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Cosmic Ray Production of ^{6}Li by Virialisation Shocks in the Early Milky Way

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Abstract: The energy dissipated by virialisation shocks during hierarchical structure formation of the Galaxy can exceed that injected by concomitant supernova (SN) explosions. Cosmic rays (CRs) accelerated by such shocks may therefore dominate over SNe in the production of ^{6}Li through $\alpha+\alpha$ fusion without co-producing Be and B. This process can give a more natural account of the observed ^{6}Li abundance in metal-poor stars compared to standard SN CR scenarios. Future searches for correlations between the ^{6}Li abundance and the kinematic properties of halo stars may constitute an important probe of how the Galaxy and its halo formed. Furthermore, ^{6}Li may offer interesting clues to some fundamental but currently unresolved issues in cosmology and structure formation on sub-galactic scales.

Keywords: cosmic rays — Galaxy: formation — Galaxy: halo — Galaxy: kinematics and dynamics — nuclear reactions, nucleosynthesis — stars: abundances

1 Introduction

Apart from ^{7}Li, the bulk of the light elements Li, Be, and B are believed to arise from nonthermal nuclear reactions induced by cosmic rays (CRs) (Meneguzzi et al. 1971). In the last decade, extensive observations of LiBeB in population II, metal-poor halo stars (MPHSs) have turned up new and unexpected results, spurring controversy as to what type of CR sources and production mechanisms were operating in the halo of the early, forming Galaxy (e.g. Vangioni-Flam et al. 2000). To date, most models of light element evolution in the early Galaxy have focussed on strong shocks driven by supernovae (SNe) as the principal sources of CRs. A general consensus is that Be and B in MPHSs mainly originate from the 'inverse' spallation process, whereby CR CNO particles are transformed in flight into LiBeB by impinging on interstellar medium (ISM) H or He atoms (Duncan et al. 1992). This can be realised if a sizable fraction of the CRs responsible for spallation comprise fresh, CNO-rich SN ejecta (e.g. Vangioni-Flam et al. 2000; Ramaty et al. 2000; Suzuki et al. 1999; Suzuki & Yoshii 2001, hereafter SY), as opposed to CRs injected from the average ISM (e.g. Fields & Olive 1999).

The origin of ^{6}Li in MPHSs (Hobbs 2000, and references therein) is more mysterious, as current models involving SN CRs face some difficulties. A peculiar aspect of Li is that in addition to spallation, the fusion process of CR α particles with ambient He atoms can be effective, and should actually dominate Li production at low metallicities. (Note that while both ^{7}Li and ^{6}Li are synthesised in comparable amounts, the CR-produced ^{7}Li component is generally overwhelmed by the 'Spite plateau' from primordial nucleosynthesis in the metallicity range under consideration, e.g. Ryan et al. 2001.) If the CR energy spectrum is taken to be a standard power-law distribution in momentum (Section 3), one requires a CR injection efficiency much higher than normally inferred to reproduce the ^{6}Li observations, whether the CR composition is metal-enriched or not (Ramaty et al. 2000; SY, see their Figure 2). This raises the question of whether there may have been other sources of ^{6}Li.

Suzuki & Inoue (2002, hereafter SI) proposed a new and more natural ^{6}Li production scenario based on a previously unconsidered CR source: CRs accelerated at virialisation shocks (VSs), i.e. shocks driven by the gravitational infall and merging of sub-Galactic gas clumps during the hierarchical build-up of structure in the early Galaxy. Such shocks are inevitable consequences in the currently standard theory of hierarchical structure formation (see, however, Section 5). We further discuss a number of testable predictions and important implications expected in our scenario for understanding the formation of our Galaxy. The potential relevance to some fundamental issues in cosmology and structure formation on sub-galactic scales is also mentioned.

2 Cosmic Ray Sources in the Early Galaxy

SNe are known to release $E_{SN} \sim 10^{51}$ erg of kinetic energy in each explosion, driving strong shocks into the ambient medium. These SN shocks are favourable sites for efficient CR acceleration through the first-order Fermi mechanism. A plausible value for the injection efficiency ξ_{SN}, i.e. the

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fraction of the SN kinetic energy imparted to CRs, is 10–20%, deduced from comparison of the SN rate and the energy content of CRs currently observed in the Galactic disk. The global energetics of SNe for the early Galactic halo can be estimated from the cosmic star formation history or the total amount of heavy elements ejected by halo SNe (see SI for details of the estimation). Both methods give $\epsilon_{\rm SN} \sim \mathcal{E}_{\rm SN}\mu m_{\rm p}/M_{\rm g} \simeq 0.15$ keV per particle as the average specific energy input from SNe.

SNe are not the only sources of mechanical energy (and hence CRs through shock acceleration) that may have been active in the early Galaxy. In the framework of the currently successful picture of hierarchical structure formation in the Universe, large scale objects are formed through the merging and virialisation of smaller subsystems, driven by gravitational forces acting on the dark matter. For each merging hierarchy, shocks should inevitably arise in the associated baryonic gas component, whereby the kinetic energy of infall is dissipated and the gas heated to the virial temperature of the merged halo (e.g. White & Rees 1978). It is quite plausible that such VSs also accelerate CRs (e.g. Miniati et al. 2001).

A guide to how structure formation may have proceeded in our Galaxy, particularly the Galactic halo, may be offered by the recent numerical simulations of Galaxy formation by Bekki & Chiba (2001, hereafter BC; see also Samland & Gerhard 2003; Abadi et al. 2003). It is expected that sub-Galactic structures eventually merge into a single entity in the central region at redshift $z \sim 2$, whereby the majority of the infall kinetic energy is virialised. The total energy dissipated at this main VS can be evaluated from the virial temperature of the merged system. The virial temperature $T_{\rm v}$ for a halo of total mass $M_{\rm t}$ virialising at redshift $z \sim 2$ is $k_{\rm B}T_{\rm v} = \mu m_{\rm p} G M_{\rm t}/2r_{\rm v} \simeq 0.26\,{\rm keV}(M_{\rm t}/3\times 10^{12}\,{\rm M}_\odot)^{2/3}$, where $r_{\rm v}$ is the virial radius, and we have assumed a cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$ (see SI). The specific energy dissipated at the VS is thus $\epsilon_{\rm VS} \sim 3k_{\rm B}T_{\rm v}/2 \simeq 0.4$ keV per particle, higher than the above estimate for SNe by a factor of $\simeq$2.6, if we adopt $M_{\rm t} = 3 \times 10^{12}\,{\rm M}_\odot$ (Sakamoto et al. 2003). The CR contribution from VSs compared to SNe should similarly be higher, as the CR injection efficiency $\xi_{\rm VS}$ should not be too different from that for SNe (Miniati et al. 2001). CRs accelerated by VSs should therefore be at least as important as SN CRs, and may well dominate at early epochs.

Another more speculative but potentially interesting possibility is outflows powered by a massive black hole(s), which may have been active in the early Galaxy. However, there are numerous ambiguities with such a picture, and here we will concentrate on CRs from VSs and SNe (see SI for further discussion).

3 Model

We employ assumptions and parameters deemed most plausible for the SN CRs. The CR injection efficiency is taken to be $\xi_{\rm SN} = 0.15$ for each SN of kinetic energy $E_{\rm SN} = 10^{51}$ erg. A standard, single power-law distribution in particle momentum is adopted for the CR spectrum (see SI). The injection spectral index is chosen to be $\gamma_{\rm SN} = 2.1$, appropriate for strong SN shocks, and consistent with the source spectrum inferred for present-day CRs. As assumed in SY, the composition of SN CRs is a mixture of SN ejecta containing freshly synthesised CNO and Fe and the ambient ISM swept up by the SN blastwave.

CRs from VSs are markedly different from SN CRs in a number of important ways. First and foremost, VSs do not synthesise fresh CNO nor Fe, so that the composition of these CRs is completely ascertained by the pre-existing ISM. When the ISM is metal-poor, these shocks induce very little Be or B production through inverse spallation, and are only efficient at spawning Li via α–α fusion. Second, VSs are not necessarily strong ones, particularly for major mergers of systems with comparable masses (Miniati et al. 2001), provided that the pre-shock gas has not cooled significantly. Shock acceleration should then lead to injection indices $\gamma_{\rm VS}$ steeper than the strong shock limit value of 2, which works in favour of Li production (Section 4). Major merger shocks may possess Mach numbers as low as $\simeq$2–3, corresponding to $\gamma_{\rm VS} \simeq 2.5$–3.3; $\gamma_{\rm VS} = 3$ is generally chosen below. As with SN CRs, we take the spectral shape to be a momentum power-law distribution and the injection efficiency to be $\xi_{\rm VS} = 0.15$.

A further distinction from SNe is that the VS CR flux should not entail any direct dependence on the metallicity, which is in fact an obstacle to predictive modelling. While the hierarchical growth of structure with respect to cosmic time may be evaluated in concrete ways using, for example, extended Press–Schechter formalisms, relating this to [Fe/H] requires additional knowledge of how the combination of star formation, SN nucleosynthesis, and chemical evolution in our Galaxy proceeded with cosmic time. This involves large uncertainties, and is not specified in our chemical evolution model. As a first step, we choose to describe the time evolution of VS CRs in a simple, parameterised way, assuming a 'step function' behaviour: VS CRs begin to be injected from a certain time $t_{\rm VS}$, maintain a constant flux for a duration $\tau_{\rm VS}$, and then return to zero. We take the injection duration $\tau_{\rm VS}$ to be roughly the dynamical time of the major merger, $\simeq 3 \times 10^8$ yr. The injection is also assumed to be uniform, since the effect of the main VS should be global throughout the gas under consideration, unlike SNe. The injected VS CR flux integrated over $\tau_{\rm VS}$ is normalised to the above values for $\xi_{\rm VS}$ and $\epsilon_{\rm VS}$. The true evolutionary behaviour of VS activity relative to metallicity should actually be probed through future observations of ^{6}Li at low [Fe/H] (Sections 4 and 5).

After injection by either SNe or VSs, the spectral flux $F_i(E, t)$ for each CR element i evolves with time during subsequent interstellar propagation. This is obtained from time-dependent solutions of the CR transport equation for a leaky box propagation model (SY). Using the transported spectra, we calculate the CR production of LiBeB in the ISM including all three types of reactions: forward spallation of ISM CNO by CR protons and αs, inverse spallation of CR CNOs by ISM H and He, and the

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fusion of CR α with ISM He. For more details, consult SY. We do not consider here the potentially complicating effects of stellar depletion, which are highly uncertain at the moment.

4 Results

For our calculations, we have selected the following sets of parameters for t_{VS}, τ_{VS}, and γ_{VS}, respectively, labelled models I–IV: I (0.22, 0.1, 3), II (0.22, 0.1, 2), III (0.32, 0.1, 3), and IV (0.1, 0.5, 3), where t_{VS} and τ_{VS} are in units of Gyr. These were chosen to provide results exemplary of light element production by VS CRs, in contradistinction to that by SN CRs. The evolution of ^{6}Li and Be versus metallicity calculated for each model until the end of halo chemical evolution ([Fe/H] $\simeq -1.5$) is shown in Figure 1, along with the current observational data in MPHSs.

We discuss some salient points regarding these results. First, it is confirmed that with our fiducial parameters, production by SN CRs alone (dashed) works very well for the observed Be (and B, not shown), yet falls short of the observed ^{6}Li. In contrast, with reasonable values for ϵ_{VS}, ξ_{VS}, and γ_{VS}, production by VS CRs is capable of explaining the current ^{6}Li data quite adequately. This is mainly due to two facts: (a) VSs are more energetic than (or at least as energetic as) SN shocks, as estimated in Section 2, and (b) VS CRs can generate ^{6}Li at early epochs independently of the metallicity. Regardless of the early evolutionary behaviour, identical ^{6}Li abundances are attained at the end of the halo phase for a given γ_{VS} (I, III, & IV), since this is determined by the time-integrated CR flux, for which we had assumed a fixed value. Compared to a flat spectral index of $\gamma_{VS} = 2$ (II), a steeper one of $\gamma_{VS} = 3$, more appropriate for low Mach number VS shocks (Section 3), results in a larger ^{6}Li yield, by about a factor of three. This is because with a constant total CR energy, a steeper index implies a larger CR flux in the subrelativistic energy range $E \sim 10$–100 MeV, where the ^{6}Li production cross-section peaks (see Figure 1 in SY). Note that a conservatively lower specific energy for VSs, $\epsilon_{VS} \sim 0.15$ keV/particle (i.e. comparable to SNe), can still be consistent with the available ^{6}Li data provided that $\gamma_{VS} \simeq 3$.

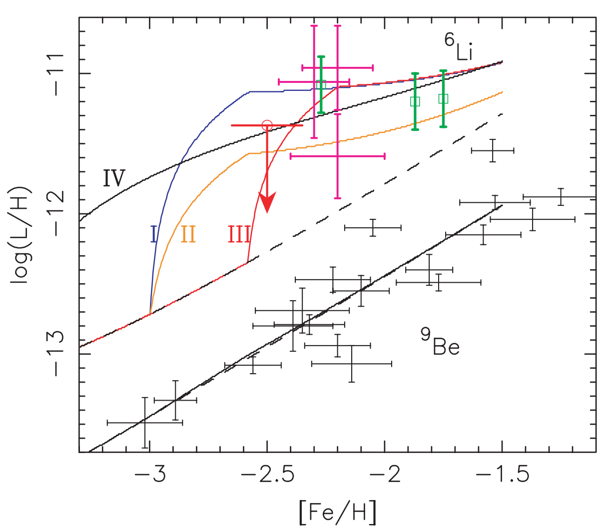

Figure 1 Model results of ^{6}Li/H (thick) and Be/H (thin) versus [Fe/H], for SN CRs only (dashed curves) and SN plus VS CRs (solid curves), each label corresponding to the parameter set described in the text. Also plotted are current observational data for ^{6}Li (thick crosses from Smith et al. 1998 and Nissen et al. 2000; squares with errors from Asplund et al. 2001; circle with upper limit from Aoki et al. 2004) and Be (thin crosses from Boesgaard et al. 1999).

As already stressed, case (b) is a consequence of ^{6}Li synthesis being dominated by α–α fusion, and VSs not creating any new Fe. Depending on the onset time and duration of the VS, the ^{6}Li abundance may potentially reach large values quickly at very low metallicity, which can be followed by a plateau or a very slow rise. On the other hand, SNe unavoidably produce freshly synthesised Fe, so a correlation with Fe/H must arise; in fact ^{6}Li/H versus Fe/H for SN CRs can never be much flatter than linear (e.g. Ramaty et al. 2000). Moreover, since VSs do not eject fresh CNO, they produce very little Be or B through spallation; only a minuscule contribution can appear as the ISM becomes metal-enriched. This may allow an extremely large ^{6}Li/Be ratio at low [Fe/H]. Conversely, we see that SN CRs must play an indispensable role in generating the Be and B observed in MPHSs.

Independent of the particular evolutionary parameters, the following abundance trends are characteristic of VS CR production and should serve as distinguishing properties of the scenario for future observations — going from high to low metallicity: a plateau or a very slow decrease in log ^{6}Li/H versus [Fe/H], followed by a steeper decline in some range of [Fe/H] corresponding to the main epoch of VS; a steady increase in ^{6}Li/Be, possibly up to values exceeding $\simeq$100, also followed by a downturn. These traits are very distinctive and are not expected in SN CR models, for which the slope of log ^{6}Li/H–[Fe/H] must be $\simeq$1 or greater, and the ^{6}Li/Be ratio constant at sufficiently low [Fe/H]. Distinctions from any production processes in the early Universe (e.g. Jedamzik 2000) should also be straightforward, as they predict a true plateau down to the lowest [Fe/H], in contrast to an eventual decrease for VS CR models. Further, unique diagnostic features are discussed in Section 5.

5 ^{6}Li as a Fossil Record of Dissipative Processes during Galaxy Formation

A truly unique and intriguing aspect of the VS CR picture is that ^{6}Li in MPHSs can be interpreted and utilised as a fossil record of dissipative gas dynamical processes in the early Galaxy. Of particular interest are various correlations expected between the ^{6}Li abundance and the kinematic properties of the stars. On the one hand, ^{6}Li arises as a consequence of gaseous dissipation through gravitationally driven shocks, and survives to this day as signatures of the dynamical history of hierarchical structure formation in the early Galaxy. On the other hand, the kinematic characteristics of stars presently observed should reflect the past dynamical state of their parent gas systems, because,

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once stars form, they become collisionless and have long timescales for phase space mixing (e.g. Chiba & Beers 2000). Interesting relationships may then exist among the two observables.

For example, recent intensive studies of the structure and kinematics of MPHSs in our Galaxy based on *Hipparcos* data (Chiba & Beers 2000) have elucidated the detailed characteristics of our Galaxy's halo, such as its two-component nature: an inner halo which is flattened and rotating, and an outer halo which is spherical and non-rotating. This dichotomy has been suggested to result from differences in the physical processes responsible for their formation, dissipative gas dynamics being crucial for the former, and dissipationless stellar dynamics determining the latter. The numerical simulations of Galaxy formation by BC support this conjecture: the outer halo forms through dissipationless merging of small sub-Galactic clumps that have already turned into stars (cf. Searle & Zinn 1978), whereas the inner halo mainly forms through dissipative merging and accretion of larger clumps that are still gas-rich (cf. Eggen et al. 1962). In our scenario, ^{6}Li production is a direct outcome of the principal gas dissipation mechanism of gravitational shock heating. If the above inferences on the formation of halo structure are correct, ^{6}Li should be systematically more abundant in stars belonging to the inner halo compared to those of the outer halo, a clearly testable prediction. An important prospect is that ^{6}Li may provide a quantitative measure of the effectiveness of gas dynamical processes during formation of halo structure, rather than just the qualitative deductions allowed by kinematic studies.

Another possibility concerns the main epoch of VSs with respect to metallicity (Section 3). As already mentioned, the relation between ^{6}Li/H and Fe/H should mirror the time evolution of dissipative energy release through VSs, but is complicated by being convolved with the uncertain ingredients of star formation and chemical evolution. The Fe abundance can be a poor tracer of time, especially at low [Fe/H] where the effects of dispersion in SN yields can be extremely large (SY). Stellar kinematics information may offer a handle on this problem. The observed relation between [Fe/H] and $\langle V_\phi \rangle$, the mean azimuthal rotation velocity of MPHSs, seems to manifest a distinctive kink around [Fe/H] ~ -2 (Chiba & Beers 2000). Through chemodynamical modelling of the early Galaxy, BC have proposed that this kink may correspond to the epoch of the major merger (Section 3). If this were true, a simple expectation in the context of the VS CR model is that ^{6}Li/H should be just rising near this value of [Fe/H], which is the range occupied by the currently ^{6}Li-detected stars; also expected are a steep decline at lower [Fe/H], as well as a plateau or slow rise at higher [Fe/H] (i.e. close to model III in Figure 1). However, any inferences related to [Fe/H] are always subject to the chemical evolution ambiguities. A more reliable and quantitative answer may be achieved by looking for correlations between ^{6}Li/H and $\langle V_\phi \rangle$ without recourse to [Fe/H], as ^{6}Li is a direct and pure indicator of dynamical evolution in the early Galaxy.

Thus the VS CR model for ^{6}Li bears important implications for understanding how our Galaxy formed. If the above-mentioned trends are indeed observed, it would not only confirm the VS origin of ^{6}Li, but may potentially point to new studies of '^{6}Li Galactic archaeology', whereby extensive observations of ^{6}Li in MPHSs coupled with detailed chemodynamical models can be exploited as a robust and clear-cut probe of dissipative dynamical processes that were essential for the formation of the Galaxy.

Furthermore, ^{6}Li in Galactic MPHSs may potentially offer interesting clues to a number of outstanding current problems in cosmology and structure formation theory, all involving physics on sub-galactic scales. (1) The global importance of dynamical feedback by SNe has been a long-standing uncertainty in galaxy formation theory (White & Rees 1978; Abadi et al. 2003). Further observations of ^{6}Li versus Fe or possibly Be and B at low metallicity and comparison with detailed theoretical models may constrain this crucial unknown. (2) The efficiency and location of VSs as commonly assumed on sub-galactic scales has recently been brought into question (Katz et al. 2003; Birnboim & Dekel 2003), with radical implications for how stars and galaxies form and how the galaxy luminosity function is shaped (Binney 2004). The early evolution of ^{6}Li may provide a direct probe of this presently speculative but important suggestion. (3) Comparison of theoretical simulations with observations of dwarf galaxy cores and of satellite galaxies of our Galaxy and within the Local Group indicate that standard cold dark matter (CDM) produces much more substructure than is actually seen. This 'CDM crisis' may point to non-standard dark matter properties, such as warm dark matter, self-interacting dark matter, or even more exotic proposals (e.g. Ostriker & Steinhardt 2003; Madau & Kuhlen 2003). On the other hand, the apparent discrepancy may be the result of strong feedback by SNe or a UV background. These different possibilities should result in differences in the early evolution of ^{6}Li, potentially constituting a unique probe. (4) From a combined analysis of measurements of cosmic microwave background anisotropies by *WMAP* and of the power spectrum on galactic and sub-galactic scales, it has been suggested that the spectrum of primordial density fluctuations deviates from a standard, single power law (Spergel et al. 2003). Although less drastic than non-standard dark matter, this would also modify the growth of structure on sub-galactic scales (Madau & Kuhlen 2003), and the consequent ^{6}Li production at early epochs. More detailed investigations of these intriguing prospects are certainly necessary, but in principle, ^{6}Li in our Galactic halo may shed light on these issues of paramount importance for cosmology and the physics of the early Universe.

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