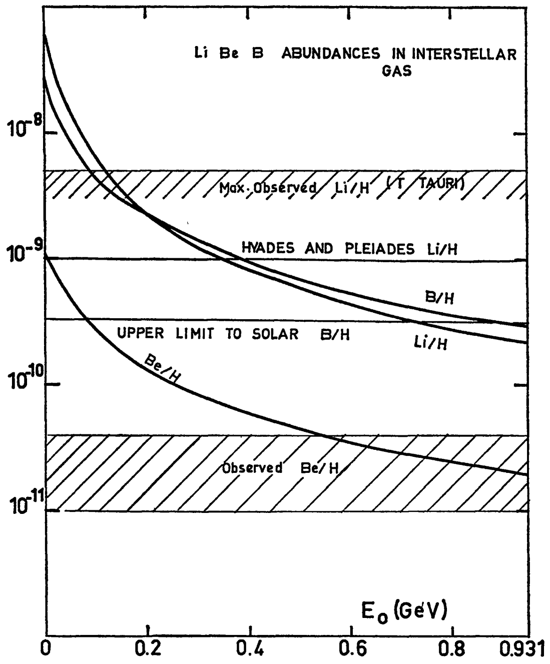

Fig. 11. Abundance of Li, Be, B in the interstellar gas after an irradiation of 10^{10} years with an injection flux in $(E_0 + E)^{-2.6}$ (Eq. 15) as a function of E_0. Also shown are the range of Be/H in normal stars, the upper limit to the solar boron, the Li/H in F stars of the Hyades and Pleiades and the largest Li/H reported in T Tauri stars

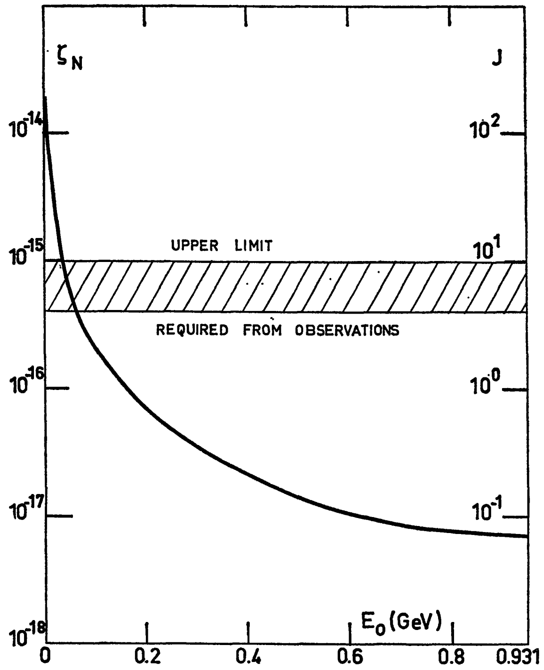

Fig. 12. Ionization rate ζ_N per unit nucleon per s of the interstellar gas (assumed neutral) (Eq. 10). The scale on the right refers to the parameter J defined in Eq. 13. The horizontal line shows the value required from observations while the upper part of the dashed region shows the upper limit discussed in the Section IIIe

> 0.5 GeV. The ratio of ^{7}Li/^{6}Li and ^{11}B/^{10}B are very insensitive to the value of E_0. On the other hand the Li/H in the Pleiades would require $E_0 < 0.4$ GeV N^{-1} while the largest T Tauri lithium value (if real) would require $E_0 < 0.2$ GeV N^{-1}. In Fig. 12 the parameter ζ_H is shown as a function of E_0. The properties of interstellar matter would require $E_0 \simeq 0.15$. *In summary: a spectrum with* $E_0 > 0.5$ GeV *is consistent with most of the data but will not explain the largest* Li *abundance nor the ionization rate of interstellar gas.*

A spectrum with $E_0 < 0.5$ GeV is hard to reconcile with the modulation capabilities of the solar wind or with the low energy L/M ratios which are practically independent of modulation effects.

In particular the spectrum in kinetic energy power would be excluded not only because of the

Table 6

E (GeV N^{-1}) \ E_0(GeV)	0.931	0.8	0.6	0.4	0.2	0.0	$R^{-2.6}$	Observed
0.03	0.17	0.17	0.16	0.14	0.11	0.03	0.06	
0.1	0.18	0.17	0.17	0.15	0.13	0.08	0.11	
0.3	0.20	0.19	0.19	0.18	0.17	0.15	0.17	0.23
1	0.22	0.22	0.21	0.21	0.21	0.21	0.21	± 0.02
3	0.23	0.23	0.23	0.23	0.23	0.23	0.23	
10	0.23	0.23	0.23	0.23	0.23	0.23	0.23	

Calculated L/M ratios in the G.C.R. with injection spectra as in Eq. (15) and in rigidity. The escape range is 6.3 g/cm². The observed flux ratio outside magnetosphere (see text) is given in the last column.

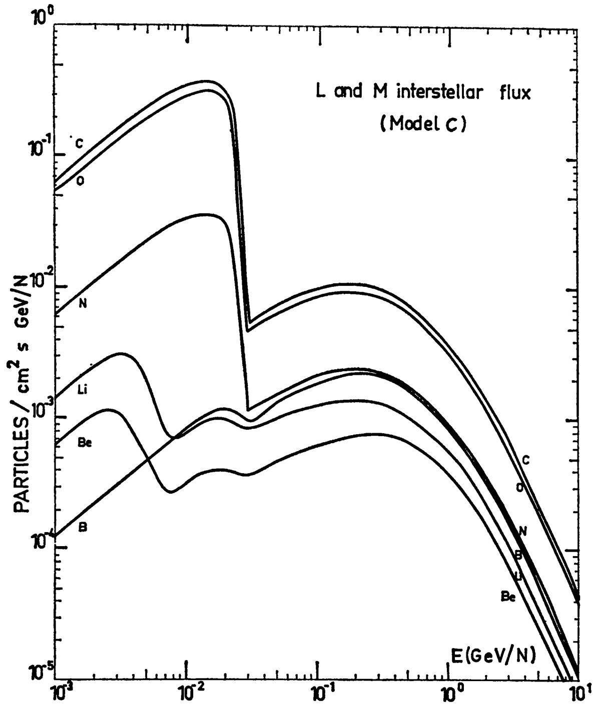

Fig. 13. Interstellar fluxes of Li, Be, B, C, N, O from an injection spectrum in which a very intense low energy carrot (below 40 MeV) (Section VIII) has been added to spectrum in total energy power (as in Fig. 4). The lowest energy bumps in the Li and Be curves are due to the effect of the $(\alpha + \alpha)$ reaction

excessive Li/H, Be/H and B/H generated but also because it would create *far too much* ionization; Meyer (1970) has already shown that the predicted $D/^4He$ ratio in low energy G.C.R. would be in conflict with the observations (Hsieh and Simpson, 1969).

Contrary to the conclusion of RFH the $^{11}B/^{10}B$ ratio cannot be used to infer the properties of the low energy spectrum shape, mostly because of the dominant effect of the alpha-induced reactions in this energy range (see Section II for more details).

VIII. The Effects of an Intense Low Energy Flux

Our previous discussion has shown that the G.C.R. flux cannot rise very steeply from the GeV range all the way until the MeV range. Below a few tens of MeV, however, quite a different situation may arise; the L element formation cross-sections decrease and according to G.F.R. no particle from this range will reach close to the earth against the solar wind.

Our aim in this section is to investigate how many particles of such energies may pervade space with none of us being the wiser. For this purpose we added to an injection spectrum in total energy power $(W)^{-2.6}$ with $W = [E + 0.931 \text{ GeV}]$, an injection spectrum which rises very high in the low energy

Table 7. L-*elements and isotopic ratios: comparison between calculations and observations. The second column is the effect of a total energy spectrum* $(W^{-2.6})$ *after* 10^{10} *years with constant intensity (same as the first column of Table 5). The third column is the additional amount of* ^{7}Li *and* ^{11}B *required to fit the planetary observation in the sixth column. The fourth column applies to the model* T, *in which some* ^{7}Li *and* B^{11} *from thermonuclear origin (third column) is added to the general background of* G.C.R. *produced elements (second column). The fifth column (Model* C) *describes the results obtained when a very intense low energy "carrot" of specified dimensions is added to the column 1. The parameters of the carrot used here were chosen to maximize the hydrogen ionization rate while keeping* L-*elements abundances within reasonable bounds. The last column refers to the solar observations. Clearly lithium has been strongly depleted by thermonuclear reactions*

	G.C.R $W^{-2.6}$	Thermo nuclear	Model T	Model C	Planets observed	Solar observed
^{6}Li/H	8×10^{-11}	0	8×10^{-11}	1.4×10^{-9}	9×10^{-11}	$< 10^{-12}$
^{7}Li/H	1.2×10^{-10}	10^{-9}	1.1×10^{-9}	2.4×10^{-9}	1.1×10^{-9}	10^{-11}
^{7}Li/^{6}Li	1.5	∞	12.5	1.7	12.5	> 10
Li/H	2×10^{-10}	10^{-9}	1.2×10^{-9}	3.8×10^{-9}	1.2×10^{-9}	10^{-11}
^{9}Be/H	2×10^{-11}	0	2×10^{-11}	6×10^{-11}	2×10^{-11}	10^{-11}
Li/Be	10	∞	60	65	60	1.0
^{10}B/H	8.7×10^{-11}	0	8.6×10^{-11}	2×10^{-10}		
^{11}B/H	2×10^{-10}	1.4×10^{-10}	3.4×10^{-10}	7.5×10^{-10}		
^{11}B/^{10}B	2.4	∞	4	3.8	4	
B/H	3.0×10^{-10}	1.4×10^{-10}	4.3×10^{-10}	10^{-9}	3×10^{-10} to 10^{-8}	$< 3 \times 10^{-10}$
B/Be	15	∞	21	16		< 30
B/Li	1.4	0.15	0.36	0.26	0.2 to 10	< 30

region (hereafter referred to as a "carrot"). The width and the height of the carrot have been selected in order to maximize the hydrogen ionization rate while keeping the L element abundances within reasonable bounds. For instance, in Fig. 13 the effect of a carrot extending from 5 MeV to 40 MeV and rising a factor of one thousand in intensity GeV^{-1} over the corresponding flat part of the total energy injection spectrum is considered. This carrot contains at the source sixty times more particles than the total energy spectrum but its energy content is merely twice as large.

We note that the carrot has been extensively "grated" by the interstellar medium especially for the lowest energies. It is useless to inject even lower energy particles.

In the Table 7 the L element production by the combined effect of the two injection spectra is given in the last column. The largest observed Li/H and Li/Be are now accounted for while the $^7Li/^6Li$ agreement is preserved and the $^{11}B/^{10}B$ is even improved (meaningfully or not). The Be/H and B/H are somewhat (but not unduly) high and this time the rate of ionization is quite large enough. However it is not evident that these low energy particles will propagate far enough to account for the ionization of large regions of the galaxy. The short range against ionization is likely to confine them around the sources.

IX. Astrophysical Discussions: two Models

From the preceding sections it appears that the hypothesis of G.C.R. flux in $(E_0 + E)^{-2.6}$ with $0.5 < E_0 < 1$ GeV constant in intensity for the last 10^{10} years will account not only for the G.C.R. observations but also for a large part of the stellar observations. However this hypothesis will not, by itself, explain the large Li/Be value found in F stars; the largest T Tauri lithium value or the meteoritic isotopic lithium ratio. We must at this point introduce some new element in the game. This can be done in two different ways. Therefore the following two models.

Model T

This model is essentially based on the fact that, out of the five L isotopes, one at least, ^7Li (and may be also ^{11}B) can also originate from thermonuclear reactions. Since many stars (in particular the G.C.R. stars) do not show any ^7Li enhancement this contribution must be inhomogeneously distributed in space and cannot be assigned to the Big Bang or to any homogeneously distributed contribution.

Some ^7Li appears in the H burning cycle, through the $^3He + {}^4He \rightarrow {}^7Be \rightarrow {}^7Li$, reaction. Cameron and Fowler (1971) have suggested that helium burning shell flashes in advanced stages of stellar evolution may be responsible for the large overabundance of Li ($Li/H \simeq 10^{-7}$) observed in some Red Giants. Since giant stars exhibit large rate of mass loss the ^7Li thereby produced may be mixed with the interstellar gas and alter the Li/H, the Li/Be and the $^7Li/^6Li$ (thermonuclear lithium is devoid of ^6Li) (this possibility has been suggested by A.G.W. Cameron in conversation). These alterations would be more important in regions of heavy star formations. Our five G.C.R. stars (section IIIc) were clearly born in regions of pure G.C.R. contribution. In the same fashion the F stars with large Li/Be and no ^6Li and also the T Tauri stars would come from "dirty" regions (regions of extensive stellar formation and matter injection).

This model gives an appropriate description of the various L isotopes in the young sun and in the planets: the planets were formed before any thermonuclear depletion of lithium could take place in the sun. The numbers given in Table 7 illustrate the situation. The thermonuclear contributions in column 3 are purely "ad hoc"; they were arranged to fit the observed data. We notice that a small addition of thermonuclear B may eventually be needed. This isotope can possibly be made as sequential to the mechanism proposed by Cameron and Fowler (1971):

$$^3He + {}^4He \rightarrow {}^7Be \rightarrow {}^7Li$$

$$^4He + {}^7Li \rightarrow {}^{11}B$$

$$^4He + {}^7Be \rightarrow {}^{11}C \rightarrow {}^{11}B$$

This model gives no account for the ionization of interstellar matter.

Model C

Here the missing lithium is assigned to a large flux intensity, in the tens of MeV range, of G.C.R. ("carrots") such as described in Table 6 and repeated in the fifth column of Table 7. The existence of such "carrots" is not totally unphysical; strong fluxes of low energy particles do probably exist, confined to the proximity of the sources; the L-nuclei generated by this part of the G.C.R. spectrum eventually diffuse throughout the galaxy. Conversely, these low energy particles may not pervade the H I regions. The question is under study (Pacheco, 1971 to be published, Cesarsky, 1970).

The model C will explain neither the $^9Be/^7Li/^6Li$ ratio in G.C.R. stars (depletion of Li is always accompanied by stronger depletion of ^{6}Li) nor the planetary lithium isotopic ratio.

Both models have their advantages and their drawbacks. We are led to prefer the Model T but we do consider that the model C is an interesting alternate solution.

Acknowledgements. This study has been initiated at the Institute of Theoretical Astronomy (Cambridge) during a summer stay of the authors. The hospitality of Pr. F. Hoyle is greatly acknowledged. Thanks are due to J. Bergeron, C. Chevalier, M. Epherre, W. A. Fowler, J. P. Meyer, J. Pacheco, and M. M. Shapiro for valuable advice and discussions.

Note added in proof: A recent paper by R. R. Zappala (Contributions from the Lick Observatory, n° 342) has given much more accurate measurements on Li/H. Within a factor 2, the "initial" stellar values are all $\cong 10^{-9}$ (including T Tauri stars). This information speaks strongly against the "autogenetic" view and makes it difficult to defend the idea of lithium inhomogeneity discussed in section IX.

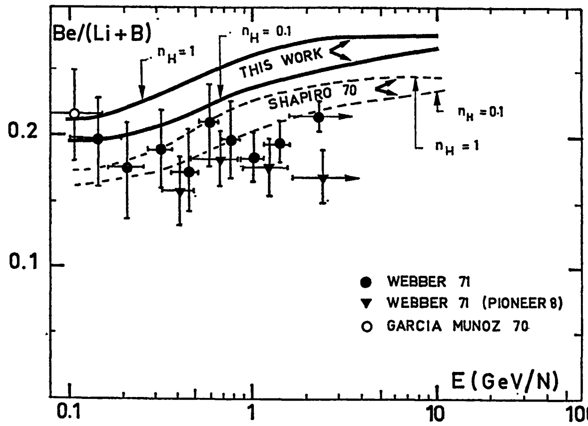

Fig. 14. Ratio of the (Be/Li + B) flux as a function of energy and of hydrogen density in the interstellar medium. At $n_H \cong 1.0$ most of the ^{10}Be survives and is counted as Be while at $n_H = 0.1$ it decays and appears as B. The two upper curves are from our calculations (MAR) while the two lower are from Shapiro and Silberberg, 1970. The discrepancy in the curves is within the estimated uncertainties. Also shown are the observed points

Appendix A
Interstellar Helium Abundances

The origin of the helium in our galaxy is still a matter of controversy. It may or it may not be primordial (Fowler, 1970), it may or it may not be homogeneously distributed in the galaxy.

It appeared of some interest to us to vary the helium to hydrogen ratio in our calculation. The results are given in Table 8. Clearly the effect is small ($\sim 10\%$) except on ^{7}Li, ^{6}Li, ^{7}Be ($\sim 50\%$) because of the ($\alpha + \alpha$) reaction.

Table 8

He/H interstellar	0.05	0.10	0.15
^{11}B/^{10}B	2.4	2.4	2.4
^{7}Li/^{6}Li	1.7	1.5	1.4
Li/Be	9	10	11
B/Li	1.6	1.5	1.3
Be/H	1.9×10^{-11}	2.0×10^{-11}	2.1×10^{-11}

Production of L elements from a power law spectrum in total energy (with $\Lambda = 6.3$ g/cm²) after 10^{10} years, with varying values of interstellar He/H.

Appendix B
The Isotopic Composition of Beryllium

There is much interest in obtaining the isotopic ratio of beryllium in G.C.R. (Table 9).

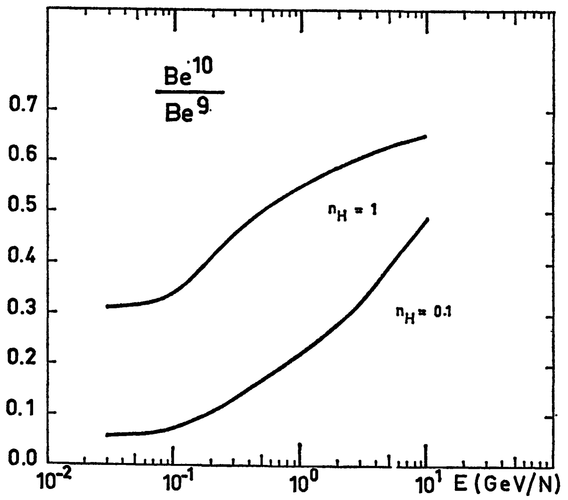

Fig. 15. Ratio of ^{10}Be/^{9}Be as a function of energy and density. No data is yet available

The abundance of ^{10}Be (half life 2.7×10^6 years) will give information on the age of G.C.R. From the escape range (Λ_e) we also obtain the average value of the density of matter traversed by the particles ($\Lambda_e = \varrho\, v\, \tau_e$).

The isotope ^{7}Be is expccted to be stable at high velocity but beta unstable at low velocity, since it can only decay by electron capture. It would be of great interest to determine the switch-over energy

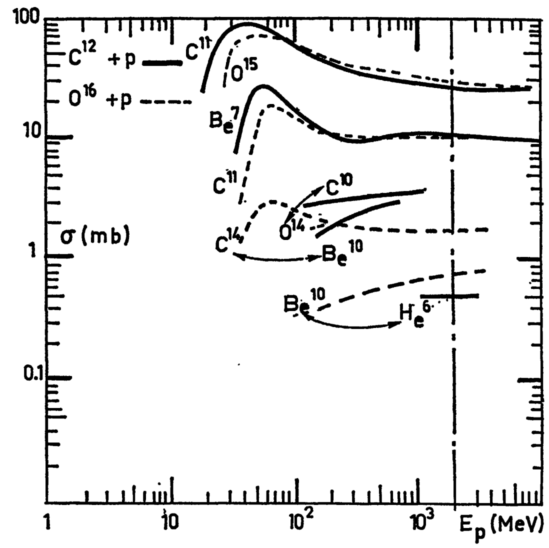

Fig. 16. Cross-sections for the productions of various isotopes by proton-induced reactions on ^{12}C and ^{16}O. Note the similarity between the excitation functions involving equivalent mechanisms (eg (p, pn), (p, pα n) etc.

(Yiou and Raisbeck, 1970). (We recall that in Fig. 4 the beta decay of Be^7 has not been included.)

The experimental situation with respect to the fractional amount of Be^7 is confused. The value would be $\sim 30\%$ according to Kish and Webber (1970), Garcia Munoz and Simpson (1969) but Webber and Kish (1970) claim a value $\geqq 50\%$. Webber (private communication) quoted a ratio of 75% in the 100–200 MeV range. In Fig. 14 the Be/(Li + B) ratio is presented for several assumed interstellar densities (leading to larger or smaller ^{10}Be fractional decay). Also shown are the calculations of Shapiro. The difference gives probably a good illustration of the effects of the various uncertainties.

The experimental points seem to favor ^{10}Be decay and low interstellar mean densities ($n_H < 0.1$), but the scatter in the experimental points (and in the calculations) *show that no definite conclusion can be drawn.*

In Fig. 15 the ^{10}Be/^{9}Be ratio is shown for $n_H = 1$ and $n_H = 0.1$. This comparison may eventually present the most sensitive test of mean hydrogen density traversed by G.C.R.

Appendix C
The CNO Group in the Galactic Cosmic Rays

The relative abundances of the stable isotopes in this group may be closely related to the mechanism giving rise to G.C.R. (Waddington, 1970).

In Table 10 are shown typical results of certain well known processes such as hydrogen burning through CNO cycle; helium burning and simple "ejection" from normal stars. These numbers should serve mostly as qualitative indications since they depend somewhat on the specific conditions in which the process has taken place (for instance: attainment or non-attainment of an equilibrium regime).

First the (C/CNO) at the sources (~ 0.45) is significantly larger than the average stellar value (~ 0.26) and certainly much larger than the CNO cycle value. On the other hand the products from helium burning (pure ^{12}C and ^{16}O) appear to be in the correct ratio (although some uncertainty remains with the nuclear parameter (Barnes, 1970)).

According to Lezniak *et al.* (1969) the flux of *N* particles may be entirely of secondary origin. This

Table 9

E (MeV N^{-1}) / Ratio	30	100	300	1000	3000	3000	10000
	^{7}Be/Be	0.73	0.69	0.60	0.54	0.52	0.51
$n_H = 1$	^{9}Be/Be	0.21	0.24	0.28	0.27	0.30	0.31
	^{10}Be/Be	0.07	0.08	0.13	0.16	0.19	0.19
		0.32	0.33	0.45	0.55	0.62	0.63
	^{7}Be/Be	0.79	0.75	0.69	0.64	0.64	0.63
$n_H \ll 1$	^{9}Be/Be	0.23	0.26	0.32	0.32	0.37	0.38

The beryllium isotopic ratios in G.C.R. The first four lines apply to $n_H = 1$ (essentially no ^{10}Be decay) while the last three line apply to $n_H \ll 1$ (^{10}Be decays entirely).

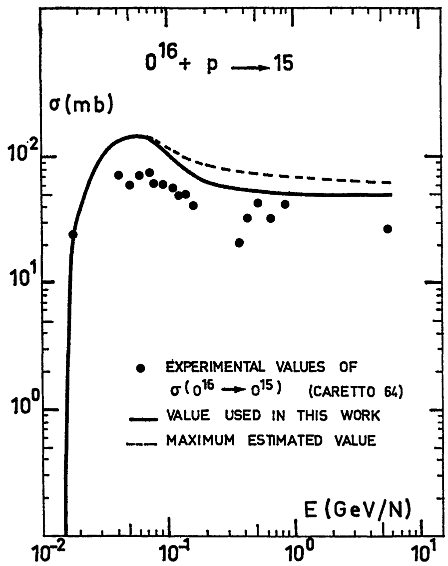

Fig. 17. Spallation cross-sections for the $^{16}O + p \rightarrow 15$ reaction

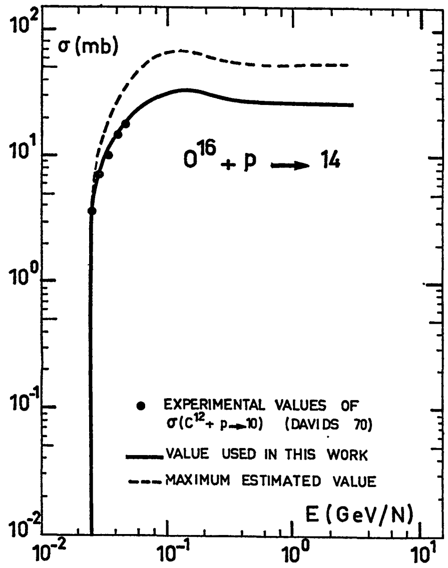

Fig. 18. Spallation cross-sections for the $^{16}O + p \rightarrow 14$ reaction

result would of course strongly support a relationship between the G.C.R. sources and the helium burning process. Shapiro and Silberberg (1970) however do not agree with the suggestion of Lezniak *et al.* (1969).

In this work we have investigated whether the present uncertainties on both the G.C.R. observations and the nuclear parameters would support a meaningful answer.

Table 10

Ratio	Hydrogen burning by CNO cycle	Helium burning	Ejection from normal stars	G.C.R. inter-stellar space	G.C.R. at the sources
C/CNO	0.01 to 0.05	0.5	0.26	0.47	0.45
N/CNO	1	0	0.07	0.13	Fig. 19
$^{13}C/^{12}C$	0.25	0	0.25 to 0.01	0.09	< 0.1

Percentage of CNO nuclei expected from various physical situations. The second column describes what we should expect if the G.C.R. are a sample of the products of CNO cycle hydrogen burning process, the third column a sample of helium-burning process (the C/CNO value would then be rather uncertain) and the fourth column a sample of a "normal" stellar atmosphere. The last two columns refer to the G.C.R. flux ratios in space or at the sources.

The most important processes are the following:

$$p + {}^{16}O \rightarrow \text{mass } 15$$

$$p + {}^{16}O \rightarrow \text{mass } 14$$

Of these only the $p + {}^{16}O \rightarrow {}^{15}O$ is well known experimentally (Caretto, 1964). In the following paragraph we shall describe some of the tricks and technique that we have used quite generally to obtain the nuclear parameters.

A survey on many reactions shows that the following relations are most generally valid

$$\sigma\,(p, 2p) < \sigma\,(p, pn)$$

$$\sigma\,(p, 2p) \cong \sigma\,(p, pn) \times 0.7$$

Hence we have chosen:

$$\sigma\,({}^{16}O + p \rightarrow 15) = 1.7\,\sigma\,({}^{16}O + p \rightarrow {}^{15}O) \quad (17a)$$

$$\sigma\,({}^{16}O + p \rightarrow 15) \leqq 2.0\,\sigma\,({}^{16}O + p \rightarrow {}^{15}O) \quad (17b)$$

the second one being our upper limit (Fig. 16).

Another survey, summarized in Fig. 17 shows that for the targets ^{12}C and ^{16}O, proton-induced reactions involving the same mechanisms (for instance ^{12}C (p, pn) ^{11}C and ^{16}O (p, pn) ^{15}O) have very similar cross-sections (Audouze *et al.*, 1967). In other words the extra alpha particle of the ^{16}O nucleus is a mere spectator.

Consequently we choose:

$$\sigma\,({}^{16}O + p \rightarrow 14) = \sigma\,({}^{12}C + p \rightarrow 10) \text{ best estimate} \quad (18a)$$

$$\sigma\,({}^{16}O + p \rightarrow 14) \leqq 2\,\sigma\,({}^{12}C + p \rightarrow 10) \text{ upper limit} \quad (18b)$$

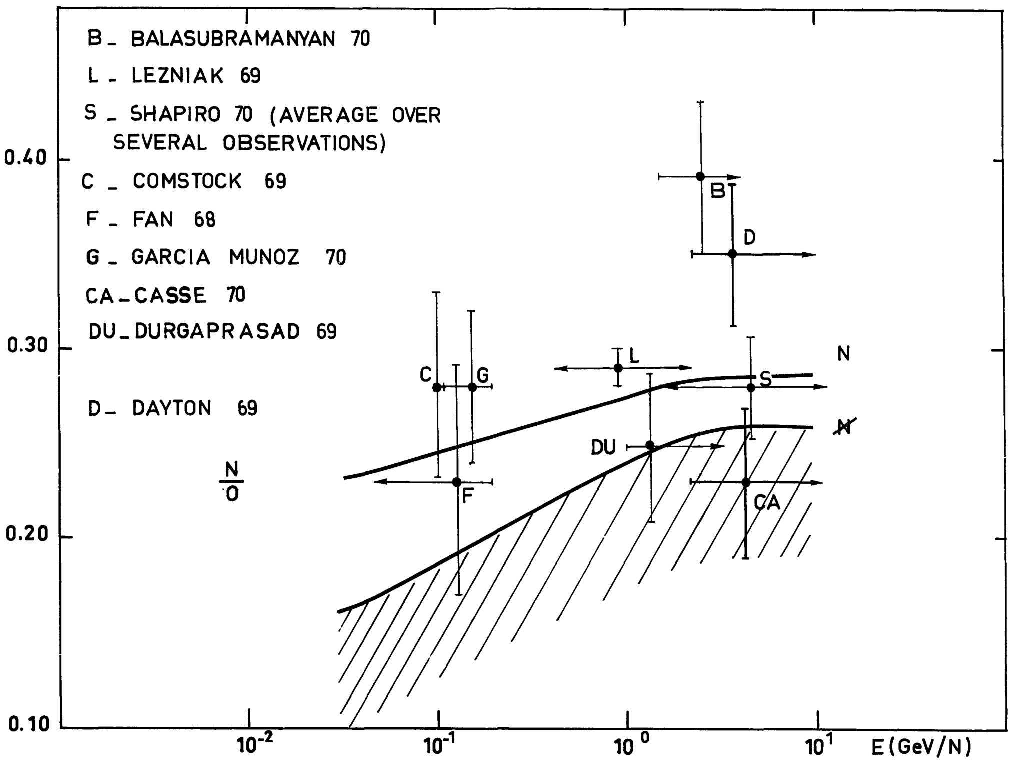

Fig. 19. Ratio of the N/O flux as a function of energy. In the case (N) the source contains a normal stellar abundance of nitrogen. The case ($\not N$) shows the upper limit of the N/O ratio when the source is devoid of nitrogen (using the upper limit cross-sections in Fig. 14 and 15)

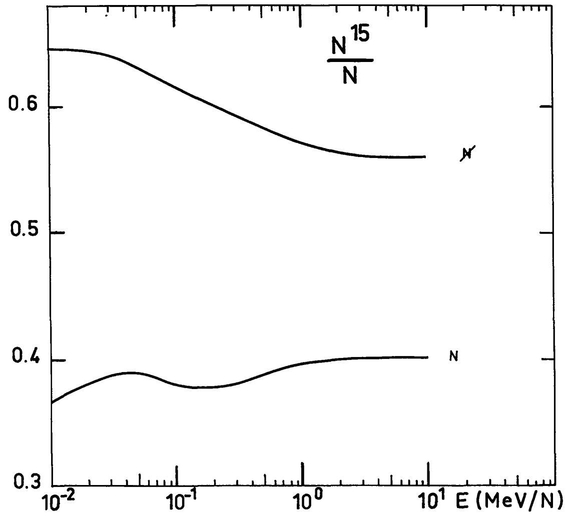

Fig. 20. The ratio of ^{15}N/N in the two cases described in the legend of Fig. 20

At high energy σ (^{12}C + p $\rightarrow$ 10) is not measured. We then took σ (^{16}O + p $\rightarrow$ 14) = 25 mb in order to have:

$$\sigma\,(^{16}\mathrm{O} + \mathrm{p} \rightarrow 14 + 15) \simeq \sigma\,(^{12}\mathrm{C} + \mathrm{p} \rightarrow 10 + 11)$$
$$= 60 \text{ mb at } 660 \text{ MeV (Zhdanov, 1960).}$$

Calculations were made with a) a source with $(\mathrm{N/CNO})_{\mathrm{source}} = 0.05$ with best estimates (17a) and (18a) (curve N in Fig. 17 and Table 3) and b) a nitrogen free source, in which case one must take the upper limit (17b) and (18b) (curve $\not N$ in Fig. 17 and Table 6). The experimental results shown in Fig. 17 appear to favour the first hypothesis (normal stellar nitrogen).

It is interesting to note that the $\not N$ curve falls faster with decreasing energy than the N curve (since the ranges are shorter at low energy, fewer secondaries are produced). Measurements below 100 MeV are thereby suggested.

In Fig. 18 the ratio of ^{15}N/N for the set of conditions described in the previous paragraphs are

Table 11. *Calculated interstellar fluxes with source spectrum* $\sim W^{-2.6}$
($N^{14} = 0$ at the source, maximum cross-sections for N production, and an escape length of 7 g cm^{-2})

Element \ E (MeV N^{-1})	1	3	10	30	100	300	1000	3000	10000
^{16}O	3.3×10^{-4}	8.0×10^{-4}	2.1×10^{-3}	4.7×10^{-3}	8.7×10^{-3}	8.6×10^{-3}	3.3×10^{-3}	5.7×10^{-4}	$4.0 \times 10^{-}$[illegible]
^{15}N	2.9×10^{-5}	7.0×10^{-5}	1.9×10^{-4}	4.9×10^{-4}	9.8×10^{-4}	1.1×10^{-3}	4.5×10^{-4}	8.2×10^{-5}	$5.7 \times 10^{-}$[illegible]
^{14}N	1.6×10^{-5}	3.8×10^{-5}	1.1×10^{-4}	2.7×10^{-4}	6.3×10^{-4}	7.5×10^{-4}	3.4×10^{-4}	6.4×10^{-5}	$4.5 \times 10^{-}$[illegible]
N	4.5×10^{-5}	1.1×10^{-4}	3.0×10^{-4}	7.6×10^{-4}	1.6×10^{-3}	1.8×10^{-3}	7.9×10^{-4}	1.5×10^{-4}	$1.0 \times 10^{-}$[illegible]
^{13}C	9.1×10^{-6}	2.2×10^{-5}	6.1×10^{-5}	1.5×10^{-4}	3.6×10^{-4}	4.9×10^{-4}	2.4×10^{-4}	4.6×10^{-5}	$3.2 \times 10^{-}$[illegible]
^{12}C	3.8×10^{-4}	9.1×10^{-4}	2.3×10^{-3}	5.3×10^{-3}	9.6×10^{-3}	9.3×10^{-3}	3.5×10^{-3}	6.0×10^{-4}	$4.2 \times 10^{-}$[illegible]
C	3.9×10^{-4}	9.3×10^{-4}	2.4×10^{-3}	5.4×10^{-3}	9.9×10^{-3}	9.8×10^{-3}	3.7×10^{-3}	6.4×10^{-4}	$4.5 \times 10^{-}$[illegible]

plotted as function of energy. A preliminary result of isotopic analysis (however possibly subjected to a systematical error) (Lund, 1970) indicates that, contrary to what we have found previously, N would be absent from the source[4]). In view of the various uncertainties and in view of the conflicting results presented here *we do not find it possible to decide at this time whether* N *is absent or present (with normal stellar value) at the* G.C.R. *sources.*

Note added in proof. Miss J. Cohen (thesis Berkeley 1971) has recently reanalyzed a number of stars (including our "G.C.R." stars) for lithium. She finds no evidence for ^{6}Li (^{6}Li/^{7}Li $\leqq 0.1$). The question of inhomogeneity thus finds no more support. It is best to think of the "G.C.R." stars as typical cases of partial Li depletion in the surface convective zone (Li/H $\simeq 2 \times 10^{-10}$).

References

Audouze, J., Epherre, M., Reeves, H. 1967, in *High energy Nuclear Reactions in Astrophysics*, Ed. B. S. P. Shen-Benjamin, p. 255.

Audouze, J., Epherre, M., Reeves, H. 1967, *Nucl. Phys.* **97**, 144.

Balasubrahmanyan, V.K., Boldt, E., Palmeira, R.A.R., Sandri, G. 1968, *Can. J. Phys.* **46**, S 633.

Balasubrahmanyan, V.K., Hagge, D.E., Ludwig, G.H., McDonald, F.B. 1966, *J. geoph. Res.* **71**, 1771.

Balasubrahmanyan, V.K., Ormes, J.F., Ryan, M.J., Silverberg, R.F. 1970, *Bull. am. phys. Soc.* **15**, 589.

Barnes, C.A. 1970, Caltech report 1970 (unpublished).

Bergeron, J., Souffrin, S. 1971, *Astr. Astrophys.* **11**, 40.

[4]) According to Webber (1971) the N mean mass in G.C.R. is $\bar{A} = 14.65 \pm 0.08$ a value which also favors N ~ 0 at sources.

Bernas, R., Gradsztajn, E., Reeves, H., Schatzman, E. 1967, *Ann. Physics* **44**, 426.

Bernas, R., Gradzstajn, E., Yaniv, A. 1969, In *Meteorite Research*, Millman-Reidel p. 123.

Burbidge, G.R. 1969, *Comments on Astrophys. Space Sci.* **1**, 101.

Cameron, A.G.W. 1968, in *Origin and Distribution of the elements*, Ahrens, Pergamon press p. 125.

Cameron, A.G.W., Fowler, W.A. 1971, *Ap. J.* **164**, 111.

Caretto, Jr. A.A. 1964, unpublished report NYO 10693, Carnegie Institute of Technology.

Casse, M., Corydon-Petersen, O., Dayton, B., Koch, L., Lund, N., Melgaard, K., Mestreau, P., Meyer, J.P., Omø, K., Risbo, T., Roussel, D. 1970, Paper presented at the COSPAR Meeting, Leningrad.

Cesarsky, C. 1970, 6th Interamerican Seminar on cosmic rays La Paz, Bolivia, July 1970.

Comstock, G.M., Fan, C.Y., Simpson, J.A. 1966, *Ap. J.* **146**, 51.

Crandall, W.E., Milburn, G.P., Pyle, R.W., Birnbaum, W. 1956, *Phys. Rev.* **101**, 329.

Danziger, I.J. 1970, *Ann. Rev. Astr. Astrophys.* **8**, 161.

Davids, C.N., Laumer, H., Austin, S.M. 1969, *Phys. Rev. Letters* **22**, 1388.

Dayton, B., Lund, N., Risbo, T. 1969, Paper OG 108—Proc. 11th Conf. on Cosmic Rays, Budapest.

Durgaprasad, N., Fichtel, C.E., Guss, D.E., Reames, D.V., O'Dell, F.W., Shapiro, M.M., Silberberg, R., Stiller, B., Tsao, C.H. 1970, *Phys. Rev.* D **1**, 1021.

Engvold, Ö. 1970, *Sol. Phys.* **11**, 183.

Fan, C.Y., Gloeckler, G., Simpson, J.A. 1968, *Can. J. Phys.* **46**, S 549.

Field, G.B., Goldsmith, D.W., Habing, H.J. 1969, *Ap. J. Letters* **155**, L 149.

Fontes, P., Perron, C., Lestringuez, J., Yiou, F., Bernas, R. 1971, to be published. ORSAY Preprint.

Fowler, W.A., Caughlan, G.R., Zimmerman, B.A. 1967, *Ann. Rev. Astr. Astrophys.* **5**, 525.

Fowler, W.A., Reeves, H., Silk, J. 1970, *Ap. J.* **162**, 49.

Garcia-Munoz, M., Simpson, J.A. 1970, Proc. 11th Int. Conf. on Cosmic Rays, Budapest. Papers OG 66 and OG 67.

Ginzburg, V.L., Syrovatskii, S.I. 1964, The origin of cosmic rays, Pergamon Press London, New York.

Gloeckler, G., Jokipii, J.R. 1969, *Phys. Rev. Lett.* **22**, 1448.
Goldsmith, D.W., Habing, H.J., Field, G.B. 1969, *Ap. J.* **158**, 173.
Goldstein, M.L., Fisk, L.A., Ramaty, R. 1970, *Phys. Rev. Letters* **25**, 832.
Gradsztajn, E. 1965, *Ann. Physique, Paris*, **10**, 791.
Greenstein, J.L., Richardson, R. 1951, *Ap. J.* **113**, 536.
Grevesse, N. 1968, *Solar Phy.* **5**, 159.
Grevesse, N. 1969, unpublished thesis, Liege University.
Hayakawa, S. 1968, Progress theoret. Phys. Suppl. p. 156.
Hayakawa, S., Nishimura, S., Takayanagi, K. 1961, *Pub. Astr. Soc. Jap.* **13**, 184.
Herbig, G.H. 1965, *Ap. J.* **141**, 588.
Herbig, G.H., Spalding, Jr. J.F. 1955, *Ap. J.* **121**, 118.
Hjellming, R.M. 1969, *Ap. J. Letters* **4**, 81.
Hjellming, R.M., Gordon, C.P., Gordon, K.J. 1969, *Astr. Astrophys.* **2**, 202.
Hsieh, K.C., Simpson, J.A. 1969, *Ap. J.* **158**, L 37.
Iben, Jr. I.I. 1967, *Ann. Rev. Astr. Astrophys.* **5**, 571.
Jones, F.C. 1970, Preprint X-641-70-129 GODDARD Sp. Fl. Center.
Kish, J.M., Webber, W.R. 1969, Midwest cosmic ray conference, Baton Rouge, La.
Krankowski, D., Müller, O. 1967, *Geochim. Cosmochim. Acta* **31**, 1833.
Kristiansson, K., Jonsson, G., Malmqvist, L. 1969, Paper OG 74, Proc. 11th Inter. Conf. on cosmic rays, Budapest.
Lal, D. 1969, *Sp. Sc. Rev.* **9**, 623.
Lal, D., Peters, B. 1967, Handbuch der Physik, **46**/2 p. 574, Springer Verlag, Berlin.
Lavrukhina, A.K., Ustinova, G.K., Ibraev, T.A., Kuznetsova R.I. 1969, in *Meteorite research*, Millman-Reidel p. 227.
Lezniak, J.A., Ormes, J.F., von Rosenvinge, T.T., Webber, W.R. 1969, *Astr. Space Sci.* **5**, 103.
Lezniak, J.A., von Rosenvinge, T.T., Webber, W.R. 1970, Paper OG 68 — Proc 11th Int. Conf. on Cosmic Rays. Budapest.
Lingenfelter, R.E., Ramaty, R., Fisk, L.A. 1971, *Ap. Letters* **8**, 93.
Lund, N., Peters, B., Cowsik, R., Pal, Y. 1970, *Physics Letters* **31**B, 553.
Meyer, J.P. 1970, *Ap. J. Letters* **7**, 61.
Mitler, H.E. 1970, Preprint, Smithsonian Ap. Observatory Special report 330.
Morton, D.C., Adams, T.F. 1968, *Ap. J.* **151**, 611.
Mullie, M., Gauvin, H. 1971, Institut de Physique Nucléaire d'Orsay. Thesis. (To be published).
O'Dell, F.W., Shapiro, M.M., Silberberg, R., Stiller, B., Tsao, C.H., Durgaprasad, N., Fichtel, C.E., Guss, D.E., Reames, D.V. 1969, Paper OG 85 — Proc. 11th Int. Conf on Cosmic Rays, Budapest.
Pacheco, J. 1969, *Astr. Astrophys.* **3**, 368.
Pacheco, J. 1970, Preprint, Nice.
Pikel'ner, S.B. 1968, *Soviet Astr.* — AJ **11**, 737.
Quijano-Rico, M., Wanke, H. 1969, in *Meteorite Research* Millmann-Reidel p. 132.
Radin, J. 1970, *Phys. Rev.* C, **2**, 793.
Reames, D.V., Fichtel, C.E. 1967, *Phys. Rev.* **162**, 1291.
Reeves, H. 1970, Tel Aviv Winter School. To be published, Gordon and Breach.
Reeves, H., Fowler, W.A., Hoyle, F. 1970, *Nature* **226**, 727.
Reeves, H. 1971, to be published.
Regnier, S. 1971, Thesis of the university of Bordeaux, unpublished.
Rosenvinge, von, T.T., Ormes, J.F., Webber, W.R. 1969, *Astr. Space Sci.* **3**, 80.
Rosenvinge, von, T.T., Webber, W.R., Ormes, J.F. 1969, *Astr. Space Sci.* **3**, 4.
Rosenvinge, von, T.T., Webber, W.R., Ormes, J.F. 1969, *Astr. Space Sci.* **5**, 342.
Rudstam, G. 1966, *Z. Naturforschung* **21**a, 1027.
Ryter, C., Reeves, H., Gradsztajn, E., Audouze, J. 1970, *Astr. Astrophys.* **8**, 389.
Salpeter, E.E. 1959, *Ap. J.* **129**, 408.
Salpeter, E.E., Wickramasinghe, N.C. 1969, *Nature* **222**, 442.
Schmidt, M. 1963, *Ap. J.* **137**, 758.
Shapiro, M.M. 1970, Invited paper at the I.A.U. XIV Assembly. Brighton 1970.
Shapiro, M.M., Silberberg, R. 1970, *A. Rev. Nucl. Sci.* **20**.
Shima, M., Honda, M. 1963, J. geophys. Research **68**, 2849.
Silberberg, R., Tsao, C.H. 1971, To be published.
Sill, C.W., Willis, C.P. 1962, *Geochim. Cosmochim. Acta* **26**, p. 1209.
Slettebak, A. 1955, *Ap. J.* **121**, 653.
Spitzer, L. Jr., Scott, E.H. 1969, *Ap. J.* **158**, 161.
Spitzer, L. Jr., Tomasko, M.O. 1968, *Ap. J.* **152**, 971.
Tobailem, J., De Lassus, Ch.L., Leveque, L. 1971, Note CEA-N-1466(1).
Waddington, C.J. 1970, 6th interamerican Seminar on Cosmic Rays, La Paz, Bolivia, July 70.
Wallerstein, G., Conti, P.S. 1969, *A. Rev. Astr. Astrophys.* **7**, 99.
Webber, W.R. 1971, Communication at the LYNGBY Meeting on isotopic composition of cosmic rays.
Webber, W.R., Damle, S.V., Kish, J.M. 1971, Measurements of the charge and isotope composition of cosmic ray Li Be B nuclei (Preprint).
Webber, W.R., Kish, J. 1970, *Bull. Am. Phys. Soc.* **15**, 620.
Yiou, F., Raisbeck, G.M. 1970, *Ap. Letters* **7**, 129.
Yiou, F., Seide, C., Bernas, R. 1969, *Journal geophys. Res.* **74**, 2447.
Zhdanov, A.P., Fedotov, P.I. 1960, *Soviet Phys. JETP* **37**, 280.

M. Meneguzzi
S.E.P., C.E.N. Saclay, B.P. n°2
F—91 Gif-sur-Yvette

J. Audouze
H. Reeves
I. A. P.
98bis Bd. Arago
F—75 Paris 14°