Li, Be, B

- RARE but of ECONOMIC VALUE

- A LITTLE HISTORY
  - 1957 "Annus mirabilis"

    B^2FH → x-PROCESS

    "We have made some attempt to explain possible modes of production of D, Li, Be and B but at present must conclude that these are little more than qualitative suggestions."

- GALACTIC COSMIC RAYS
  - Early recognition by H. Reeves that Li, Be, B abundant in GCRs

    → CAMBRIDGE SEMINAR

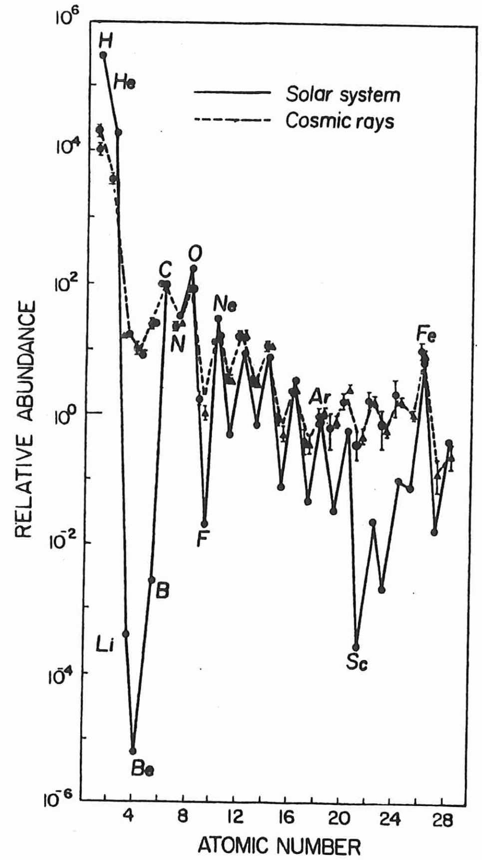


Fig. 9.1. Abundances in primary cosmic rays reaching the top of the Earth's atmosphere, compared to Solar-System abundances. (Both normalized to C = 100.) After Rolfs and Rodney (1988). Copyright by the University of Chicago. Courtesy Claus Rolfs.

In 1969, I presented these conclusions in a seminar at the former IOTA (Institute of Theoretical Astronomy) in Cambridge (UK) . During my seminar , Fred Hoyle kept on talking to Willie Fowler. I could overhear some of his words : "I have been repeating that to you for many years. You should have listened to me" Later on, he told me that he had considered this scenario for a long time. We published a paper together on this subject. (Reeves Fowler and Hoyle 1970)

ABUNDANCE DATA ≃ LIMITED

1. RARE NUCLIDES

2. ATOMIC STRUCTURE LIMITATIONS

3. 'NO' OBSERVABLE MOLECULES

BUT

- TEST OF BIG BANG
- INSIGHTS INTO N-S BY SPALLATION
- TESTS OF MIXING IN STARS
-

ATOMIC SPECTROSCOPY

			ALKALI	He-LIKE	H-LIKE
Li			Li I 6707 Å COOL * ISM	Li II ✗	Li III ✗
Be		Be I ✗	Be II 3130 Å WARM *	Be III ✗	Be IV ✗
B	B I UV ✓ WARM *	B II UV ✓ BA * ISM	B III UV ✓ B *	B IV ✗	B V ✗

ISOTOPIC RATIOS:

$^{6}Li/^{7}Li$ COOL *s, ISM

$^{7}Be/^{9}Be$ NOVAE

$^{10}B/^{11}B$ B STARS, ISM

LIGHT ELEMENT SYNTHESIS - SUMMARY

^6Li : SPALLATION : GCRs

^7Li :
- BB
- SPALLATION : GCRs
- MASSIVE ✱/SN IIa : ν PROCESS
- NOVAE : $^3He \to {}^7Be \to {}^7Li$
- RED GIANTS : ✓
- AGB STARS : ✓

^9Be : SPALLATION : GCRs

^{10}B : SPALLATION : GCRs

^{11}B : SPALLATION : GCRs

MASS. ✱/SN II : ν PROCESS

EVIDENCE

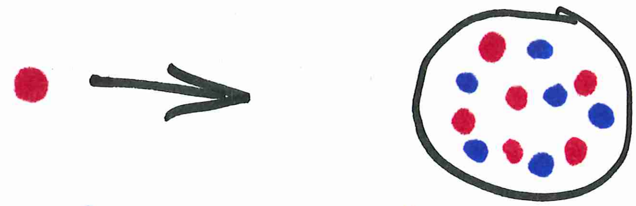
METEORITES / ISM / STARS

SPALLATION – Ord. of mag. PREDICTIONS

PAGEL : CHAPTER 9

ILIADIS : § 5.7.2

- AT CR ENERGIES, CR PARTICLE (p, α) APPEARS V. SMALL REL. TO TARGET NUCLEUS



- TARGET IS 'SPALLATED'
  - LITTLE BITS BLOWN OUT, i.e., $^{12}C \rightarrow {}^{6}Li, {}^{7}Li$ + bits

    $^{20}Ne \rightarrow {}^{19}F$ etc.

- $\sigma(E)$ MEASURED

- **ALSO FUSION REACTIONS**

$$\alpha + \alpha \rightarrow {}^{6}Li, {}^{7}Li, {}^{7}Be$$

($^{7}Be \rightarrow {}^{7}Li$ by EC)

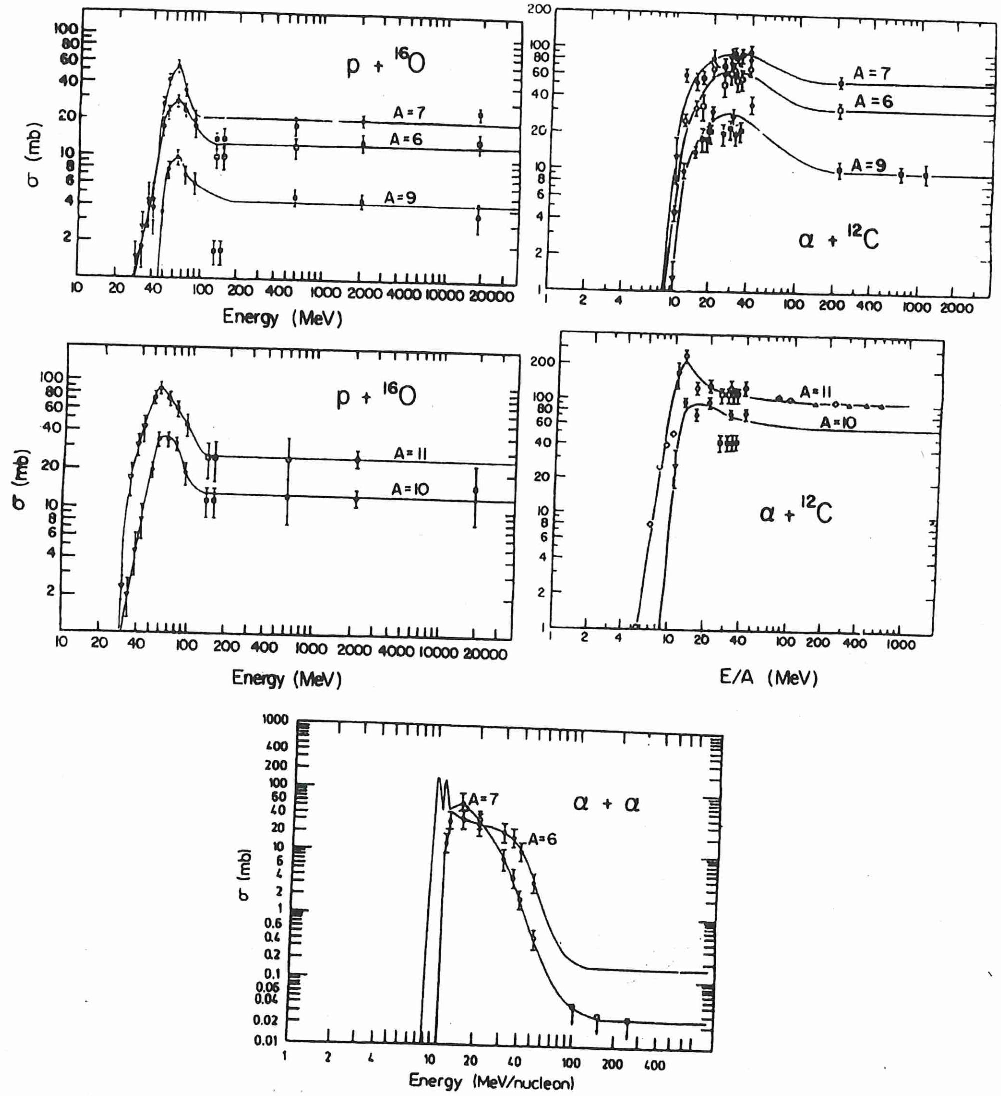


Fig. 9.4. Reaction cross-sections, as a function of energy per nucleon, for the production of light elements for some typical cases. Adapted from Read and Viola (1984). Courtesy Vic Viola.

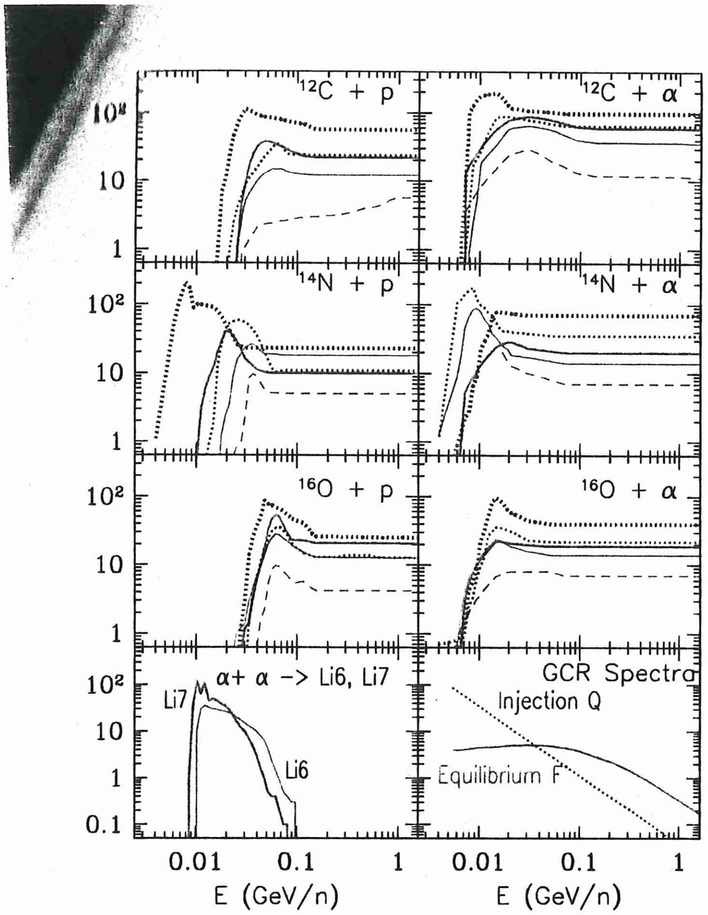


Fig. 10. Cross sections (mb) for the production of Li, Be and B by spallation of CNO nuclei with protons and alphas, as a function of particle energy per nucleon. Data are from Read and Viola (1984) and Mercer et al (2001, $\alpha + \alpha$ reactions). In all panels *thick dotted* curves correspond to production of ^{11}B, *thin dotted* to ^{10}B, *thick solid* to ^{7}Li, *thin solid* to ^{6}Li and *dashed* to ^{9}Be. In the *bottom right* panel appear the adopted GCR spectra (arbitrary units): injection Q (*dotted*) and equilibrium F (*solid*) .

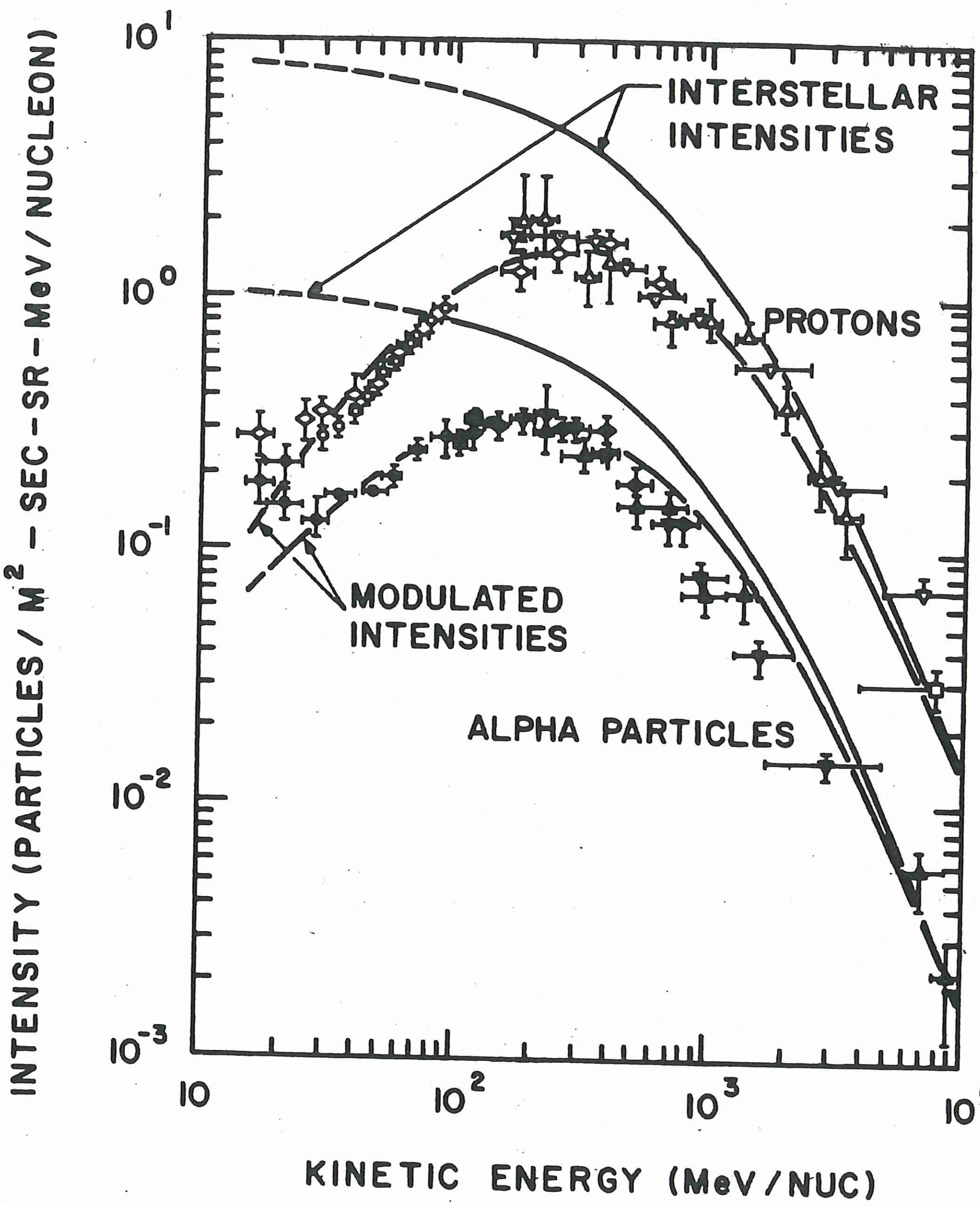


Fig. 9.3. Proton and α-particle spectra of primary cosmic rays and their demodulated versions. After Goldstein *et al.* (1970). Courtesy Reuven Ramaty.

Pagel §9.3

See also Austin, S. Prog. in Particle & Nucl. Phys. 7, 1, 1981

Walker, T et al. ApJ 299 745 1985

Prantzos, A&A 542 A67 2012

Simple approach

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

$$\simeq N_{CNO} \langle \bar{\sigma} \rangle \phi_{CR}$$

where $\phi = \int \phi(E) dE$ up to ~~??~~ from ~150 MeV

$$\frac{L}{H} \simeq \frac{CNO}{H} \langle \bar{\sigma} \rangle \phi_p t$$

$$\simeq 4 \times 10^{-12} \left[\frac{T}{10\,Gyr}\right] \langle \sigma_{mb} \rangle$$

PAGEL

Table 9.2. *Results of simple calculations of light element abundances*

	$\overline{\sigma}_{CNO}$ (mb)	$10^{11}\frac{L}{H}$	$10^{11}\frac{L}{H}$	$10^{11}\frac{L}{H}$	
	$E > 150$ MeV	Eq. (9.11)	WMV 85[a]	meteoritic	
^{6}Li	13	5	7	17	√
^{7}Li	20	8	10	210	××
^{9}Be	4	1.6	1.5	2.6	√
^{10}B	16	6	7	15	√
^{11}B	34	14	18	62	×
^{6}Li/^{9}Be/^{10}B		3/1/4	5/1/5	7/1/6	√

[a] Numerical calculation by Walker, Mathews and Viola (1985).

^{6}Li/^{9}Be/^{10}B ≈ ✓

but not ^{7}Li (way off)

and ^{11}B (not too far off)

AUSTIN (1981)

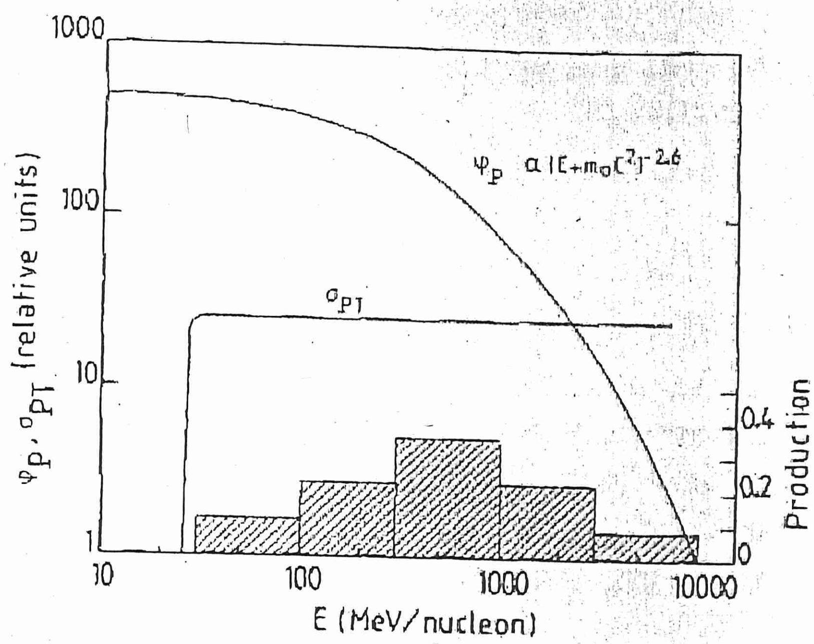


Fig. 7. Factors entering the integrand of eqn. (4.1). The height of the shaded histograms on the right hand scale shows the fraction of element production in the corresponding interval.

Table 5. Simple estimate of LiBeB production by the galactic cosmic rays

Nuclide	σ^i_{pC} [a] (mb)	σ^i_{pO} [a] (mb)	$(N_i/H)_{theory}$ [b]	$(N_i/H)_{expt}$ [c]	Theory/Expt
^6Li	14.8	13.9	45×10^{-12}	70×10^{-12}	0.64(0.90)[d]
^7Li	20.5	21.2	66×10^{-12}	900×10^{-12}	0.07
^9Be	6.2	4.4	16×10^{-12}	14×10^{-12}	1.13
^{10}B	22.7	12.7	51×10^{-12}	30×10^{-12}	1.71
^{11}B	57.0	26.5	118×10^{-12}	120×10^{-12}	0.98

[a] Cross sections from Lindstrom *et al.* (1975) at 2.1 GeV.
[b] From eqn. (4.4) with σ's from columns 2 and 3; $N_C/H = 480 \times 10^{-6}$ and $N_O/H = 850 \times 10^{-6}$ from Meyer (1978); $\phi_P(E > 30) = 8.3\ \text{cm}^2\ \text{sec}^{-1}$ from Meneguzzi, Audouze and Reeves (1971); and $t_{galaxy} - t_{sun} = 9 \times 10^9$ yr.
[c] From Table 4.
[d] Number in parentheses includes rough estimate of contribution from $\alpha + \alpha \rightarrow {}^6Li + np$.

In Eq. (1) one may substitute typical values - see MAR - for GCR fluxes (F_p^{GCR} ~10 p cm^{-2} s^{-1} for protons and scaled values for other GCR nuclei), for the corresponding cross sections (averaged over the GCR equilibrium spectrum $\sigma_{p,a+CNO\longrightarrow Be}$ ~10^{-26} cm^2) and for ISM abundances (Y_{CNO} ~10^{-3}); integrating for Δt ~10 Gyr, one finds then that Y_{Be} ~2 10^{-11}, i.e. approximately the meteoritic Be value (Lodders 2003). Satisfactory results are also obtained for the abundances of ^{6}Li and ^{10}B. Despite the crude approximations adopted (constant GCR fluxes and ISM abundances for 10 Gyr, average production cross sections, secondary production channels ignored), the above calculation correctly reproduces both the absolute values (within a factor of two) and the relative values (within 10 % of the solar abundances) of ^{6}Li, ^{9}Be and ^{10}B. This constitutes the

[1] The full calculation should include production by spallation of other primary and secondary nuclides, such as ^{13}C; however, this has only second order effects.

Prantzos (2012)

MORE REFINED MODELS

See Prantzos (2012)
– pay attention to energetics

Table 3. Contributions (%) of various sources to solar LiBeB production

	SBBN	GCR	ν in CCSN	Low-mass stars[a]
^{6}Li		100[b]		
^{7}Li	12	18	<20	50-70
^{9}Be		100		
^{10}B		100		
^{11}B		70	30	

a: Red giants, AGBs, novae ; *b*: Assuming no pregalactic ^{6}Li.

COSMIC RAYS

- **SOURCES** (Fig. 3 / Prantzos)

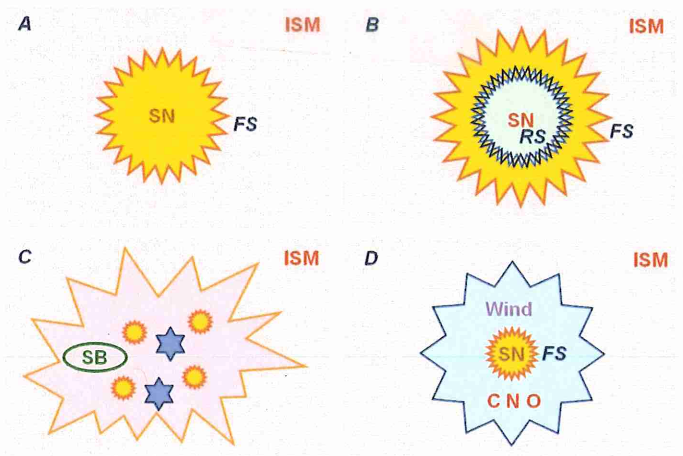


Fig. 3. Scenarios for the origin of GCR. *A*: GCR originate from the interstellar medium (ISM) and are accelerated from the forward shock (FS) of SN. *B*: GCR originate from the interior of supernovae and are accelerated by the reverse shock (RS), propagating inwards. *C*: GCR originate from superbubble (SB) material, enriched by the metals ejected by supernovae and massive star winds; they are accelerated by the forward shocks of supernovae *and* stellar winds. *D*: GCR originate from the wind material of massive *rotating* stars, *always rich in CNO* (but not in heavier nuclei) and they are accelerated by the forward shock of the SN explosion.

- **ACCELERATION** [?]

PROPAGATION THRU' ISM

- "LEAKY BOX"

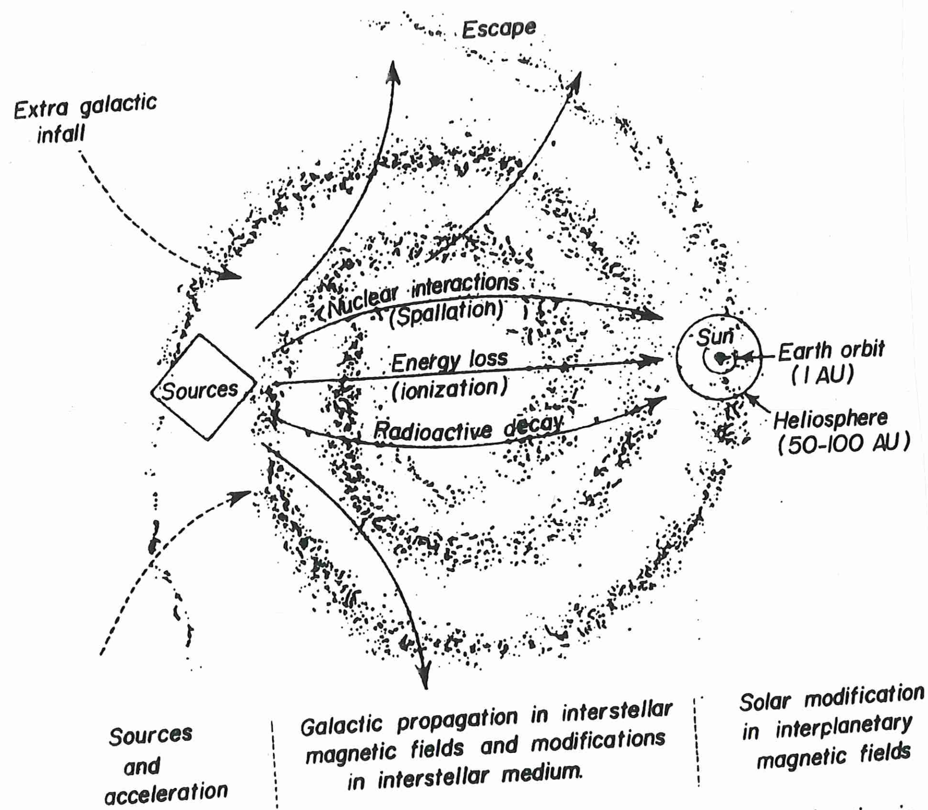


Fig. 9.2. Schematic view of the life history of a cosmic ray from acceleration in the source through propagation in the Galaxy to observation above the Earth's atmosphere. Adapted from Rolfs and Rodney (1988).

ADOPT INJECTION SPECTRUM and CALCULATE EQUILIBRIUM ISM SPECTRUM

SIMPLE IDEAS AND OBSERVATIONS

$$Y_L = N_L / N_H$$

$$\frac{dY_L^{ISM}}{dt} = F_{p,\alpha}^{GCR}\, \sigma_{p\alpha+CNO}\, Y_{CNO}^{ISM} \quad \text{(DIRECT)}$$

$$+ F_{CNO}^{GCR}\, \sigma_{p\alpha+CNO}\, Y_{p,\alpha}^{ISM}\, P_L \quad \text{(REVERSE)}$$

$$+ F_{\alpha}^{GCR}\, \sigma_{\alpha+\alpha}\, Y_{\alpha}^{ISM}\, P_L \quad \text{(SPALLATION-FUSION)}$$

P_L = probability that product L is thermalized (not destroyed) and remains in ISM

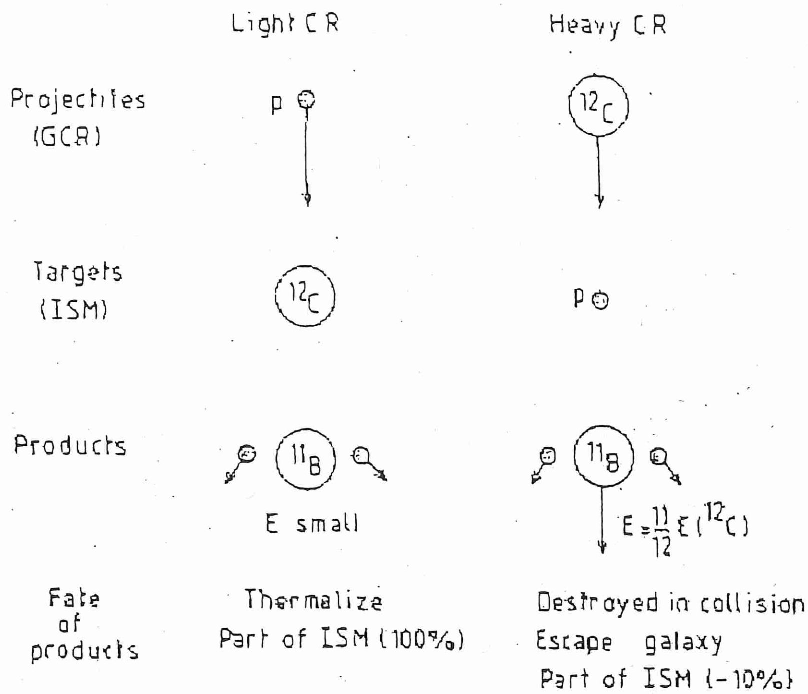


Fig. 6. Fate of reaction products from light and heavy cosmic rays.

DIRECT production

$$\frac{dY_L^{ISM}}{dt} \propto \frac{dN_{SN}}{dt} N_O^{ISM}$$

but O from SN : $\frac{dN_{SN}}{dt} \propto \frac{dO}{dt}$

$$\frac{dY_L^{ISM}}{dt} \propto O \frac{dO}{dt}$$ or $\boxed{Y_L \propto O^2}$

SECONDARY

REVERSE production

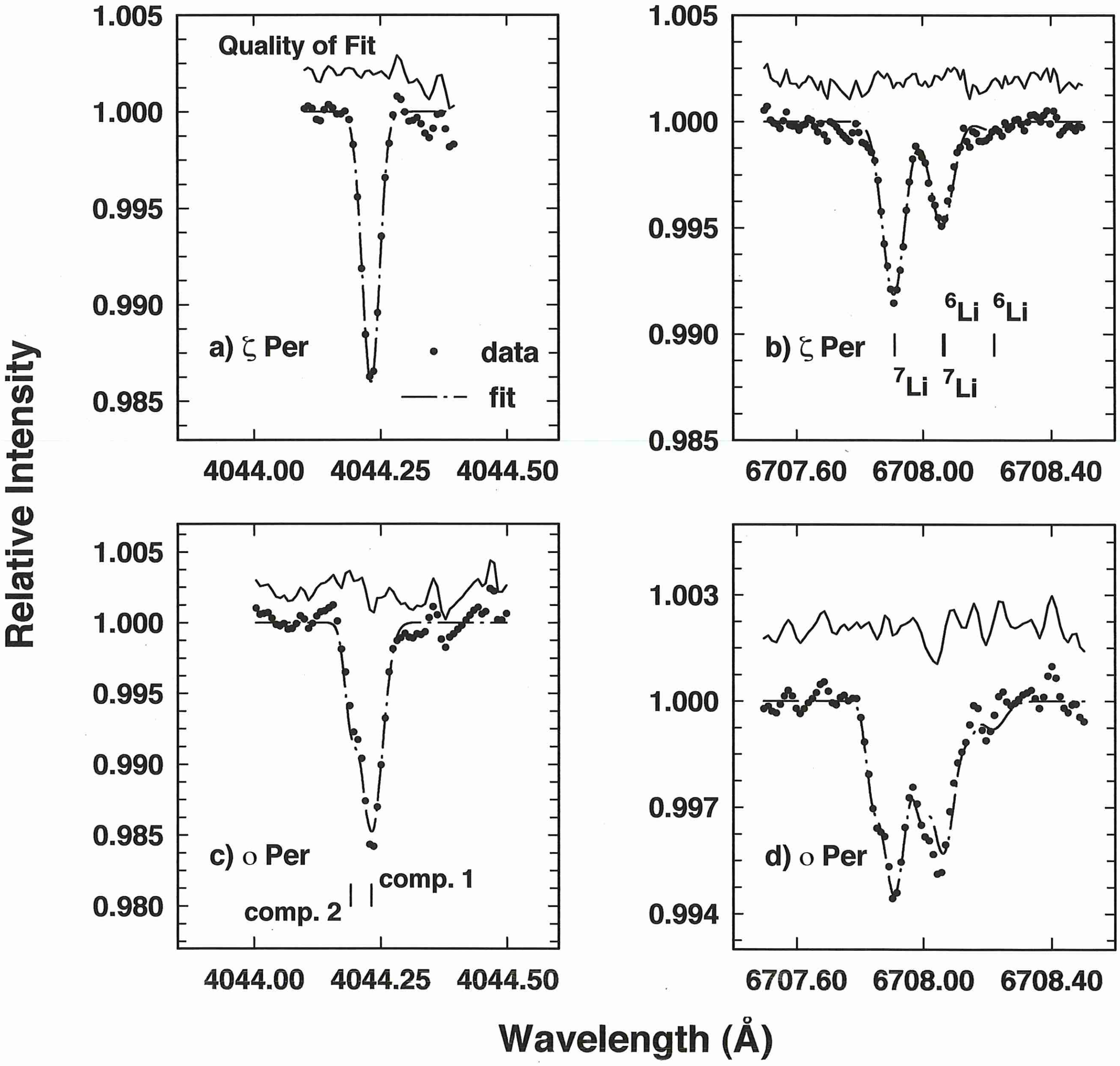
Say, $O_{CCR} + P_{ISM} \rightarrow L$

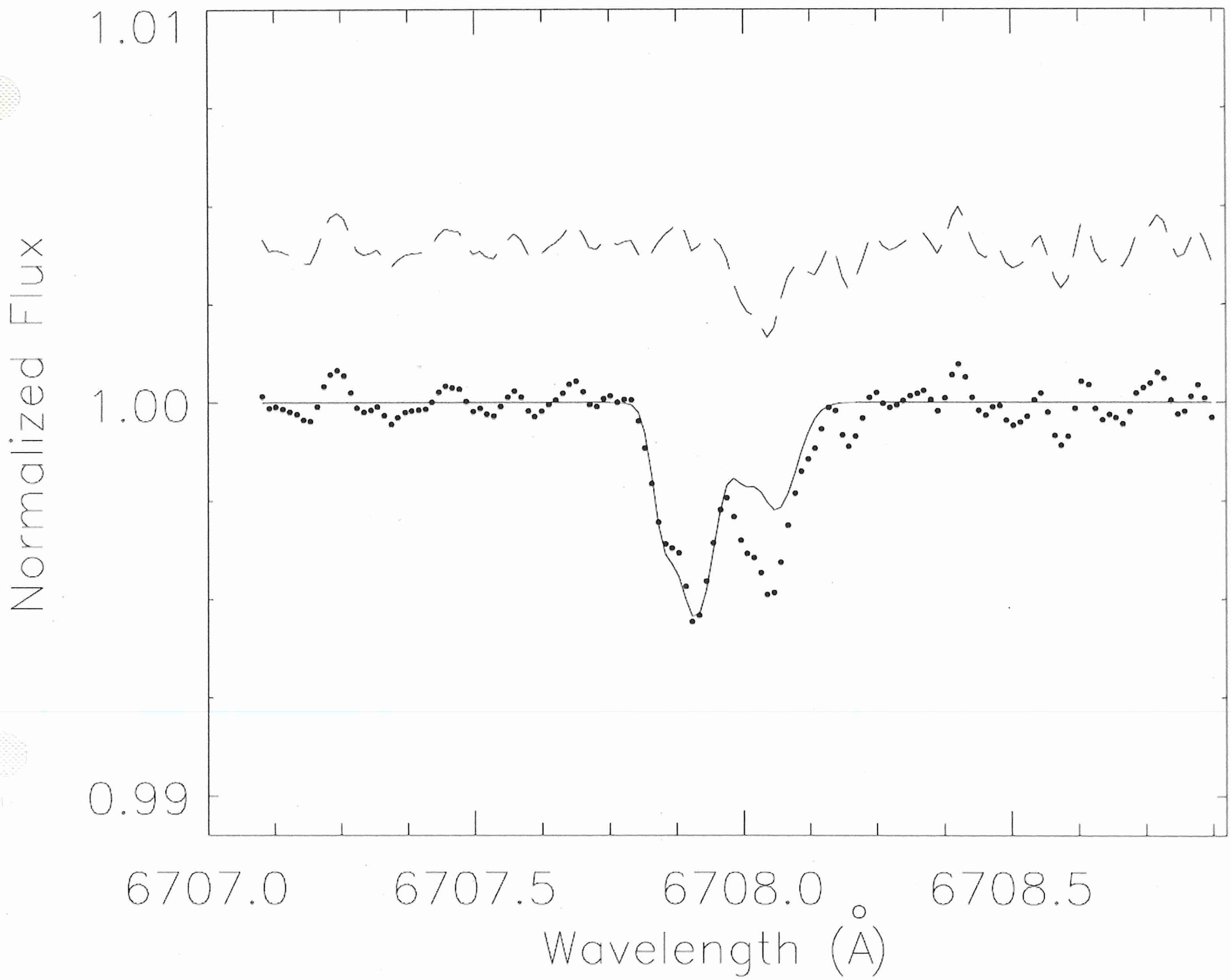
$$\frac{dN_L}{dt} \propto \frac{dN_{SN}}{dt} \propto \frac{dO}{dt}$$

$$\boxed{Y_L \propto O}$$

PRIMARY

LOCAL ISM EXAMPLES OF ISOTOPIC RATIOS





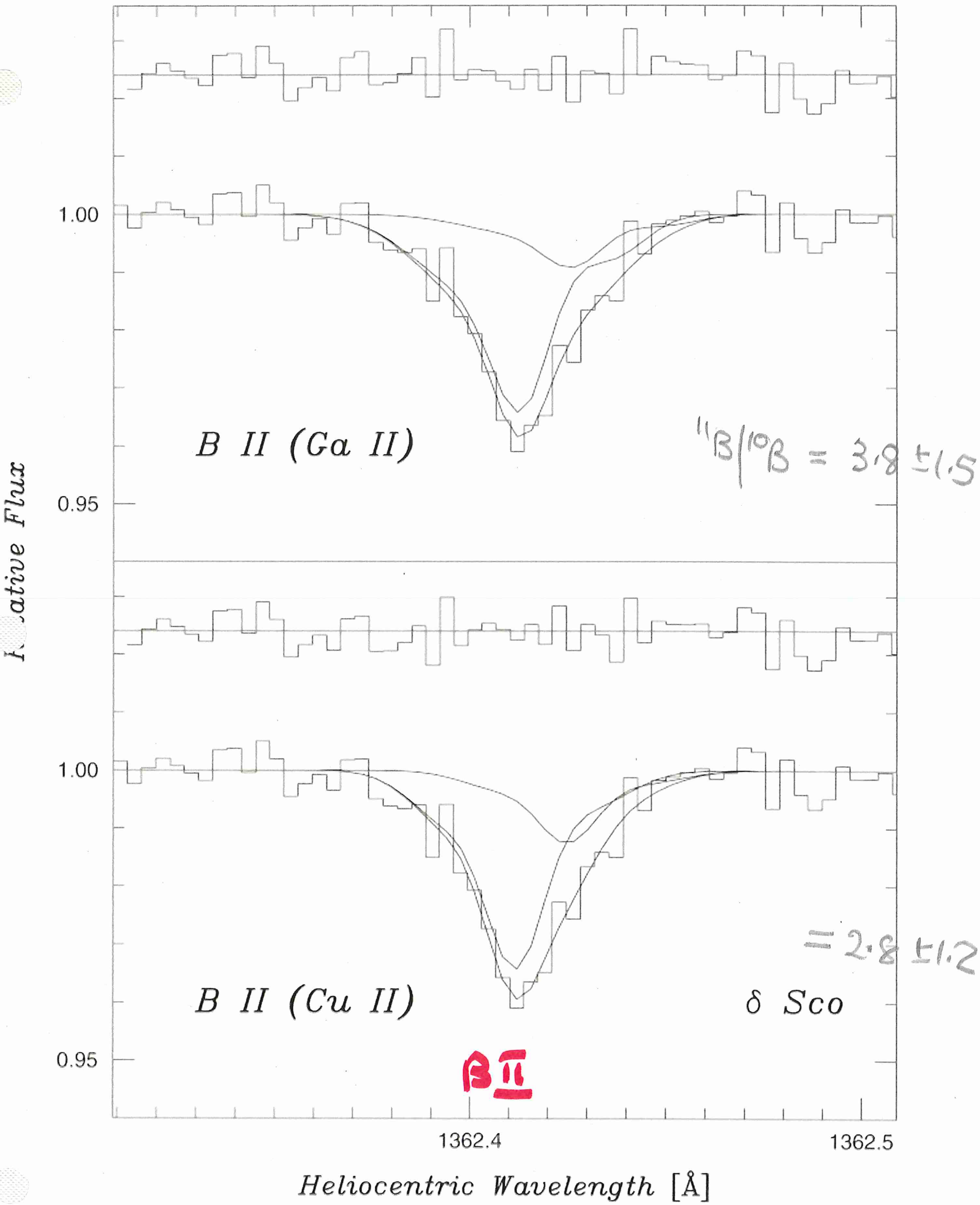
o Per

$^7Li/^6Li = 2.1 \pm 1.1$

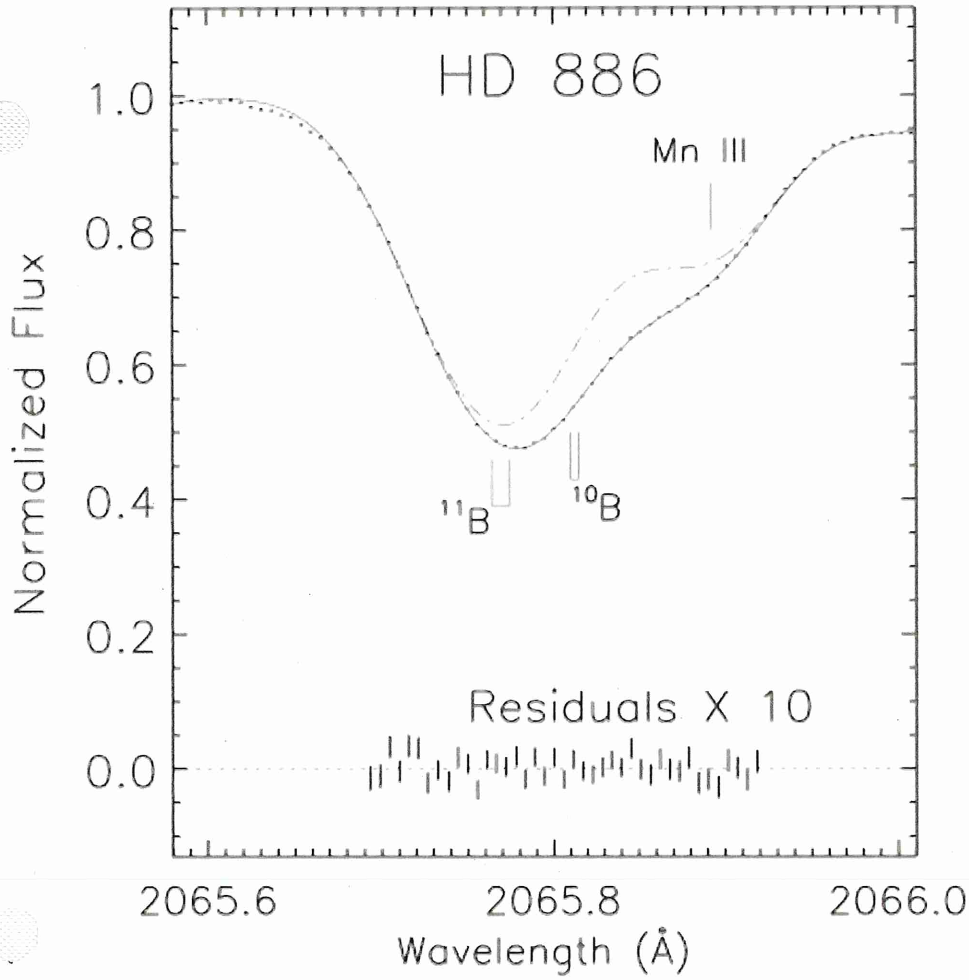
meteorites

$^7Li/^6Li = 12.3$

LINE OF SIGHT PASSES CLOSE TO SUPERNOVA REMNANT



Meteorites $^{11}B/^{10}B = 4.0$



B STAR

—·— No ^{10}B
—— $^{11}B/^{10}B = 4$

STELLAR BOCON

Proffitt et al. ApJ 516 342 1999

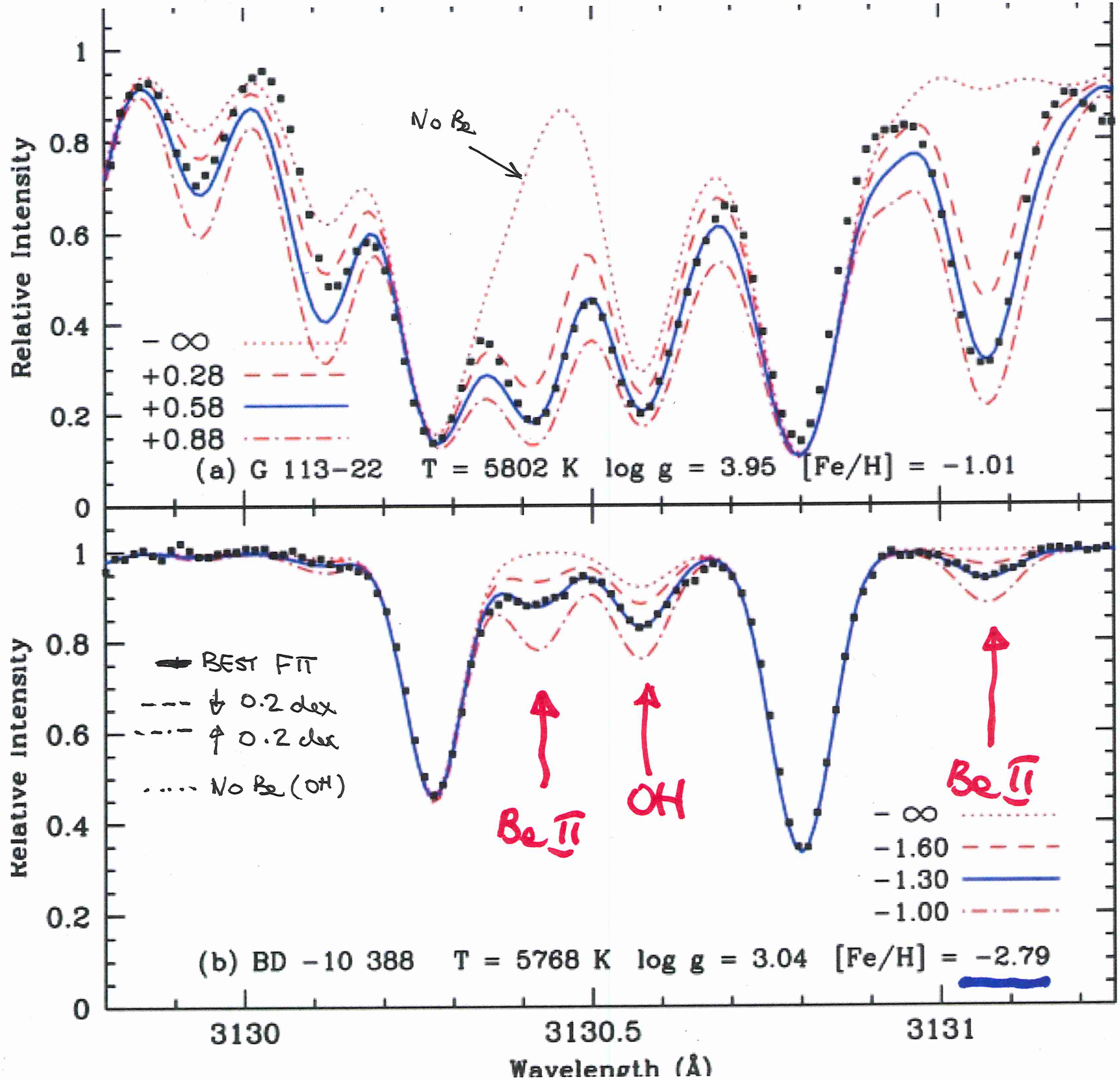
Be OBSERVATIONS

- ^{9}Be BELIEVED TO BE PURE SPALLATION PRODUCT
  - TO [Fe/H] ~ −3.5 from Be II λ3130
  - LESS SUSCEPTIBLE TO INTERNAL DESTRUCTION THAN Li
- NO ^{9}Be SPITE-LIKE PLATEAU
  - A CHECK OF SOL'NS TO Li-PROBLEM

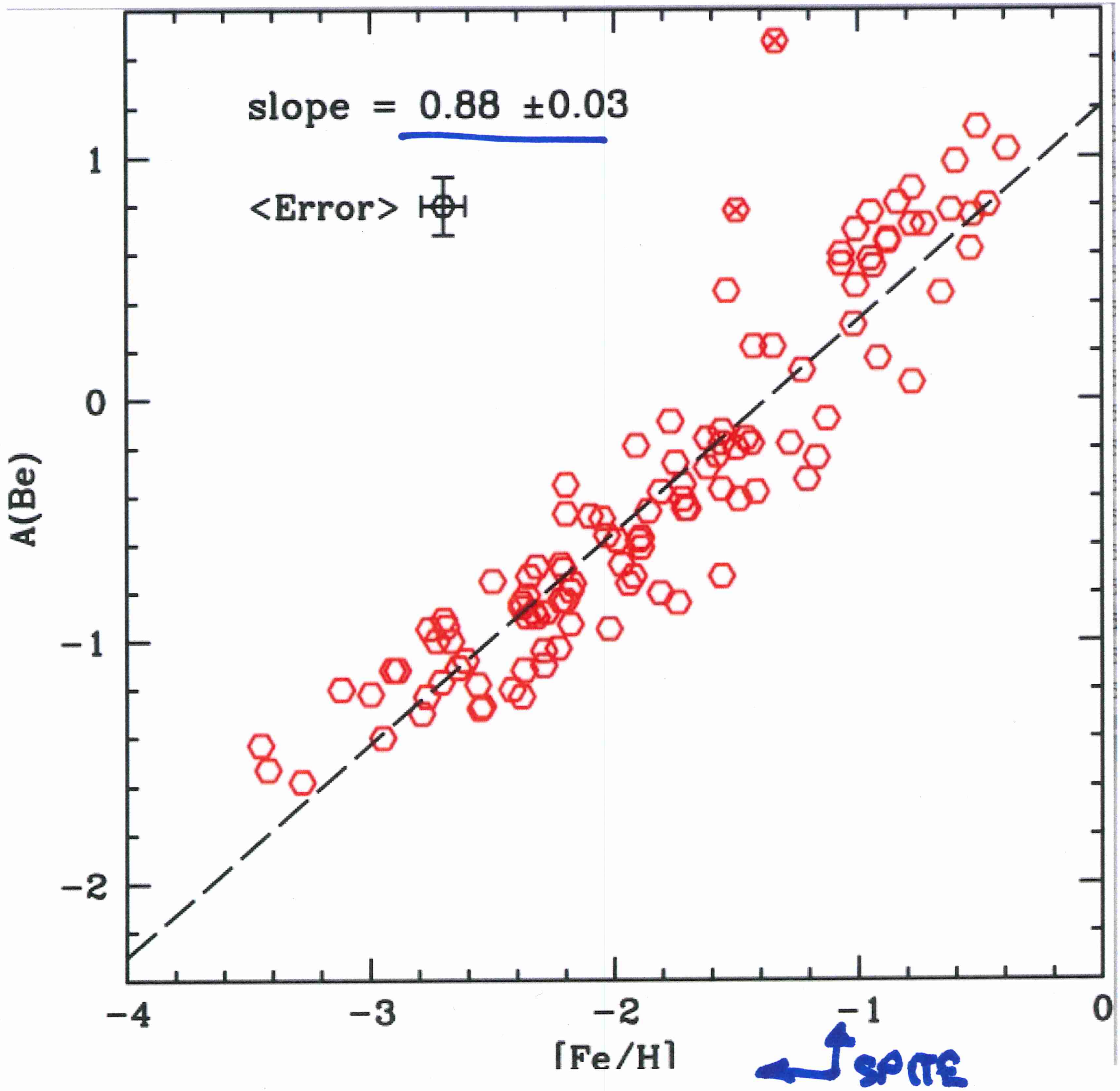
BOESGAARD, et al.
2011 ApJ 741 140

from KECK/HIRES

Be II, OH, Fe, Mg

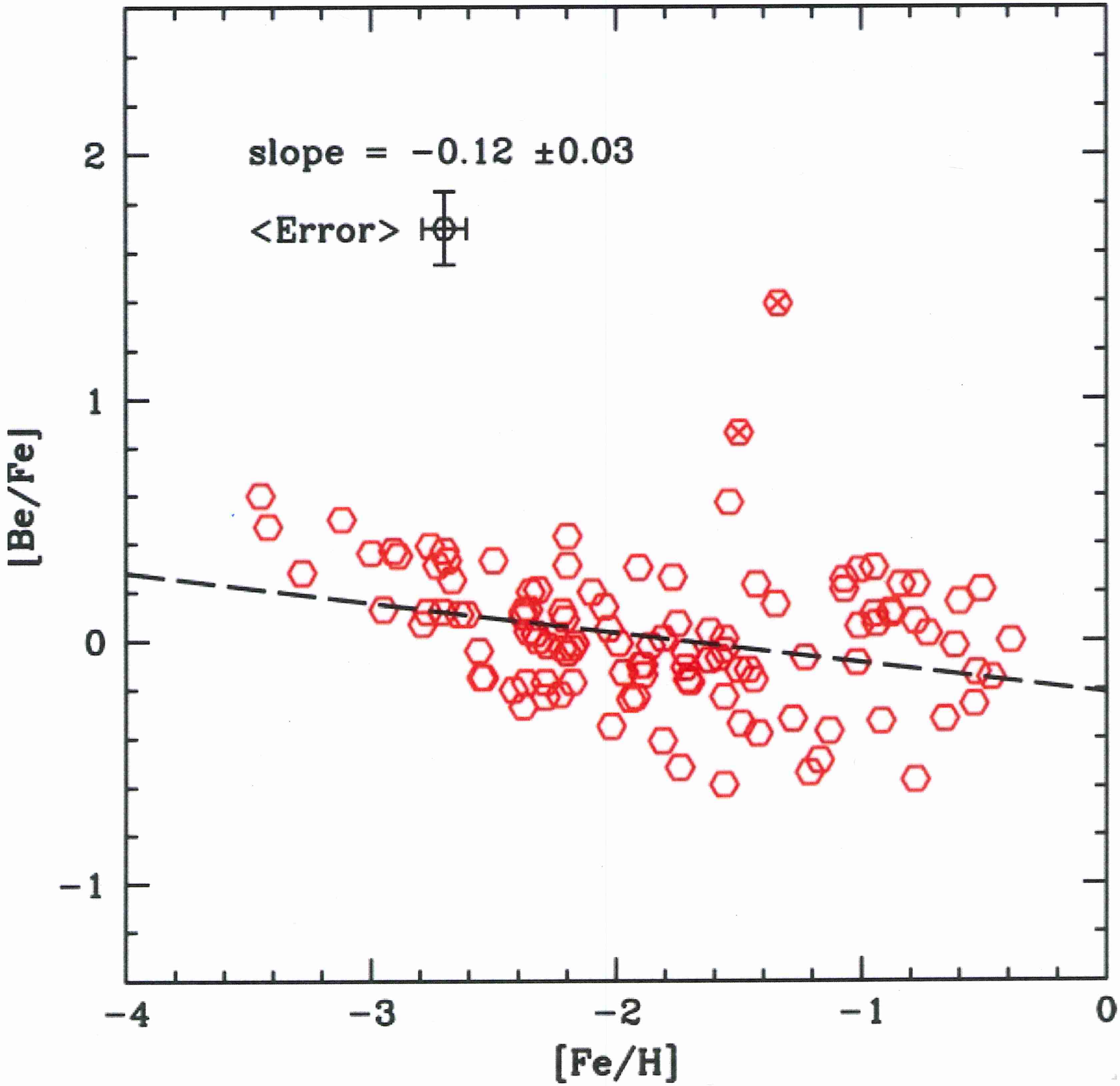


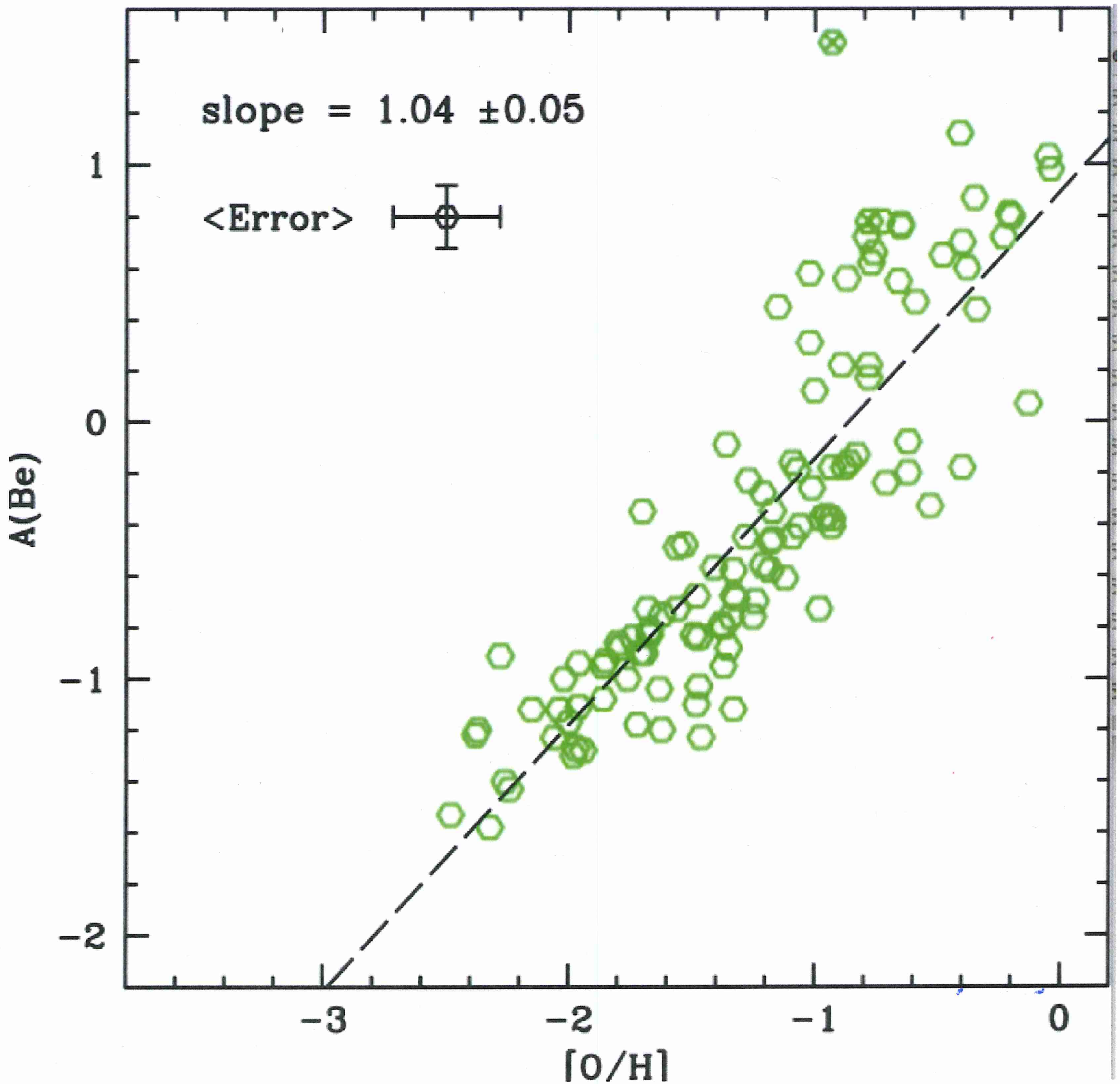
Relative Intensity
1
0.8
0.6
0.4
0.2
0
No Be
− ∞
+0.28
+0.58
+0.88
(a) G 113−22 T = 5802 K log g = 3.95 [Fe/H] = −1.01
BEST FIT
0.2 dex
0.2 dex
No Be (OH)
Be II
OH
Be II
− ∞
−1.60
−1.30
−1.00
(b) BD −10 388 T = 5768 K log g = 3.04 [Fe/H] = −2.79
3130
3130.5
3131
Wavelength (Å)

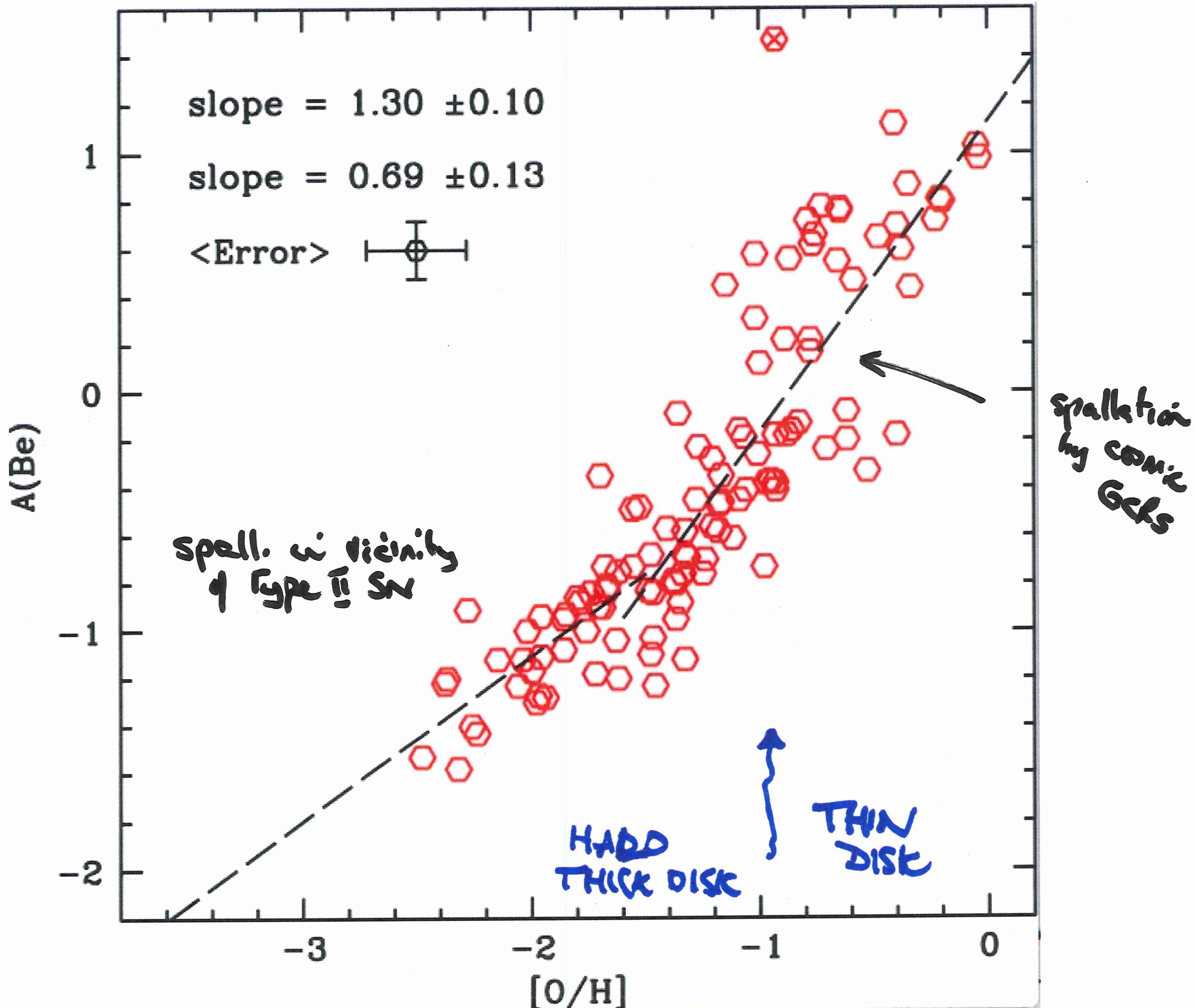


slope close to reverse production

SPITE


slope = −0.12 ±0.03
<Error>
[Be/Fe]
[Fe/H]
2
1
0
−1
−4
−3
−2
−1
0


slope = 1.04 ±0.05
<Error>
A(Be)
1
0
−1
−2
−3
−2
−1
0
[O/H]



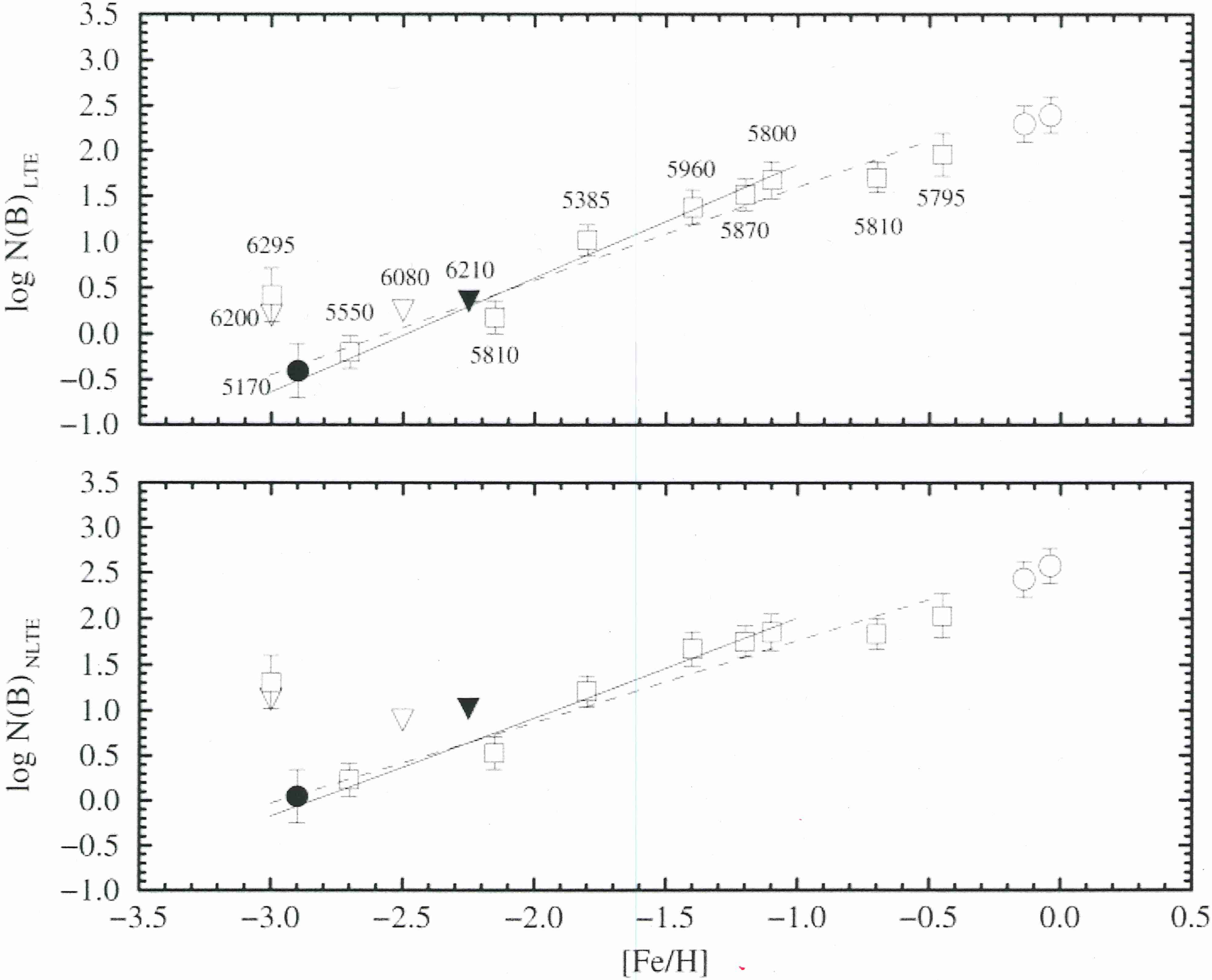
slope = 1.30 ±0.10
slope = 0.69 ±0.13
<Error>
A(Be)
1
0
−1
−2
−3
−2
−1
0
[O/H]
spallation by cosmic GCRs
spall. w/ vicinity of Type II SN
HALO THICK DISK
THIN DISK

B OBSERVATIONS

FGK MAIN SEQ.

- B vs Fe & O for GCE
- B in hot stars for destruction studies (rotationally-induced mixing)

- B II from HST



log N(B)LTE
log N(B)NLTE
[Fe/H]
6295
6200
5170
5550
6080
6210
5810
5385
5960
5870
5800
5810
5795
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5

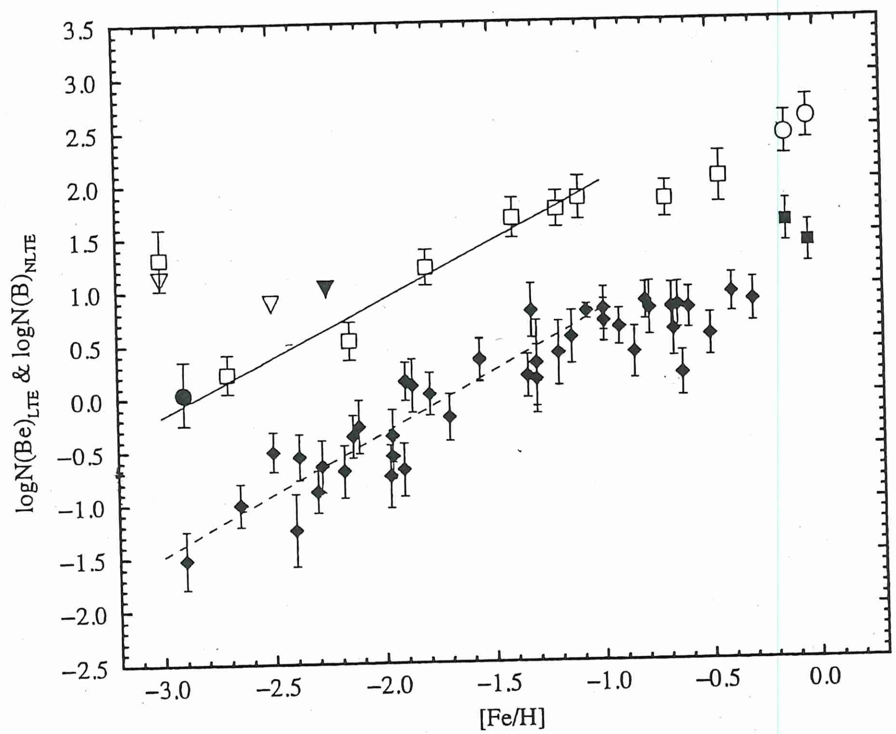


FIG. 10.—Boron (NLTE) and beryllium abundances against metallicity. Beryllium data were taken from García López et al. (1998) and represent a large sample of metal-poor stars with abundances derived using high-resolution CCD spectra. Be abundances for the solar-metallicity stars ι Peg and θ UMa, taken from Lemke et al. (1993) (*filled squares*), are shown for comparison. The solid line is a least-squares linear fit to boron abundances of stars with $T_{\rm eff} < 6000$ K and [Fe/H] < -1, and the dashed line corresponds to a similar fit to the beryllium data.

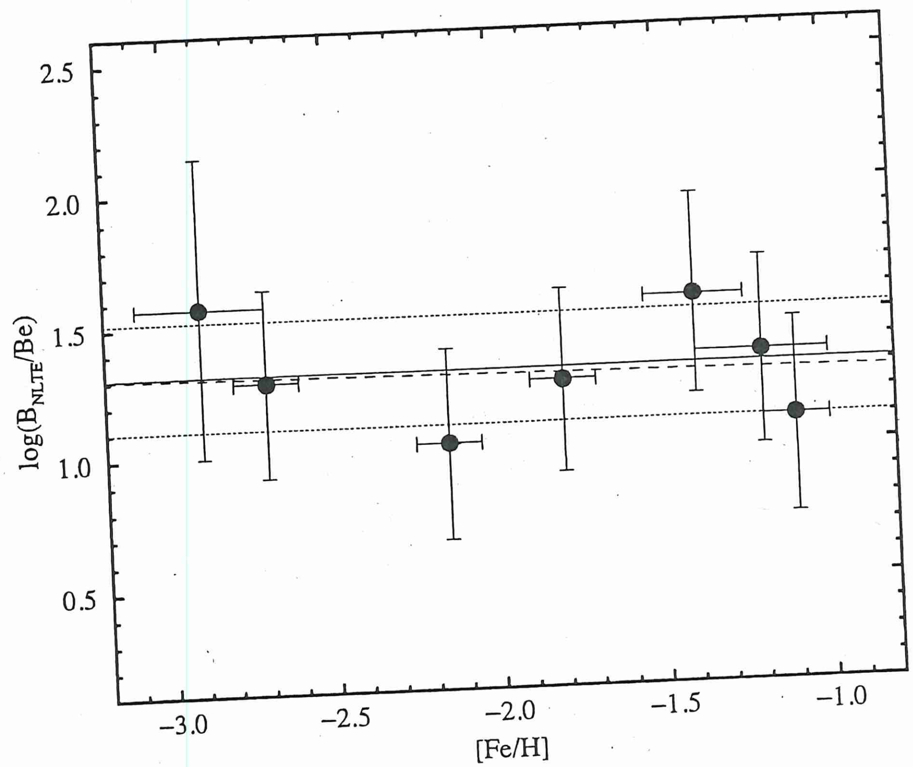
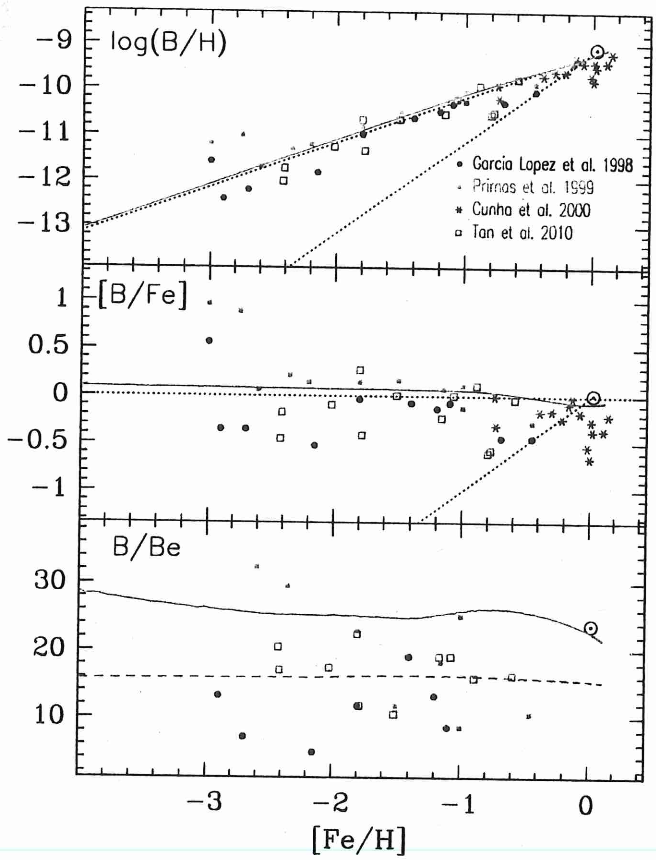


FIG. 11.—Boron (NLTE) to beryllium (LTE) ratios against metallicity for those seven stars with $T_{\rm eff} < 6000$ K and [Fe/H] < -1.



B ∝ Fe

Fig. 14. From top to bottom: evolution of B/H, B/Fe and B/Be. In the first two panels *dotted lines* indicate primary and secondary evolution. In the bottom panel, the *solid* curve corresponds to the total ^{11}B production (GCR + ν-nucleosynthesis) and the *dotted* curve to ^{11}B produced by GCR alone. Data are from: Primas et al. (1999, *filled squares*), Garcia-Lopez et al. (1999, *filled circles*), Cunha et al. (2000,*asterisks*), and Tan et al. (2010, *open squares*).

PRANTZOS
compilation

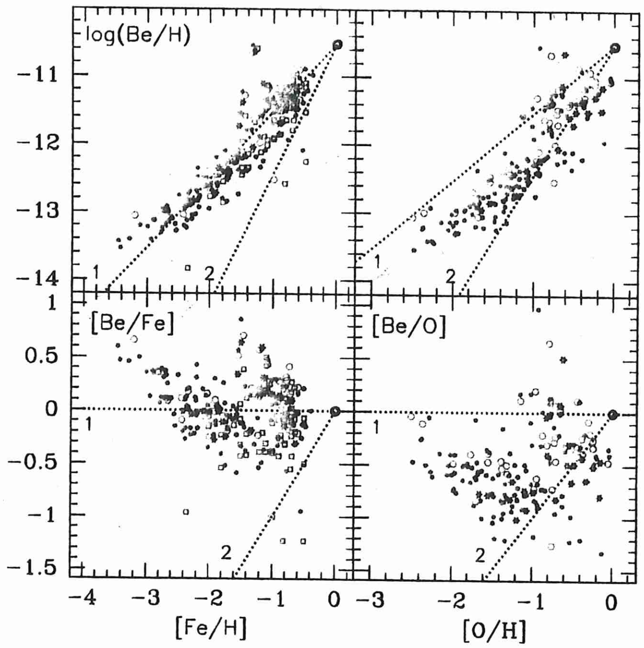


Fig. 1. Observations of Be vs. Fe (*left*) and vs. O (*right*). In all panels, *dotted lines* indicate slopes of 1 (primary) and 2 (secondary). Data are from Primas (2010, *circles*), Tan et al. (2009, *asterisks*), Smiljanic et al. (2009, *open squares*), and Boesgaard et al. (2011, *dots*).

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Astronomy & Astrophysics

Production and evolution of Li, Be, and B isotopes in the Galaxy

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ABSTRACT

Context. We reassess the problem of the production and evolution of the light elements Li, Be and B and of their isotopes in the Milky Way in the light of new observational and theoretical developments.

Aims. The main novelty is the introduction of a new scheme for the origin of Galactic cosmic rays (GCR), which for the first time enables a self-consistent calculation of their composition during galactic evolution.

Methods. The scheme accounts for key features of the present-day GCR source composition, it is based on the wind yields of the Geneva models of rotating, mass-losing stars and it is fully coupled to a detailed galactic chemical evolution code.

Results. We find that the adopted GCR source composition accounts naturally for the observations of primary Be and helps understanding why Be follows Fe more closely than O. We find that GCR produce ~70% of the solar $^{11}B/^{10}B$ isotopic ratio; the remaining 30% of ^{11}B presumably result from ν-nucleosynthesis in massive star explosions. We find that GCR and primordial nucleosynthesis can produce at most ~30% of solar Li. At least half of the solar Li has to originate in low-mass stellar sources (red giants, asymptotic giant branch stars, or novae), but the required average yields of those sources are found to be much higher than obtained in current models of stellar nucleosynthesis. We also present radial profiles of LiBeB elemental and isotopic abundances in the Milky Way disc. We argue that the shape of those profiles – and the late evolution of LiBeB in general – reveals important features of the production of those light elements through primary and secondary processes.

Key words. Galaxy: evolution – nuclear reactions, nucleosynthesis, abundances – stars: abundances – cosmic rays

1. Introduction

The idea that the light and fragile elements Li, Be and B are produced by the interaction of the energetic nuclei of galactic cosmic rays (CGR) with the nuclei of the interstellar medium (ISM) was introduced 40 years ago (Reeves et al. 1970; Meneguzzi et al. 1971, hereafter MAR). In those early works it was shown that taking into account the relevant cross-sections and with plausible assumptions about the GCR properties – source composition, intensity, and spectrum – one may reproduce the abundances of those light elements observed in GCR and in meteorites (=pre-solar) reasonably well. The only exception is Li, which can have only a minor contribution (<20%) from GCR and requires a stellar source. Despite more than 30 years of theoretical and observational work, the stellar source of Li remains elusive at present.

A new impetus was given to the subject by observations of halo stars in the 1990ies showing that Be and B behave as Fe, i.e. as primary elements (Gilmore et al. 1992; Ryan et al. 1992; Duncan et al. 1992), contrary to theoretical expectations. The reason for this "puzzling" behaviour was rapidly inferred by Duncan et al. (1992): GCR must have a metallicity-independent composition to produce primary LiBeB (see also Prantzos 1993). Other ideas (e.g. Prantzos et al. 1993) were only partially successful in that respect (see Reeves 1994 for a summary of the situation in the mid-90ies). Ramaty et al. (1997) showed that a metallicity-independent GCR composition is the only viable alternative for energetic reasons: if in the early Galaxy GCR had a metallic content much lower than today, they would need much more energy than supernovae can provide to always yield primary Be. It was claimed that GCR can aquire a metallicity-independent composition in the environment of superbubbles, powered and enriched by the ejecta of dozens of massive stars and supernovae (Higdon et al. 1997). In the absence of convincing alternatives, the "superbubble paradigm" became the physical explanation for both the origin of GCR (e.g. Parizot et al. 2004) and – by default – for primary Be (despite some criticism, e.g. in Prantzos 2006a).

Independently of the crucial question of the GCR origin, the Be and B observations of the 1990ies made it necessary to link the physics of GCR to detailed models of galactic chemical evolution (Prantzos et al. 1993; Ramaty et al. 1997). In the past few years, important developments occured in both observations and theory, making a reassessment of this vast subject necessary.

From the observational side, large surveys of Be in stars of low metallicities (Primas 2010; Tan et al. 2009; Smiljianic et al. 2009; Boesgaard et al. 2011) considerably improved the statistics of the Be vs. Fe, but also of Be vs. O relationships, providing combined and tighter constraints to models than those previously available. Furthermore, observations of Li isotopic ratios became available, both in low-metallicity halo stars (Asplund et al. 2006; Garcia-Perez et al. 2009) and in the local ISM (Kawanomoto et al. 2009). The former, suggesting a surprisingly high $^{6}Li/^{7}Li$ ratio in the early Galaxy, stimulated a large body of theoretical work (see Prantzos 2006b, and references therein) but remains controversial (Spite & Spite 2010, and references therein); the latter, combined to the well-known meteoritic ratio of $^{6}Li/^{7}Li$, constrains the late evolution of Li isotopes in the local region of the Galaxy.

On the theoretical side, Prantzos (2012) argued that GCR are accelerated mainly by the forward shocks of supernova explosions, propagating through the winds of massive stars and the