Origin and evolution of light elements

light elements have fragile nuclei
they break up in thermonuclear reactions

high abundance of Li, Be, B in
galactic cosmic rays

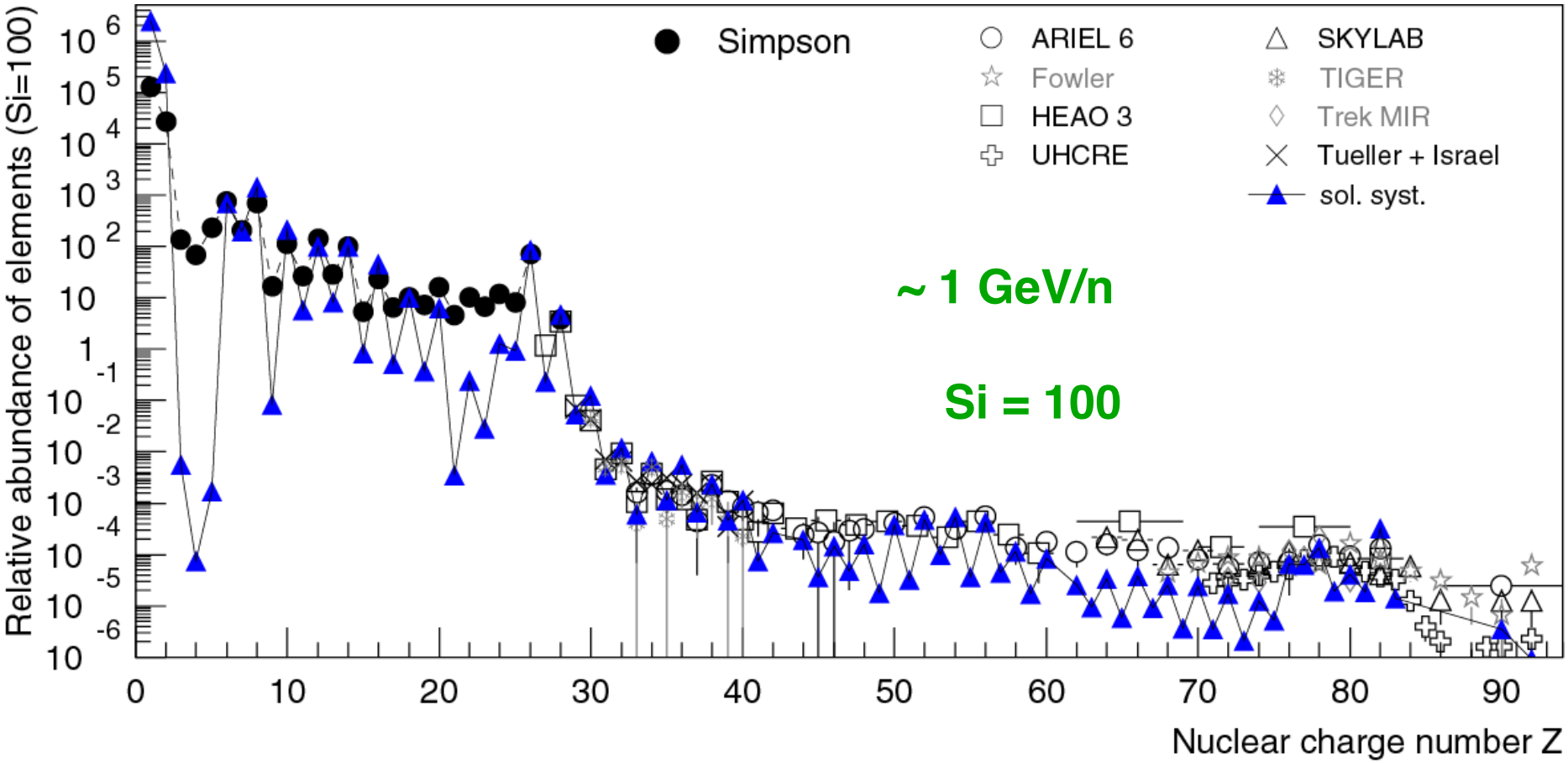
CRs are accelerated in strong shock fronts
of SNR and propagate in diffusive process
through the galaxy
close to the Sun : solar modulation

Table 9.1. *Destruction of light nuclei in stellar interiors*

^{2}D	destroyed by	$(p,\gamma)\,^{3}$He	for $T >$	0.5×10^{6} K
^{6}Li	" "	$(p,\alpha)\,^{3}$He	for $T >$	2×10^{6} K
^{7}Li	" "	$(p,\alpha)\,^{4}$He	for $T >$	2.5×10^{6} K
^{9}Be	" "	$(p,\alpha)\,^{6}$Li; $(p,\mathrm{D})\,^{8}\mathrm{Be} \rightarrow 2\,^{4}\mathrm{He}$	for $T >$	3.5×10^{6} K
^{10}B	" "	$(p,\alpha)\,^{7}\mathrm{Be}\,(EC)\,^{7}\mathrm{Li}$	for $T >$	5.3×10^{6} K
^{11}B	" "	$(p,\alpha)\,^{8}\mathrm{Be} \rightarrow 2\,^{4}\mathrm{He}$	for $T >$	5×10^{6} K
^{3}He	" "	$(^{3}\mathrm{He},\alpha)\,^{4}\mathrm{He} + 2\,^{1}\mathrm{H}$	for $T >$	$\sim 10^{7}$ K

Relative abundance of elements at Earth

cosmic rays - solar system



JRH, Adv. Space Res. 41 (2008) 442

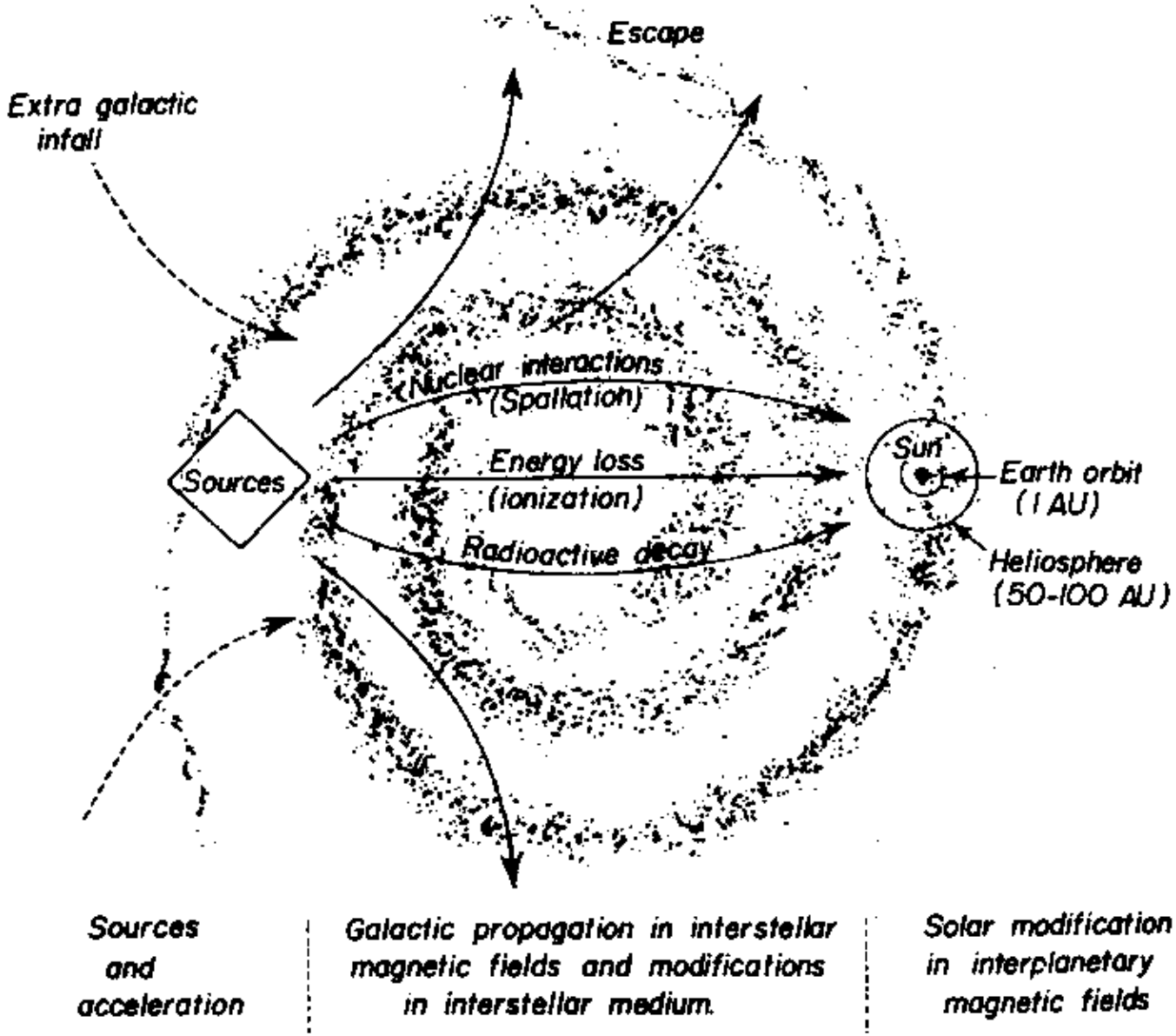
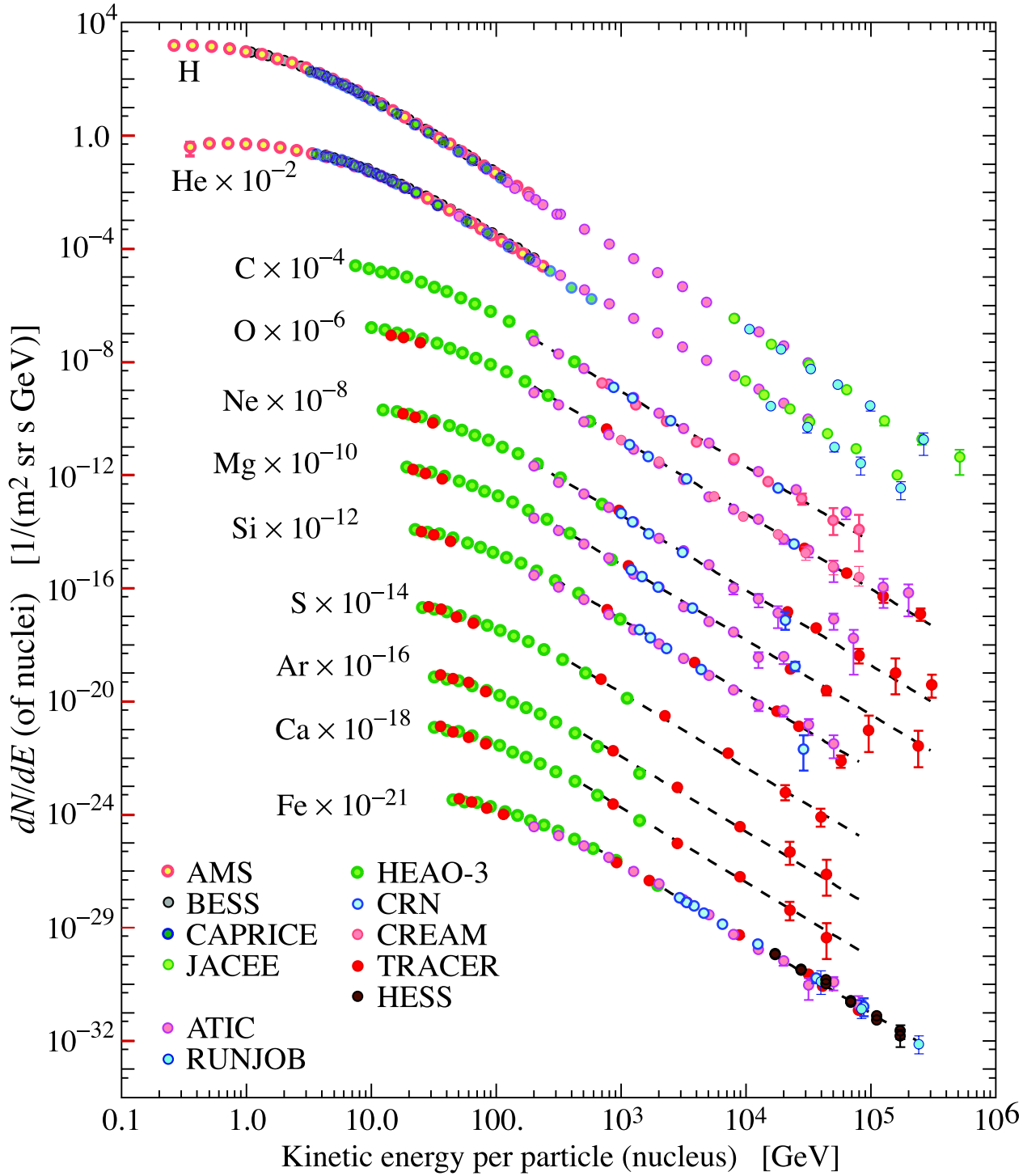


Fig. 9.2. Schematic view of the life history of a cosmic ray from acceleration in the source through propagation in the Galaxy to observation above the Earth's atmosphere. Adapted from Rolfs and Rodney (1988).

Energy spectra of main elements in cosmic rays



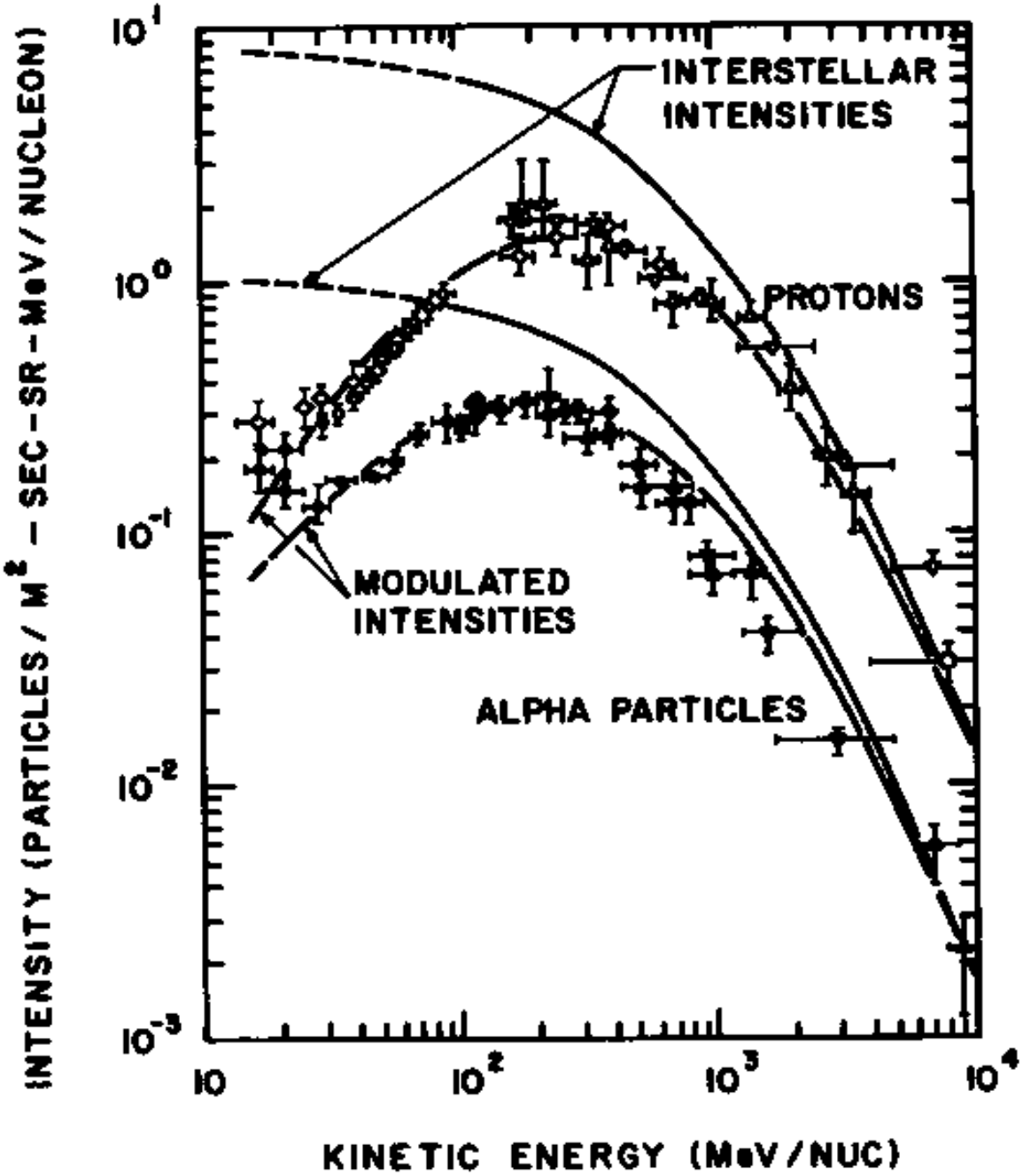


Fig. 9.3. Proton and α-particle spectra of primary cosmic rays and their demodulated versions. After Goldstein *et al.* (1970). Courtesy Reuven Ramaty.

transport equation of cosmic rays through galaxy

"radioactive clocks" from ^{10}Be decay

CRs travel $\sim 17 \cdot 10^6$ a through the galaxy

spallation of CNO elements $\rightarrow$ Li, Be, B

$\rightarrow$ pathlength of CRs in galaxy

B/C ratio decreases with energy

$\rightarrow$ path length decreases with energy

$\Rightarrow$ Leaky Box model $\Lambda_{esc}(E) = C \cdot E^{-\delta} + \Lambda_0$

path length decreases from ~ 10 g/cm^2 at GeV

to a few g/cm^2 at 10^3 GeV/amu

Transport equation for cosmic rays in the Galaxy

diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

$$\frac{\partial N_i}{\partial t} = \nabla(D_i \nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - n\nu\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} n\nu\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

source term

production through spallation of heavy neulcei

production through decay of heavy nuclei

„Age“ of galactic cosmic rays

THE AGE OF THE GALACTIC COSMIC RAYS DERIVED FROM THE ABUNDANCE OF ^{10}Be*

M. GARCIA-MUNOZ, G. M. MASON, AND J. A. SIMPSON†
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Received 1977 March 14; accepted 1977 April 21

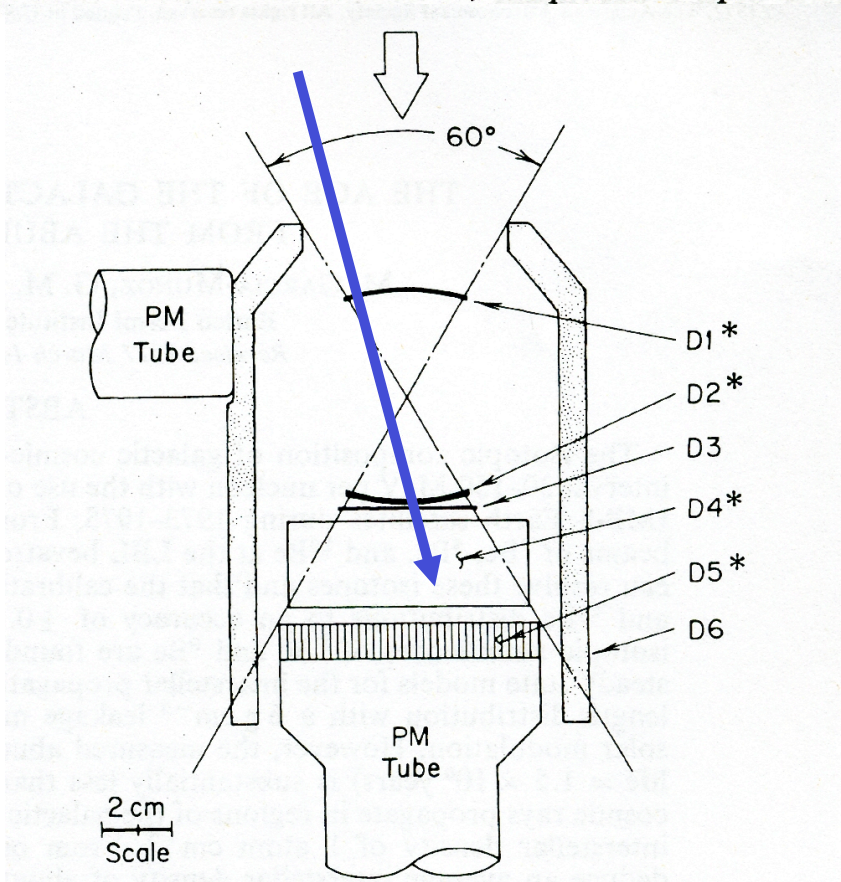
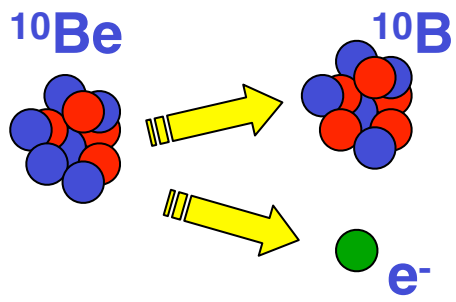


FIG. 1.—Cross section of the IMP-7 and IMP-8 telescopes. D1, D2, and D3 are lithium-drifted silicon detectors of thickness 750, 1450, and 800 μm, respectively. D4 is an 11.5 g cm^{-2} thick CsI (Tl) scintillator viewed by four photodiodes. D5 is a sapphire scintillator/Cerenkov radiator of thickness 3.98 g cm^{-2}, and D6 is a plastic scintillation guard counter viewed by a photomultiplier tube. Asterisks denote detectors whose output is pulse-height analyzed.

Residence time in Galaxy

$^{10}Be \rightarrow {}^{10}B + e^-$ (τ=2.4 10^6 a)



$\tau = 17*10^6$ a

THE ASTROPHYSICAL JOURNAL, 217:859–877, 1977 November 1

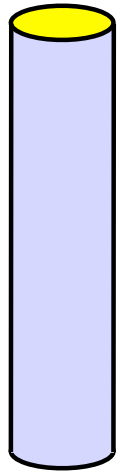
Pathlength of cosmic rays

VOLUME 29, NUMBER 7 PHYSICAL REVIEW LETTERS 14 AUGUST 1972

Composition of Cosmic-Ray Nuclei at High Energies*

Einar Juliusson, Peter Meyer, and Dietrich Müller
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 26 May 1972)

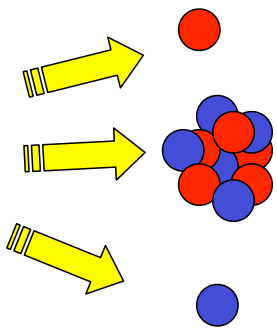
We have measured the charge composition of cosmic-ray nuclei from Li to Fe with energies up to about 100 GeV/nucleon. A balloon-borne counter telescope with gas Cherenkov counters for energy determination was used for this experiment. Our first results show that, in contrast to low-energy observations, the relative abundances change as a function of energy. We find that the ratio of the galactic secondary nuclei to primary-source nuclei decreases at energies above about 30 GeV/nucleon.



g/cm²

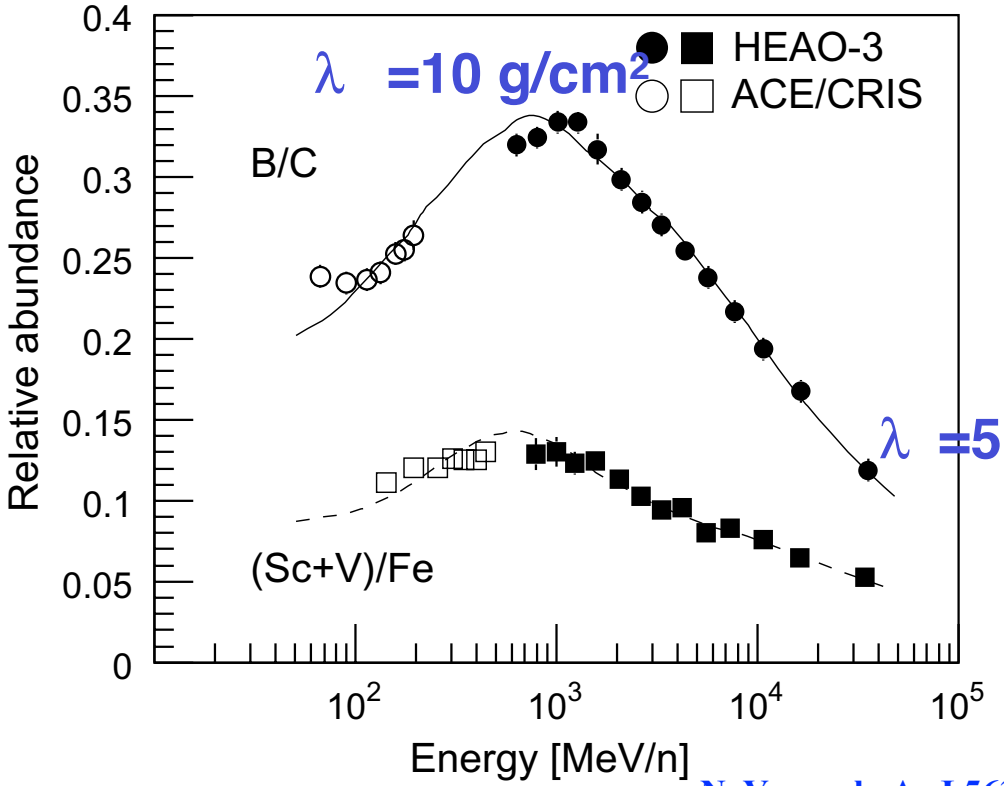
spallation

C → B + n + p



$$\lambda(E) \propto E^{-0.6}$$

primary/secondary-ratio



N. Yanasak, ApJ 563 (2001) 768

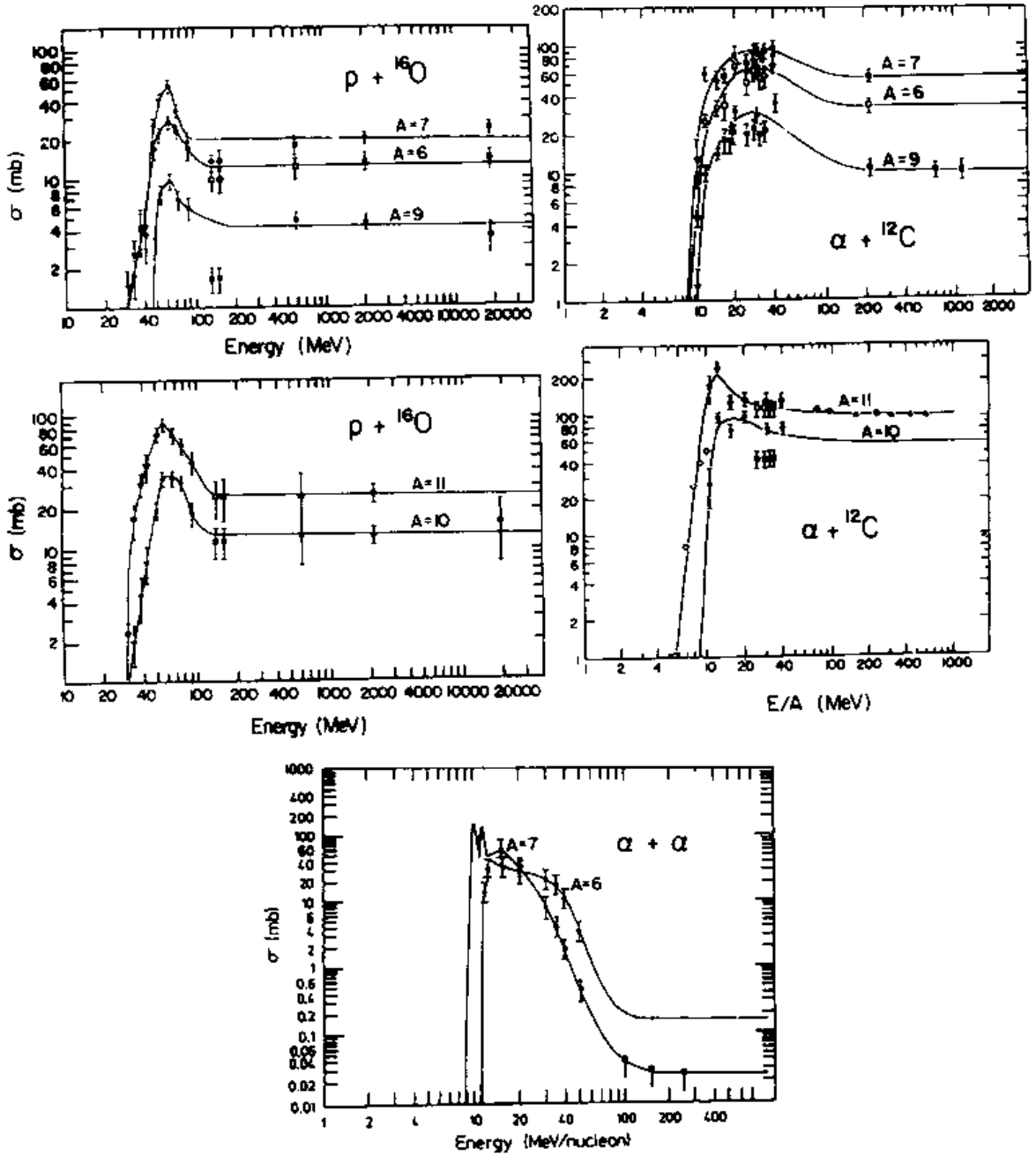
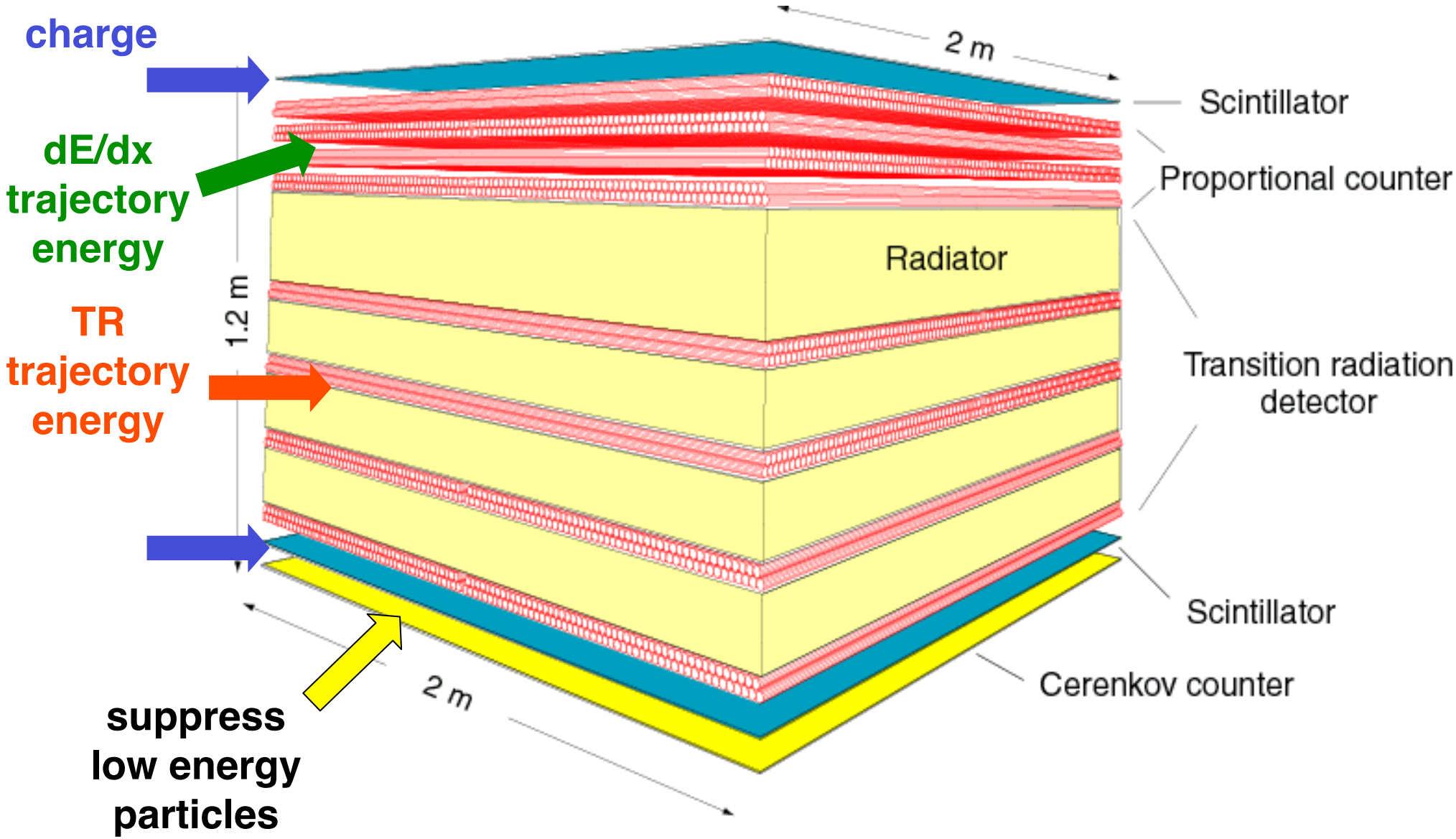


Fig. 9.4. Reaction cross-sections, as a function of energy per nucleon, for the production of light elements for some typical cases. Adapted from Read and Viola (1984). Courtesy Vic Viola.

TRACER - Mc Murdo, Antarctica, 2003

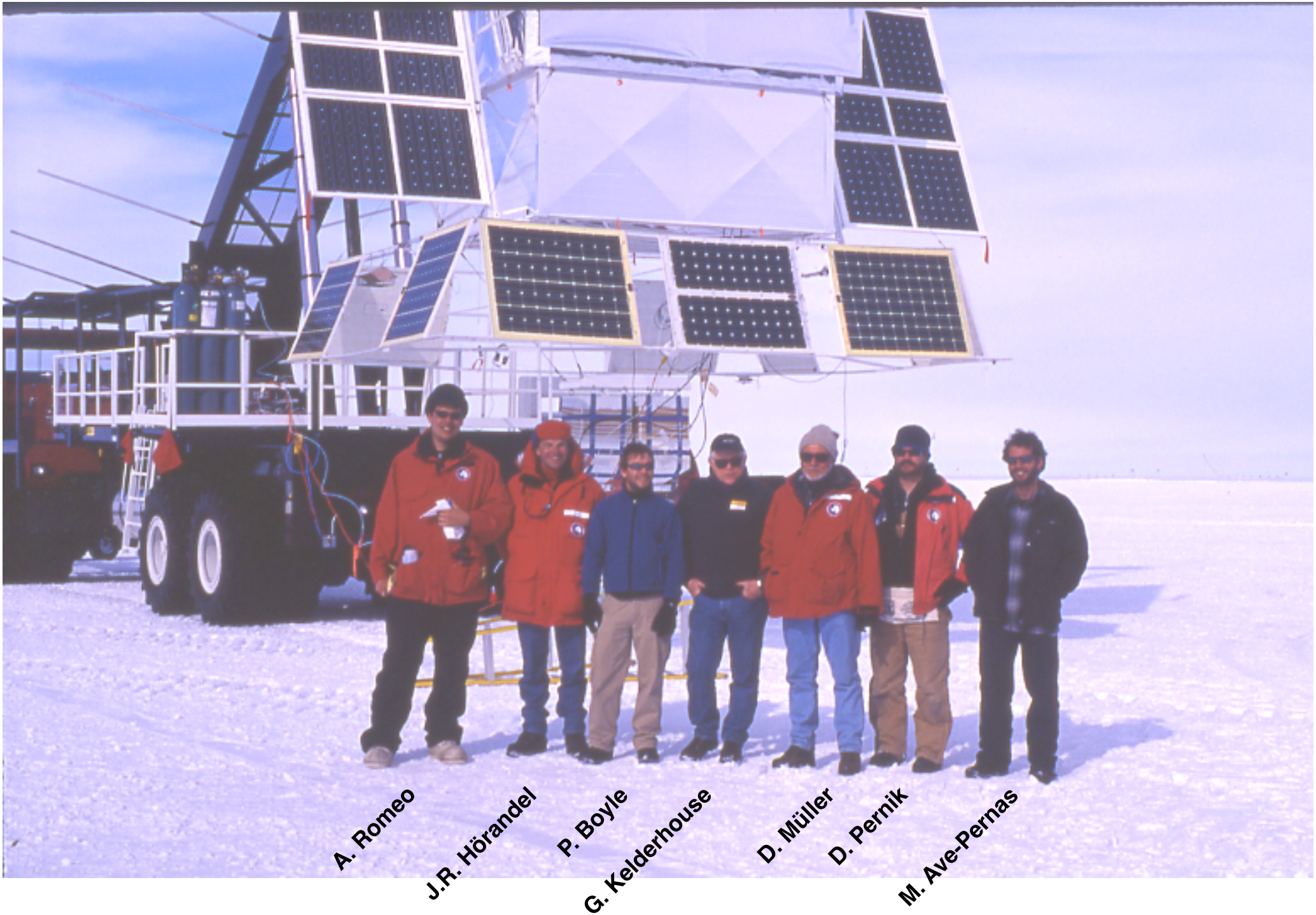
Transition Radiation Array for Cosmic Energetic Rays



Geometric factor: 5 m² sr

1600 proportional tubes total

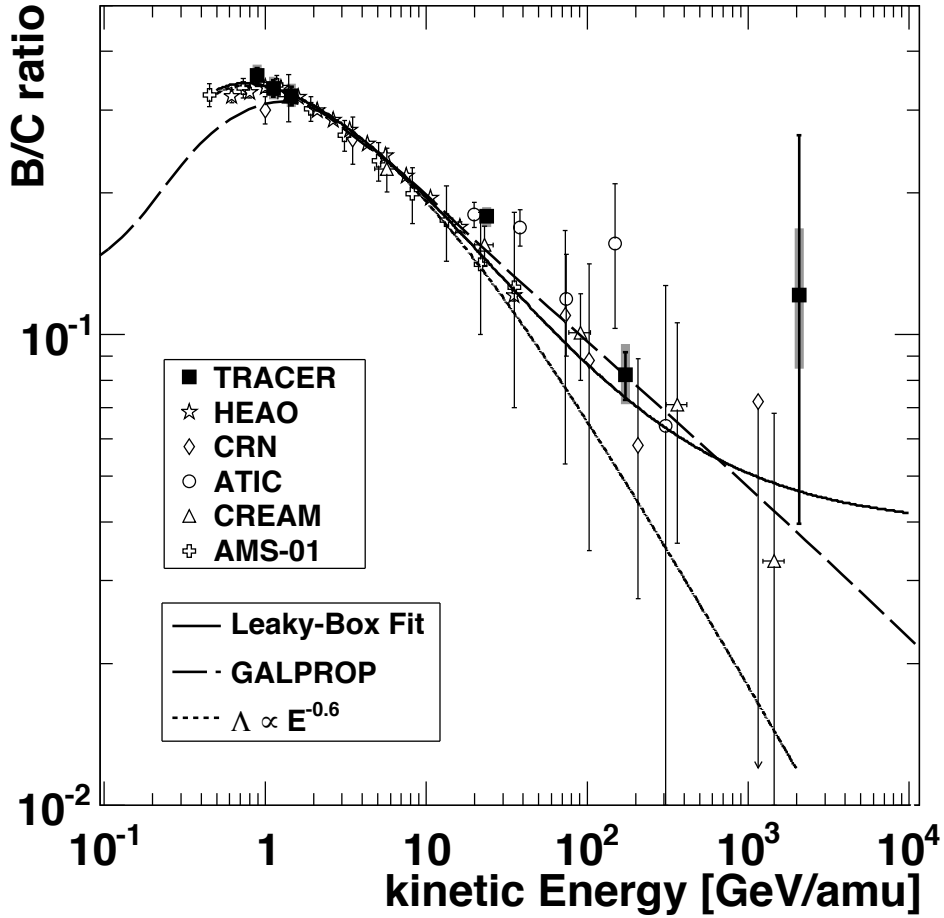
TRACER - Mc Murdo, Antarctica, 2003



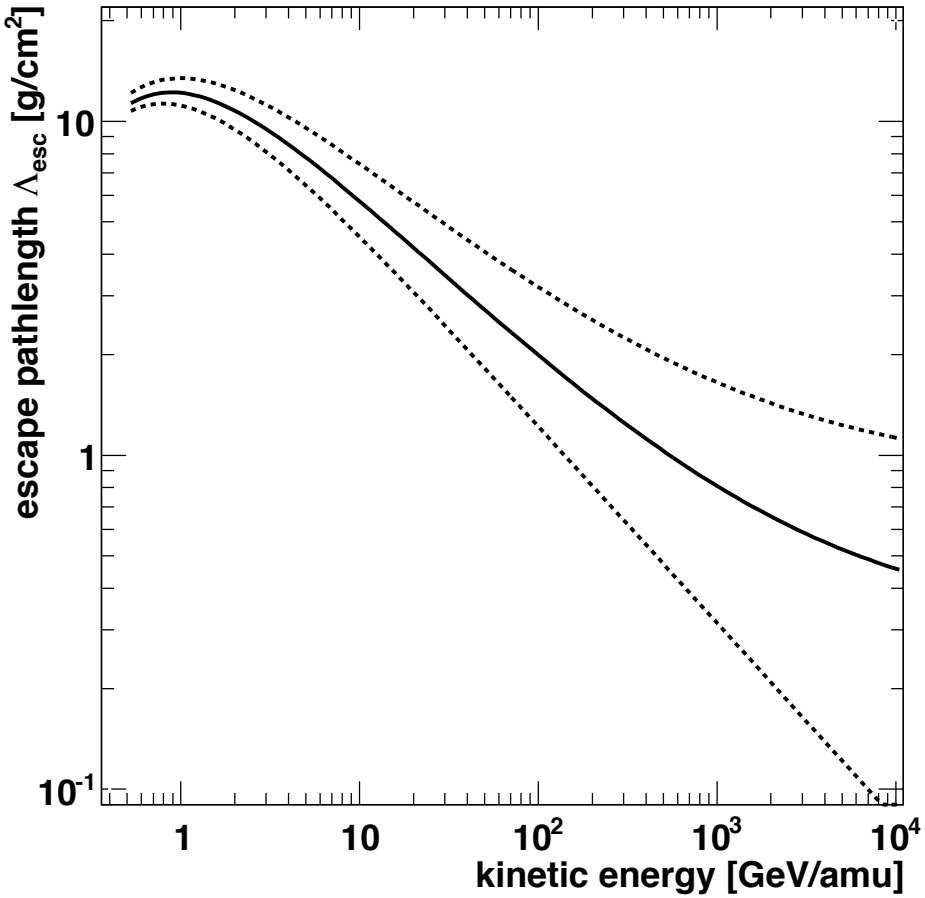

SOUTHERN OCEAN
FALKLAND ISLANDS (UK)
South Orkney Is.
Scotia Sea
ARGENTINA
Weddell Sea
KERGUELEN (Fr.)
South Shetland Is.
Larsen Ice Shelf
Ronne Ice Shelf
HEARD & MCDONALD ISLANDS (Austr.)
CHILE
Antarctic Penin.
Alexander I.
Bakkner I.
Amery Ice Shelf
ANTARCTICA
Vinson Massif 4897 m
South Pole
Thurston I.
INDIAN OCEAN
Mt. Kirkpatrick 4528 m
Ross Ice Shelf
Roosevelt I.
Ross Sea
SOUTHERN OCEAN
Balleny Is.
PACIFIC OCEAN
MACQUARIE I. (Austr.)
CAMPBELL IS. (N.Z.)
AUCKLAND IS. (N.Z.)
ANTIPODES IS. (N.Z.)
AUSTRALIA
NEW ZEALAND
60°
70°
80°
100°
120°
140°
160°

Cosmic-ray propagation

B/C ratio



path length



A. Obermeier et al., ICRC (2011)

A. Obermeier, PhD thesis, RU Nijmegen (2011)

Light element production

two processes: CR's + ISM

- fusion reactions

$$\alpha + \alpha \rightarrow {}^6Li + p + n$$
$$\rightarrow {}^7Li + p$$
$$\rightarrow {}^7Be \ (EC) \ {}^7Li + n$$

- spallation reactions

$$C, N, O + p, \alpha \rightarrow {}^{6,7}Li, \ {}^9Be, \ {}^{10,11}B$$

constant production rate

$$\frac{dN_L}{dt} = N_{CNO} \int \bar{\sigma}_{CNO}(E) \, \phi(E) \, dE$$
$$\approx N_{CNO} \langle \bar{\sigma} \rangle \phi$$

abundance relative to H

$$\frac{L}{H} = \frac{CNO}{H} \langle \bar{\sigma} \rangle \phi_p T = 4 \cdot 10^{-12} \left(\frac{T}{10\,Gyr} \right) \langle \bar{\sigma} \rangle_{mol}$$

T age of the Galaxy

$\sigma(E) \approx$ const. for relevant E

Galactic chemical evolution of light elements

using instantaneous recycling approximation

$$(1) \quad \frac{d}{ds}(g z) = q + \beta R z - z + \frac{N_{CNO}\,\sigma\,\phi\,A m_H + z_P F - z_E F}{\psi}$$

$0 \leq \beta \leq 1$ allows for astration

$\beta = 0$ for complete destruction

A mass number of light element

$\alpha - \alpha$ fusion reactions have been neglected

if SFR is assumed proportional to mass of gas

$$\frac{ds}{dt} = \omega g \qquad \omega = \text{const.}$$

→ abundance of primary element increases linearly with time

$$z = \omega t$$

or, in general $z(t) = \int_0^t \omega(t')\, dt' \equiv u$

(1) with u

(2) $$\frac{d}{du}(g z) = g\left(p + \frac{A}{A_{CNO}}\, \sigma\, z_{CNO} \frac{\phi}{\omega} - \frac{z}{\alpha'}\right) + \frac{z_F F - z_E E}{\omega}$$

p yield from stellar production

$$\alpha' \equiv \frac{\alpha}{1-\beta(1-\alpha)}$$

→ α for complete distruction

→ 1 for no distruction

pure CR spallation products ^6Li, Be, B

(2) becomes

$$\frac{d}{du}(g z) + \frac{g z}{\alpha'} = \frac{A}{A_{CNO}} g\, z_{CNO}\, \sigma \frac{\phi}{\omega} + \frac{z_F F - z_C C}{\omega}$$

ϕ proportional to SN rate $\propto$ SFR ψ

$$\frac{\phi/\omega}{(\phi/\omega)_1} = \frac{g}{g_1}$$

$_1$ refers to the present epoch

simple model $\quad C = F = 0 \quad g = e^{-u} \quad z_{CNO} = P_{CNO}$

$$\frac{dz}{du} + (\alpha'^{-1} - 1) z = \frac{A}{A_{CNO}} \sigma P_{CNO} \frac{\phi_1}{\omega_1} u\, e^{-(u-u_1)}$$

$$= k \left(\frac{\sigma \phi}{\omega}\right) u\, e^{u_1 - u}$$

$$z = k \left(\frac{\sigma \phi}{\omega}\right)_1 e^{u_1} \frac{e^{-u}\left(e^{v'} - (1+v')\right)}{(2 - 1/\alpha')^2}$$

with $k = \frac{A}{A_{CNO}} P_{CNO}$

$$v' = (2 - 1/\alpha')u \approx \frac{u}{2} \quad \text{for } \alpha' = \frac{2}{3}$$

$\Rightarrow$ limiting behaviours

$$z \propto \frac{1}{2}u^2 \qquad u \to 0$$

$$\propto \frac{e^{-(u-v')}}{(2 - 1/\alpha')^2} \qquad u \to \infty$$

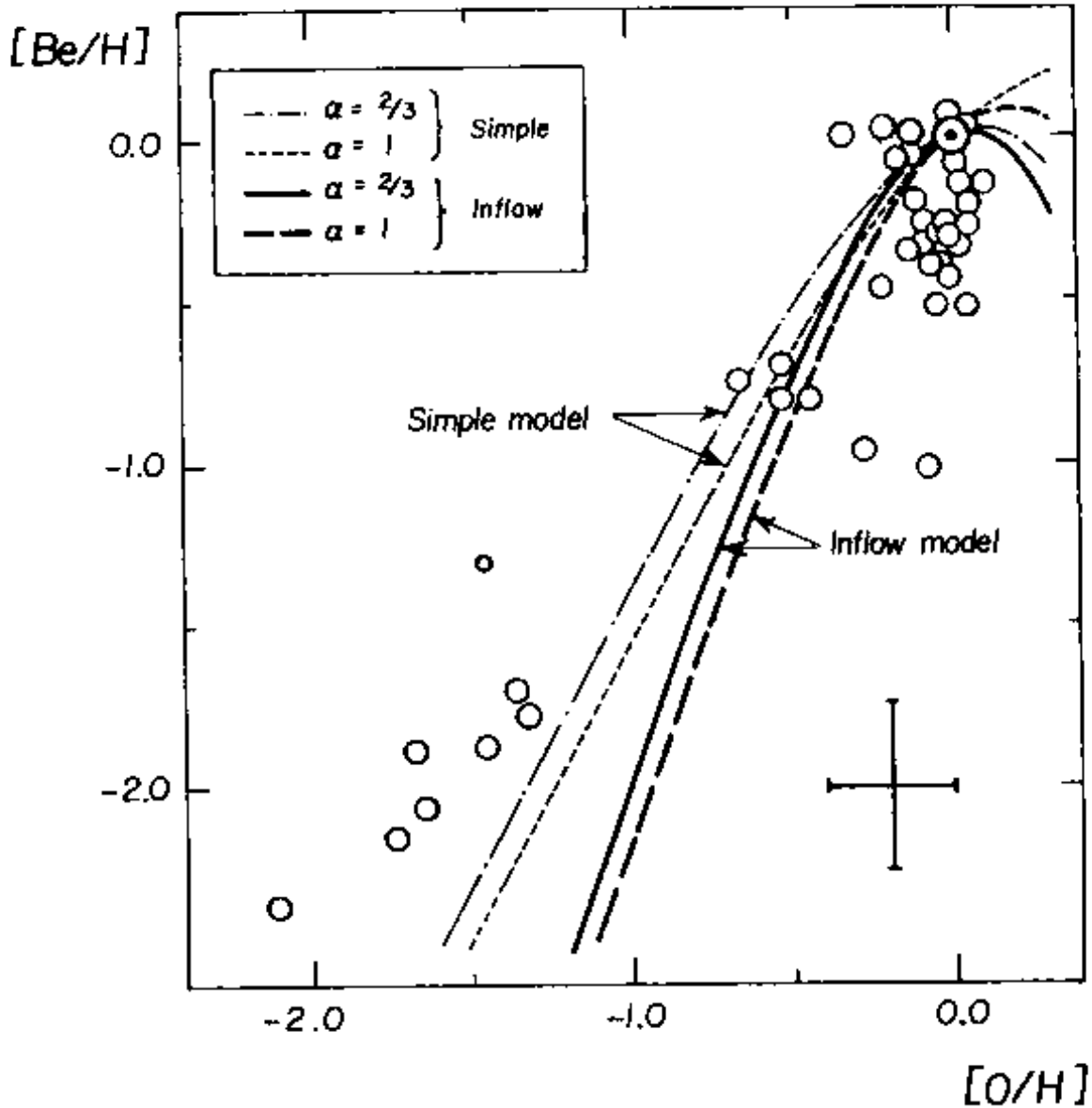


Fig. 9.6. Beryllium abundance as a function of oxygen abundance, according to models (curves) and observations (open circles) by Gilmore *et al.* (1992). (α in the key is actually the quantity called α' in the text.) After Pagel (1994). With kind permission from Kluwer Academic Publishers.