

## The evolution of the Light Elements, Be and B (also Li), in the Galaxy

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**Abstract** We consider the evolution of the light elements, especially beryllium and boron but also lithium, in the Galaxy as derived from observations within 1 kpc of the Sun. The interest in Li has much to do with the evaluation of the universal baryon abundance via primordial nucleosynthesis, but the difficulties of interpretation have led to the need to understand Li synthesis within the Galaxy, and this entails understanding many processes, both stellar and interstellar. In the case of Be, and B although measurable abundances produced in the primaeval fireball were predicted in certain models, these are largely (but not totally) discounted observationally. However understanding the evolution of Be and B as tracers of Galactic chemical evolution is important. While most experts in nucleosynthesis have concentrated on the linear relation between B/Be and Fe, (or O) in the Galactic halo, and taken disc evolution rather for granted, we show that it is vital to use a valid chemical evolution model for the disc to explain the observations. We present such a model, and emphasize its implications for the infall of low metallicity gas to the disc as the driving element in star formation during the whole disc lifetime.

**Key words:** Galaxy: Disc, Gas accretion, Evolution, Nuclear Reactions, Nucleosynthesis, Abundances

### 1 THE EVOLUTION OF LITHIUM IN THE GALACTIC DISC

The basic data set on which our understanding of the evolution of the Li abundance in the Galactic disc is based is that shown in Fig. 1, in which we present observations of the Li abundances measured in stars within 1 kpc of the Sun, as a function of metallicity represented by the iron abundance  $[\text{Fe}/\text{H}]$ . We can note three patterns of evolution here, as seen in the upper envelope of the diagram. Firstly at low metallicity, below  $[\text{Fe}/\text{H}] \sim -1.5$ , the envelope is virtually flat, with a lithium abundance of  $\log N(\text{Li}) = 2.2$  (where  $\log N(\text{H}) = 12$ ). This is the part of the diagram dominated by primordial lithium, as first suggested in the classical paper by Spite and Spite (1982). There are more data points recently acquired in this range, but we are not going to discuss this part of the diagram in great detail, so we will refer the reader to articles such as Ryan, Norris and Beers (1999) for an enhanced set of observations in this area. There have been observational studies of the fine details of this “Spite plateau”

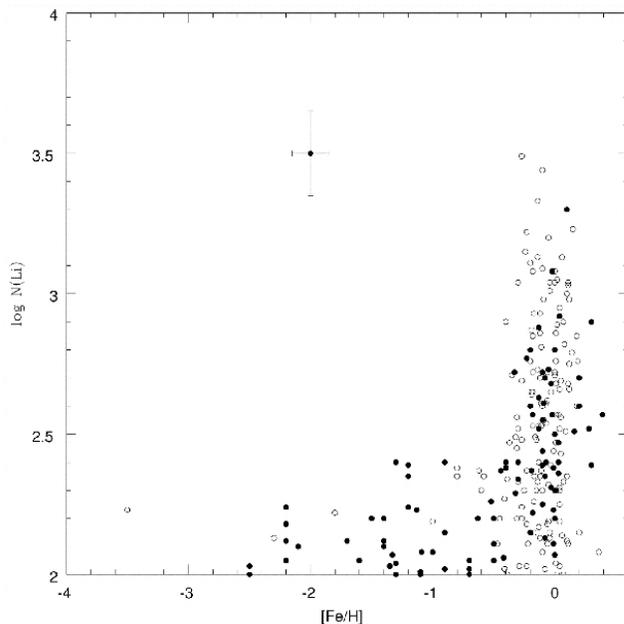
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Thorburn (1994), and some questions about whether or not the Li abundance quoted above represents a primordial value or is slightly depleted, but the consensus is that the abundance  $\log N(\text{Li}) = 2.2$  is close to the primordial value. From the point of view of the present article the important point is that the Galactic Li production rate in the halo epoch does not appear to be sufficient to make a significant contribution to the Spite plateau for metallicities below  $[\text{Fe}/\text{H}] = -2$ , and that there are tens of stellar observations of Li below this metallicity, sufficient to give a reliable observational value for the plateau (and hence the primordial) Li abundance.

The second part of the plot, in the range  $-1.5 \leq [\text{Fe}/\text{H}] \leq -0.5$  shows an upper envelope in Li at an abundance of  $\log N(\text{Li}) \sim 2.4$ , and we can consider this as being representative of the thick disc stellar population, while in the third part of the diagram, with  $\log N(\text{Li}) \geq -0.5$ , the upper envelope of the Li abundance plot shows a spectacular rise to values well over  $\log N(\text{Li}) = 3$ . We note that so far we have been referring exclusively to the upper envelope in the diagram. It is well known that depletion processes within stars tend to reduce their Li abundances, so that the points below the envelope are considered to be from stars which have depleted Li during their own lifetimes, while the points on the upper envelope are from stars with shallow convection zones, where depletion has been at a minimum. The presence of the  $^6\text{Li}$  isotope in some stellar atmospheres confirms that there are indeed stars where Li depletion is negligible, as  $^6\text{Li}$  is a much more fragile nuclide than  $^7\text{Li}$ . The result is that we can consider the upper envelope as representative of the Li abundance in the interstellar star forming gas at the epoch when the star with the given Fe abundance was formed.

There is still no firm agreement about the processes which dominate Li production in the Galactic disc, and in particular to what extent these are stellar or interstellar. In Casuso and Beckman (1997, 2000) we show that alpha+alpha production of both isotopes of Li via Galactic Cosmic Ray (GCR) processes in the interstellar medium is capable of yielding the observed variation of the Li abundance with metallicity (as measured via the O or Fe abundance). The argument is that the late onset of strong Li production implies processes based on a cumulative component of the Galactic disc. This rules out processes strongly dependent on star formation, such as those due to type II SNe, and for GCR processes is in agreement with reactions such as alpha+alpha which are caused by low energy cosmic rays. Discussion of the acceleration mechanisms is complex, but Fermi processes at the interfaces of stellar winds and the ISM accompany low and intermediate mass stars as well as high mass stars, and are therefore present throughout the galactic disc; they could be largely responsible for accelerating the He nuclei released also from low and intermediate mass stars (e.g. during the He flash) and thus providing the low energy GCR needed to produce Li. Alternatives entailing combined multiple mechanisms: novae, massive AGB stars and G stars as well as GCR production, have been suggested (Romano 1999). Although it is not possible to exclude a combination of processes as long as these are due to low and intermediate mass stars, (thus explaining the steepness of the envelope in Fig. 1) we believe that it may not be necessary to propose a substantial stellar contribution to the Galactic Li abundance. Interstellar production may well be sufficient. What is clear, however, is that the IS production mechanism cannot be identical with those for Be and B, because the form of their abundance curves vs.  $[\text{Fe}/\text{H}]$  or  $[\text{O}/\text{H}]$  is very different from that of Li, as we will see below. We have also emphasized that to explain the details of Fig.1 we must use an adequate overall chemical evolution model, a point which we will stress further in the section below on Be and B. Whatever the final answer to the Li production question, it is clear that the low metallicity plateau can be used to constrain cosmological models. It is also true that the presence of primordial Li, and the relatively modest growth of the Li abundance during the halo epoch makes Li a poor tracer of halo processes, since its abundance is masked by the primordial abundance until  $[\text{Fe}/\text{H}]$  reaches values of  $\sim -1$ . We will see that this is not the case for Be and B, which makes them useful for both halo and disc evolution diagnostics.

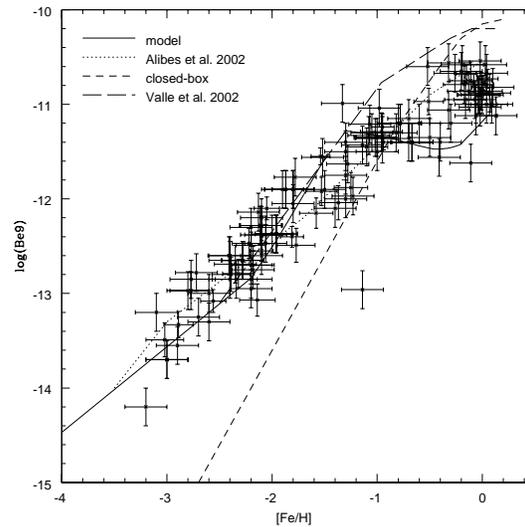


**Fig. 1** Compilation of Li abundances in local dwarf stars as a function of the iron abundance  $[\text{Fe}/\text{H}]$  ranging from metallicities close to solar down to halo values. The compilation is incomplete at the low metallicity end. For further references to low metallicity Li abundances see papers reference in text. As well as the “Spite plateau” at low metallicities, one can see an intermediate small plateau due to the thick disc population, and a very steep rise in the disc metallicity range. These are the features which models must explain. The wealth of points below the upper envelope are from stars with significant internal depletion. This figure is taken from Casuso and Beckman (2000).

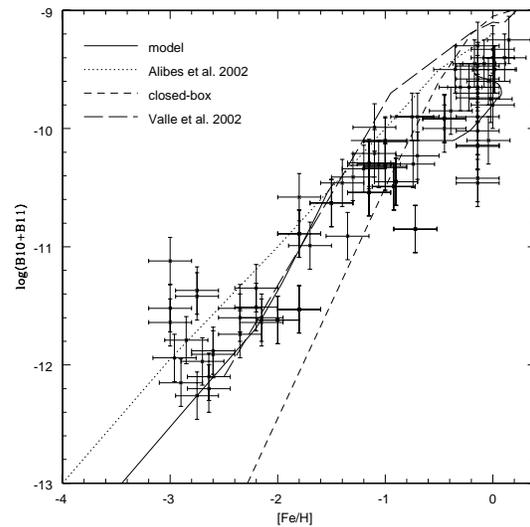
## 2 THE EVOLUTION OF BE AND B IN THE GALACTIC DISC (AND THE HALO)

As in the case of lithium, we base our discussion of the Be and B abundance distribution in the disc strictly on the observational evidence. This is presented in Figs. 2 and 3, where we have made an extensive compilation of observational data of Be and B as functions of  $[\text{Fe}/\text{H}]$  respectively. Both of these abundance-abundance distributions have similar structures. As for Li we first look at the halo distributions, i.e. at the ranges with  $[\text{Fe}/\text{H}] \leq -1.5$ . Here to first order there is a linear dependence of Be and B on Fe, clearer for Be, for which in any case we have many more data points. We can cite five publications in which modellers have explained the halo Be and B abundance distributions with reasonable success: Alibe’s et al. (2002), Fields et al. (2000), Parizot and Drury (?), Ramaty et al. (2000) and Valle et al. (2002). We give here figures from several of these papers to show that this part of the observational curve can be rather well reproduced, though with a number of different assumptions to explain the linear dependence, when simpler considerations would have suggested that as Be is a secondary element its abundance should bear a quadratic relation to that of Fe.

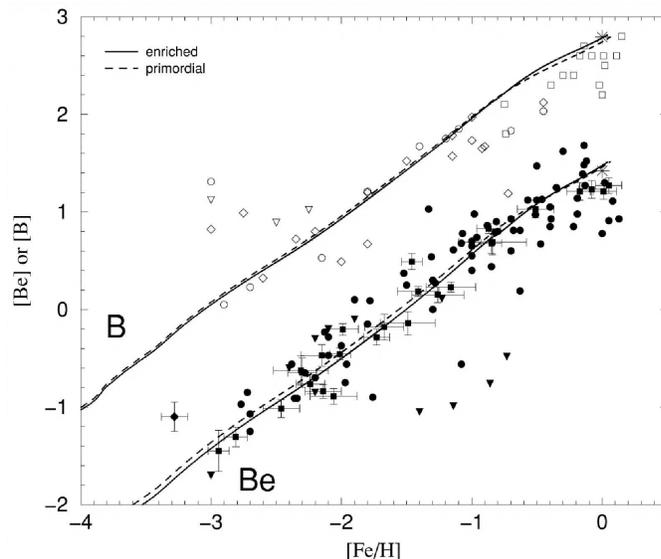
Figure 4 gives a nice looking fit to the plots of Be and B vs. Fe in the halo, but note that the predicted linear dependence continues on into the disc metallicity range, ( $[\text{Fe}/\text{H}] \geq -1.5$ ). Production of Be and B is interstellar, from GCR’s accelerated in the superbubbles produced by supernovae around hot stellar complexes. It is interesting to note that in this model the authors



**Fig. 2** Compilation of Be abundances in local dwarf stars as a function of the iron abundance  $[Fe/H]$ , ranging from metallicities close to solar down to halo values. The distribution can be considered in three parts: the halo, where there is a broadly linear relation between Be and Fe, the disc, where the distribution loops back in a two-valued curve, and an intermediate section where the thick disc is contributing. Modellers have paid most attention to the halo distribution, and taken it as given that this simply extrapolates to higher metallicities, which as can be seen is an inappropriate simplification. For the sources of data see Casuso and Beckman (2004) from which the figure is taken. Models are from the sources shown in the figure, and from Casuso and Beckman (1997).

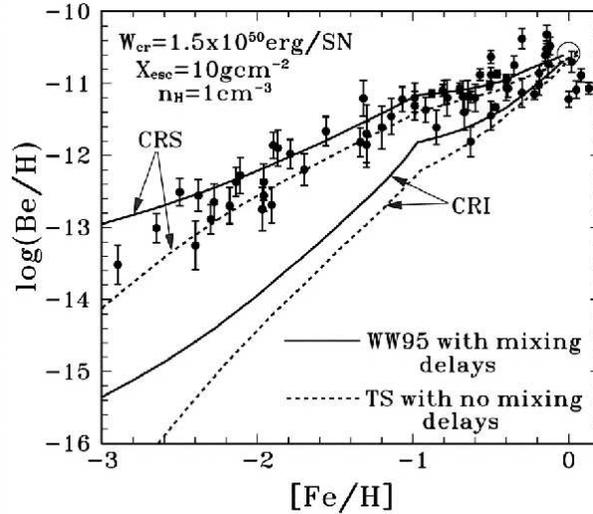


**Fig. 3** Compilation of B abundances in local dwarf stars as a function of the iron abundance  $[Fe/H]$ . The broad features of the distribution match those for Be in Fig. 2, though the scatter is larger, as the number statistics are much poorer. Even so it is clear that the halo and disc distributions do not form a curve with a single simple analytical form, as has been often assumed. For sources of data see Casuso and Beckman (2004) from which the figure is taken. Models are from sources shown in the figure, and from Casuso and Beckman (1997).



**Fig. 4** Model fits to observed metallicity distributions of Be and B in the Galaxy, covering the whole range of  $[\text{Fe}/\text{H}]$  (halo, thick disc, disc) taken from Alibé’s et al. (2002) where the details of the modelling assumptions can be found. The fits to the halo observations are quite satisfactory, but the selective disc data compilation and the log-log presentation (quite normal for these kinds of data) do not allow the modellers to do much more than extrapolate linearly from halo to disc, as has been the rule for much work in this area.

assume infall of metal poor, primordial gas during the halo phase, as part of the initial collapse of the Galaxy to form the spheroidal component. It is worth remarking that we (Casuso and Beckman (1997)) were able to explain the quasi linear halo Be-Fe and B-Fe dependences using only the assumption of gas flow during halo formation, independently of the precise mechanism for producing the B and Be. The model assumes that the halo stars formed in a spheroidal system in which gas flows to the centre, leaving the stellar population in orbits occupying a larger volume of space. This, from the stellar point of view, is an “outflow” model, but as emphasized by Edmunds (1989) outflow has very similar effects to inflow in terms of its effects on the metallicity frequency distribution of a stellar population, and of element-element distribution. In other words in an evolutionary model of the halo in which gas flow is correctly taken into account, it is not necessary to invoke particular production mechanisms for Be and B to explain their observed dependence on Fe, so the differences in the use of supernova injection of GCR’s presented by different authors as the answers to the observed halo linearity are not in fact of great importance, since the linearity is the result of gas flows. Nevertheless, as the mechanisms are of astrophysical interest we will outline some of these alternatives, to explain their bases. Ramaty et al. (2000) have Be and B produced exclusively within superbubbles, which are metal rich, so that their GCR production is automatically proportional to the abundance of O, from which they are produced by spallation. Assuming that O and Fe are themselves proportional Ramaty et al. then derive a linear dependence of Be and B on Fe. One of their plots is shown in Fig. 5 in which the observational points for Be vs.  $[\text{Fe}/\text{H}]$  are fitted with the results of a model in which the production of Be is due to cosmic rays with composition that of enriched material within a superbubble. Also compared are models in which cosmic ray composition is that of



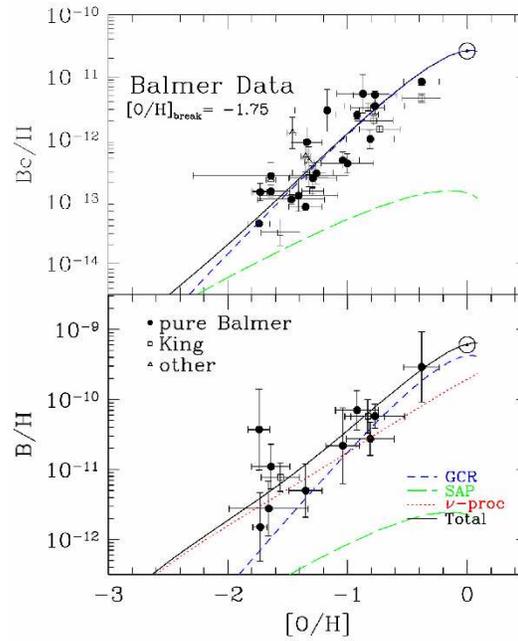
**Fig. 5** The abundance evolution of Be as a function of  $[\text{Fe}/\text{H}]$  from a series of models described in detail in Ramaty et al. (2000) from which this figure is taken. In the CRS models the galactic cosmic rays (GCR's) which produce the Be are produced, and act, entirely within the superbubbles around young star clusters; they come from supernova ejecta. CRI models are from GCR's produced in the average ISM. The nuclear physical assumptions about the Be production processes, their situations within the ISM, and their timing, are sophisticated. The CRI models yield fair agreement for the halo data, but the disc is less well modelled, and the data selection is incomplete.

the normal ISM, which as shown do not give fits approaching the data. We remark here that the halo is clearly well fitted, and that the disc Be appears to be fitted too, apart from a subset of points to the far right of the diagram. We will return to the disc later. For full details of the models the reader is of course referred to Ramaty et al. (2000).

Figure 6 is one of the diagrams in which Fields et al. (2000) explain the Be and B abundances as functions of metallicity in terms of models in which the two light elements are formed in GCR processes affected by superbubbles. They combine a fraction of GCRs with “normal” ISM composition with a further fraction having SB (superbubble) enriched composition, i.e a fraction of their production is secondary (proportional to  $\text{O}_2$ ) and a fraction is primary (proportion to O). In the diagram the B and Be are shown proportional to  $[\text{O}/\text{H}]$ , and Fields et al. derive a predicted dependence on  $[\text{Fe}/\text{H}]$  using as an established result the continued rise of  $[\text{O}/\text{Fe}]$  with falling metallicity within the halo as given by Israelian et al. (1998,2001). In Fig.6 there is a model curve falling well below the observations which is the prediction for production only by GCR's originating in superbubbles. It is notable that Ramaty et al. (2000) and Fields et al. (2000) come to very different conclusions about the origin of the cosmic rays producing the Be and B, and some of the difference is due to their evaluation of the results of  $[\text{O}/\text{Fe}]$  measurements in halo stars. These are still quite controversial; although the group of Israelian et al. support their conclusion that  $[\text{O}/\text{Fe}]$  rises monotonically in the halo to low abundances with considerable theoretical modelling, some workers dispute their conclusions, affirming that the results depend on the details of the modelling technique used as well as the depths in the stellar atmosphere of the lines used for the abundance determinations, i.e. their relative susceptibility to non-LTE effects.

Nissen et al. (2002) give a thorough appraisal of these effects, and apply their work to measurements of O/Fe based on VLT spectra, reaching the conclusion that  $[\text{O}/\text{Fe}]$  stops rising below  $[\text{Fe}/\text{H}] = -2.0$ . This work would tend to suggest that the “truth” about Be and B production in the halo lies somewhere between the Ramaty et al. (2000) and the Fields et al. (2000) models. However we must insist that the linearity of the data in the halo in Figs. 2 and 3 says more about gas flow in the halo than about specific GCR production mechanisms for Be and B. In this sense the bimodal predictions by Parizot and Drury (?) in which some of the Be and B are produced by isolated supernovae, surrounded by metal poor ISM, and some by supernovae in superbubbles, surrounded by metal rich ISM, while they may in fact be valid, are not required to explain the linearity in the low metallicity portion of Figs. 2 and 3, and as such will be very difficult to test. In fact of the authors cited above, only Valle et al. (2002) recognize that unless one incorporates one’s production process for the light elements into a suitable evolutionary model for the Galaxy, discrepancies between observations and models are not very meaningful. In their paper they produce such model predictions for Li, Be and B, in the halo and the disc, and we show those for Be and B in Figs. 7 and 8. It is a tribute to the honesty of their presentation that their fits to the halo data are fair, while their fits to the data at higher metallicity are moderate to poor as the metallicity increases to near solar. They do include model estimates of both thick and normal disc contributions, and show clearly that closed box models are invalid both in the disc and the halo, and they do show in more detail that the previously cited authors in this section, the data set which they are modelling, at least in the case of B, although for Be their data set is a sparse subset of the observations available in the literature. (They also model the Li vs.  $[\text{Fe}/\text{H}]$  observations with model predictions, achieving a good fit to the halo data in the Spite plateau but not to the disc observations).

It is important to point out a rather trivial aspect of the presentation of the Be and B evolution observations which in spite of its purely formal nature has led modellers into a set of inadequate predictions. It is perfectly normal to present element vs. element abundance plots in a log-log plane, for the obvious reason that this is the only way to take in a large dynamic range in the abundances, and in one diagram to cover the whole range of stellar metallicities. In most work of this kind the diagrams in practice do not take in metallicities much lower than  $[\text{Fe}/\text{H}] = -2$ , or in articles dedicated mainly to chemical evolution in the halo the diagram might take in metallicities only lower than  $[\text{Fe}/\text{H}] = 1.5$ , down to say  $-3$ . However as we can see in the Figures presented in this article, in dealing with light element evolution the authors normally present a full data set going from solar metallicity down to well below  $[\text{Fe}/\text{H}] = -3$ . If we look at any of the figures in the present section, from Fig. 2 to Fig. 8, we can see that the major portion of these figures is occupied by the metallicity range from  $-3.5$  to  $-1.5$ , which represents two orders of magnitude, and refers basically to the halo, with some contribution from the thick disc in the upper part of the range. In the figures, the halo production curve, which is quasi-linear, is dominant, and in any case most of the authors cited were more interested in the halo as the halo production of Be and B might give way at the lowest metallicities, to Big Bang production, which was suggested by a number of authors in the eighties, (see e.g. Malaney and Fowler (1989)). This has led the modellers to skim rather lightly over the disc observations, as seen by the data presented in Figs. 4 through 8 (though Valle et al. (2002) do a rather better job than the other cited authors). They are given as a quasi-linear prolongation of the halo data, but as we see in Fig. 2 if the fullest available data sets are used, this extrapolation is seen not to be justified. To be more quantitative, if the highest measured abundances of Be or B are assigned scaled values of unity, the complete contribution of the halo production of these elements takes the abundances from  $\sim 5 \times 10^{-4}$  to 0.1 in other words only 10% of the Be or B production in the Galaxy took place in the halo, while the remaining 90% was produced within the disc, some 10% in the thick disc epoch, and the remaining 80% in the normal disc epoch.

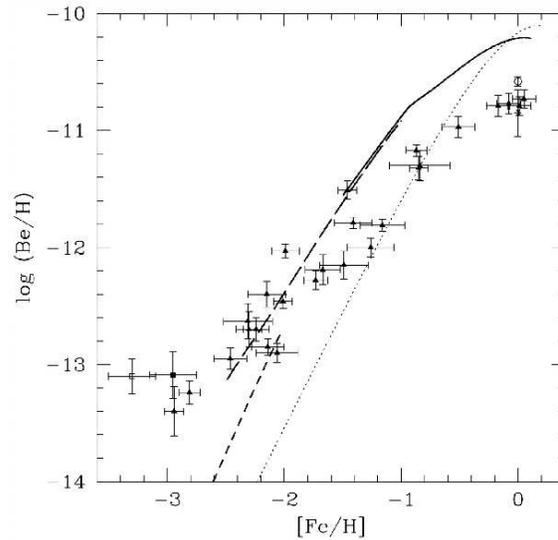


**Fig. 6** The abundance evolution of Be (upper panel) and B (lower panel) presented against  $[O/H]$  representing metallicity, from Fields et al. (2000) where the details of the models can be found. In contrast to the predictions of Ramaty et al. (2000) the best fits are obtained using GCR's produced in the general ISM (curves labelled GCR) rather than those with the composition found from supernova ejecta (SAP). One reason for this is that Fields et al. take the O/Fe ratio to rise continuously to low metallicities, following Israelian et al. (1998,2001); O spallation is a key source of Be and B. This behaviour of O/Fe is not accepted by all workers (see Nissen et al. (2002)). We show in this article that without a careful Galactic evolution model the data do not allow us to distinguish Be and B production modes in this way. Note rather sparse data selections here, notably in the disc metallicity range (which was not the objective of Fields et al.).

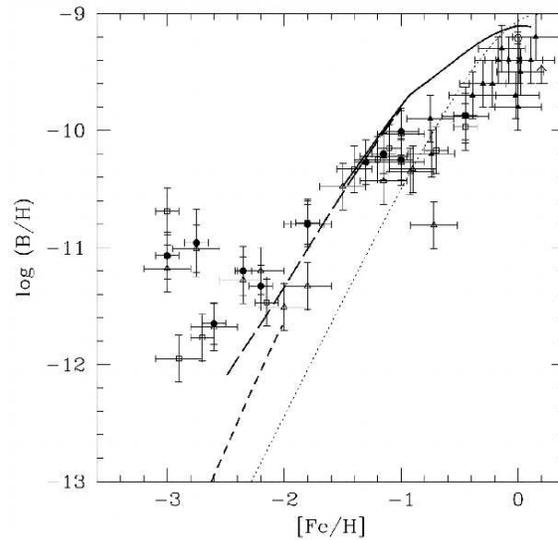
The impact of the log-log representation is to devalue these ratios completely. This is one of the reasons why adequate models for Be and B evolution in the disc have not been addressed in the articles cited, with the exception of Valle et al. (2002). These authors recognize, and stress the importance of a correct evolutionary model when trying to interpret the Be and B data, but are locked in to the convention that gaseous infall must be declining with time in the disc epoch, so their models do not give a realistic account of the observations, as they themselves note.

### 3 CONCLUSIONS: CHEMICAL EVOLUTION OF THE DISC

For a full account of the detailed modelling process from which we derived the good model fits to the disc evolution of Be and B, as shown in Figs. 2 and 3, the reader is referred to Casuso and Beckman (1997). It is interesting to note that these models were developed in the first place not to explain the Be and B data, but to account for the general metallicity distribution of late-type dwarfs in the solar neighbourhood. In Casuso and Beckman (2004) we explain how these models, in which the secular infall of low metallicity (not necessarily primordial) gas to the Galactic disc has to be held virtually constant over periods of Gyrs, (though with



**Fig. 7** The Be abundance vs.  $[\text{Fe}/\text{H}]$  modelled by Valle et al. (2002), from which this figure is taken. The authors have employed a complete Galactic evolution model, with different forms of the contribution in the halo (thick short dashed line) thick disc (thick long dashed line) and “normal” disc (continuous solid line) as well as a closed box model (dotted lines) for comparison. In spite of this their fit to the disc distribution in particular is not very good. We attribute this to the fact that they have not used an infall model which gives a satisfactory account of the G-dwarf metallicity distribution, i.e. with a flat or increasing infall rate with time. We note also that their data set is quite sparse, especially in the disc, compared to what is available in the literature, (see Fig.2).



**Fig. 8** The B abundance vs.  $[\text{Fe}/\text{H}]$  modelled by Valle et al. (2002) from which his figure is taken. Curve style descriptions as in Fig.7. The authors have used a significantly more complete data set for B than for Be (cf. Fig 3 above), and this shows up even more clearly the discrepancy between their model and the data in the disc, a discrepancy which we have been able to remove using our specific infall model (see Casuso & Beckman 1997,2004).

evidence for major shorter term fluctuations) throughout the disc lifetime, and with a slight tendency for the infall rate to grow with time, gives a good explanation of the peaked metallicity distribution for local G-dwarfs. However this was a “post-diction” as the model was derived on the basis of existing data. When comparing its results with recent observations of K-dwarfs, mostly published after the model appeared (Casuso and Beckman (2001)), agreement between model predictions and data was even better! The slow rise in gaseous infall rate gives rise to a suitably narrow peak in the distribution, in good agreement to that observed. It is a virtue of this model that it accounts very nicely indeed for the distribution of the Be vs. [Fe/H] and B vs. [Fe/H] distributions in the disc metallicity range, as shown in Figs. 2 and 3. The halo “outflow” model, giving rise to the quasi-linear behaviour at low metallicities in Figs. 2 and 3 was presented some time ago (Casuso and Beckman (1997)) when this dependence was first detected. Over the full metallicity range the relation between light element abundance and general metallicity (whether represented by the Fe or the O abundance) depends more on the ambient model than on the precise processes by which Be and B are produced. However none of this work puts in question that Be and B are produced in the ISM by processes involving Galactic cosmic rays, or that Li production in the disc must be dominated by processes which are different in type from those producing Be and B, whether they be purely interstellar, largely stellar, or a combination of both. A purely observational separation is sufficient to isolate and identify the cosmological Li contribution, and similar work at the lowest metallicities might eventually show whether there has been measurable Big Bang production of Be and B, though at much lower “plateau” levels than for Li.

**Acknowledgements** This work has been partly supported by grant AYA2001-0435 from the Spanish Ministry of Science and Technology, and by project P3/86 of the Instituto de Astrofísica de Canarias.

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