JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
37: 447 ~ 454, 2004

COSMIC RAYS AND GAMMA-RAYS IN LARGE-SCALE STRUCTURE

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ABSTRACT

During the hierarchical formation of large scale structure in the universe, the progressive collapse and merging of dark matter should inevitably drive shocks into the gas, with nonthermal particle acceleration as a natural consequence. Two topics in this regard are discussed, emphasizing what important things nonthermal phenomena may tell us about the structure formation (SF) process itself. 1. Inverse Compton gamma-rays from large scale SF shocks and non-gravitational effects, and the implications for probing the warm-hot intergalactic medium. We utilize a semi-analytic approach based on Monte Carlo merger trees that treats both merger and accretion shocks self-consistently. 2. Production of ^{6}Li by cosmic rays from SF shocks in the early Galaxy, and the implications for probing Galaxy formation and uncertain physics on sub-Galactic scales. Our new observations of metal-poor halo stars with the Subaru High Dispersion Spectrograph are highlighted.

Key words : cosmic rays – cosmology: theory – galaxy: formation – gamma-rays: theory – intergalactic medium – stars: abundances

I. INTRODUCTION

In the standard picture of hierarchical structure formation in the universe, shock heating of baryonic gas associated with the gravitational merging and virialization of dark matter halos is an inevitable process during the formation of large scale structure such as galaxies, groups and clusters (e.g. Sunyaev & Zeldovich 1972, Rees & Ostriker 1977). Such structure formation (SF) shocks should also naturally accelerate nonthermal electrons and protons/ions with potentially important radiative and dynamical consequences, which was a central theme of this conference. Besides being interesting from a high energy astrophysics perspective, nonthermal phenomena induced by SF shocks may also provide us with important information on how structure formation and evolution proceeded in the universe, in a way complementary to the better-studied thermal phenomena. From this viewpoint, we discuss here two topics. 1. Inverse Compton gamma-rays from large scale SF shocks and the connection with the warm-hot intergalactic medium, employing a self-consistent semi-analytic approach based on Monte Carlo merger trees. 2. Production of ^{6}Li by SF cosmic rays during Galaxy formation, in relation to the results of the latest observations of metal-poor halo stars by telescopes such as Subaru and VLT.

Proceedings of The 3rd Korean Astrophysics Workshop on *Cosmic Rays and Magnetic Fields in Large Scale Structure*

II. INVERSE COMPTON GAMMA-RAYS FROM STRUCTURE FORMATION SHOCKS AND THE WARM-HOT INTERGALACTIC MEDIUM

The majority of the baryons in the universe today are believed to reside in a warm-hot intergalactic medium (WHIM) at temperatures $T \sim 10^5 - 10^7$ K, as a result of shock heating during the hierarchical buildup of large scale structure in the universe (Cen & Ostriker 1999, Davé et al. 2001). They are often referred to as 'missing baryons', since direct observational proof of their existence is still lacking (or at best very tentative), hampered by heavy Galactic obscuration in the relevant extreme UV to soft X-ray bands. Current indirect estimates of the cosmic fraction of baryons in the WHIM f_{WH} range from ~20 to ~40 % (Fukigita, Hogan & Peebles 1998, Fukugita & Peebles 2004). In view of the importance of understanding this fundamental component of the universe, dedicated satellite missions such as the *Diffuse Intergalactic Oxygen Surveyor* (Ohashi et al. 2004) or the *Missing Baryon Explorer* (Fang et al. 2003) are being planned to detect emission lines from the WHIM and constrain f_{WH}.

On the other hand, the same large scale structure formation (SF) shocks that create the WHIM may give rise to GeV-TeV gamma-ray emission through nonthermal electron acceleration and inverse Compton upscattering of the cosmic microwave background. Such gamma-rays may be observable either as a contribution to the cosmic gamma-ray background (CGB; Loeb & Waxman 2000) or as individual sources (Totani & Kitayama 2000). This interesting possibility has spawned a number of studies using numerical simulations (Miniati 2002, Keshet et al. 2003) or semi-analytic methods (Gabici & Blasi 2003b, 2004), although most such works had limited their scope to treating purely gravitational effects. In reality, the global hydrodynamical evolution of intergalactic gas and the associated gamma-ray emission can be crucially affected by non-gravitational effects such as radiative cooling (with consequent star formation and feedback) and photoionization heating.

By considering such non-gravitational effects in a simplified way, we show here that there should be a nontrivial connection between SF gamma-rays and the baryonic fraction in the WHIM. The problem is addressed through semi-analytic modeling of SF shocks based on Monte Carlo merger trees with multiple mergers (Somerville & Kollatt 1999), which allows a self-consistent treatment of major and minor merger shocks as well as diffuse accretion shocks. The full details can be found in a forthcoming paper (Inoue and Nagashima, in prep.).

(a) Formulation

An important point in considering nonthermal effects due to SF shocks is that such shocks can be either strong or weak, with Mach numbers $\mathcal{M}$ ranging from very large ones ($\gg 1$) for minor mergers between systems with large mass ratios or accretion of relatively cold gas onto a large object, to values as low as $\sim$1.5–3 in the case of major mergers between virialized objects of comparable masses (Takizawa 1999, Berrington & Dermer 2003, Ryu et al. 2004). This implies that the spectral index of shock accelerated particles p can be either the strong shock limit of $p \simeq 2$ or much steeper with $p > 2$, leading to considerably differenct effects at high energies (Gabici & Blasi 2003a). Thus it is imperative to account for the distribution of shock Mach numbers appropriately.

One way to address this problem is through full-scale cosmological hydrodynamical simulations (Miniati 2002, Keshet et al. 2003, Ryu et al. 2004). Here we opt for a semi-analytic approach based on the extended Press-Schechter (PS) formalism of structure formation (Lacey & Cole 1993), which gives a simple yet reasonably accurate description of the hierarchical gravitational growth of dark matter halos. In particular, we employ the multiple merger tree algorithm of Somerville & Kolatt (1999), which accurately reproduces the total and conditional halo mass functions and also accounts for diffuse accretion. At each time step in the merger tree, we also employ an accurate mass function derived from very high resolution N-body simulation results (Yahagi, Nagashima & Yoshii 2004). More detailed descriptions of the merger tree formulation can be found in Nagashima & Yoshii (2004). Note that the semi-analytic model of Gabici & Blasi 2003a (GB03) is built on the simpler binary merger tree algorithm of Lacey & Cole (1993), which cannot treat accretion and is known to produce self-inconsistent results when the merger tree is extended to high redshifts (Somerville & Kolatt 1999). (However, we find that the differences are not very large at low redshifts, and our results below for SF gamma-rays are in basic agreement with Gabici & Blasi when appropriate comparisons are made.)

Our basic assumptions are as follows. (1) The adopted cosmological parameters are Ω_m=0.3, Ω_Λ=0.7, Ω_b=0.044 and h=0.7. The normalization and spectral index of primordial fluctuations are respectively σ_8=0.9 and n=1. (2) At each step, a multiple merger event between more than two halos is pictured as an ensemble of binary mergers with the primary (i.e. most massive) progenitor. Associated with each binary pair are two shocks propagating within them. Mass below a certain mass scale (see below) in the timestep accretes spherically onto the primary. (3) An effective Mach number is assigned to each merger shock. The temperature of the preshock gas is the virial value for the relevant progenitor. The relative infall velocity v is given by $v^2 = 2G(M_{A+B})[(f_0(M_B/M_A)+1)/(R_A+R_B) - 1/2R_{AB}]$, where M_i and R_i are the masses and virial radii for A, B and A+B denoting the two progenitors and merged halo, respectively. This is similar to Gabici & Blasi (2003a), except that we include a parameter f_0 that is calibrated to match the simulation results for major mergers Takizawa (1999). Diffuse accretion shocks are always strong. (4) The electron injection efficiency is fiducially a fraction $\xi_e = 0.05$ of the energy dissipated at the shock, i.e. the difference between the post-shock and pre-shock thermal energies. The injection spectral index p is related to the shock Mach number $\mathcal{M}$ as $p = 2(\mathcal{M}^2+1)/(\mathcal{M}^2-1)$ (test particle assumption). The emitted inverse Compton spectrum is a broken power-law, with energy indices $(p-1)/2$ and $p/2$ respectively above and below the cooling break energy where the electron cooling time equals the shock crossing time, and a high energy cutoff where the cooling time equals the acceleration time. Only primary electrons are considered. (5) The gas fraction inside halos is Ω_b/Ω_m when affected solely by gravity. Non-gravitational effects due to radiative cooling and photoionization heating which can be effective in certain mass ranges are incorporated in a simplified way as described below.

Two characteristic mass scales are important concerning non-gravitational effects. One is the scale of the post-reionization Jeans mass (more accurately the filtering mass), below which gas cannot appreciably cool and collapse inside virialized halos due to photoionization heating by the UV background (Gnedin 2000). This may be considered the natural boundary distinguishing diffuse accretion and clumpy merging and is identified with the mass resolution scale in our merger tree algorithm. Taking its velocity dispersion V_{acc} as a parameter, a realistic range may be $V_{acc} \simeq 20-70$ km/s as suggested by detailed modeling (Gnedin 2000). We assume a fiducial value of $V_{acc} = 40$ km/s, corresponding to mass few times $10^{10} M_\odot$ at $z = 0$. The other important scale is the maximum cooling mass above which gas cannot significantly cool because of the reduced cooling function in the pertinent temperature range; its velocity dispersion is parameterized by V_{cut}. In halos between V_{acc} and V_{cut}, gas can cool efficiently and condense into stars, i.e. become galaxies. The observed galaxy luminosity function indicates $V_{cut} \simeq 150 - 250$ km/s, and we fiducially take $V_{cut} = 200$ km/s or few times $10^{12} M_{\odot}$ at $z = 0$ in terms of mass. SF shocks and associated emission will be suppressed in systems which have converted a large fraction of its gas into stars, and we treat this effect simply by removing SF shocks in a fraction f_{GF} of halos between V_{acc} and V_{cut} and account only for mass growth through their merging.

An interesting connection can be made between our principal parameters V_{acc}, V_{cut}, f_{GF}, and the present-day fraction of baryons in the universe in different forms. Following Davé et al. (2001) in dividing cosmic baryons into four phases, diffuse ($T < 10^5$ K), condensed (stars and cold gas), warm-hot ($10^5 < T < 10^7$ K), and hot ($T > 10^7$ K), these respectively relate in our picture to systems with velocity dispersion $V < V_{acc}$, a fraction f_{GF} of $V_{acc} < V < V_{cut}$, the rest $1 - f_{GF}$ of $V_{acc} < V < V_{cut}$ plus a part of $V > V_{cut}$ with $T < 10^7$ K, and the remainder of $V > V_{cut}$ with $T > 10^7$ K. If we take our fiducial values $V_{acc} = 40$ km/s and V_{cut}=200 km/s, there is a one to one relation between f_{GF} and f_{cond}, the baryonic fraction condensed into stars and cold gas, which in turn can be related to f_{WH}. For example, cosmological simulations including radiative cooling and galaxy formation (Davé et al. 2001) indicate a range $f_{cond} \simeq 0.2 - 0.4$ and $f_{WH} \simeq 0.2 - 0.4$ at $z = 0$, which corresponds to $f_{GF} \simeq 0.6 - 0.9$ through a simple extended PS analysis. Alternatively, a recent observational census (Fukugita & Peebles 2004) suggests $f_{cond} \simeq 0.1$ and $f_{WH} \simeq 0.4$, which is consistent with $f_{GF} \simeq 0.4$.

A further non-gravitational effect that might be important is feedback (pre-)heating by supernovae-driven winds or AGN outflows, as indicated by the observed X-ray scaling relations of groups and clusters (Sanderson & Ponman 2003 and references therein). Since the details of such processes are highly uncertain at present, we defer a consideration of these effects to future work (see Totani & Inoue 2002 for an early, crude discussion).

One important caveat is in order concerning our formulation. In the PS picture, all the dark matter in the universe is described as being bound inside spherically virialized halos of some mass. This is a fairly good approximation, as many comparisons with N-body simulations demonstrate (e.g. Yahagi et al. 2004 and references therein.) However, the same cannot be said about the gas component. In fact, we have explicitly assumed the fraction of gas with $V < V_{acc}$ to be in diffuse form outside bound halos due to photoionization heating. It is less clear how much of the WHIM, particularly the gas with $V_{acc} < V < V_{cut}$, can be considered to be inside or outside bound objects. Although hydrodynamical simulations indicate that a large part of the WHIM arises through shock heating by gravitational infall onto filamentary or sheet-like structures (Cen & Ostriker 1999, Davé et al. 2001), much of the gas in such structures may actually be interpreted as residing inside sufficiently small halos if seen at high enough resolution. Since the essential driving force of WHIM evolution is the gravity of the dark matter, most of which is indeed in bound form, we have chosen to describe the WHIM as gas inside bound haloes with the corresponding range of virial temperatures which do not condense into stars. Just how good such a description (or some alternative, e.g. Furlanetto & Loeb 2004) may be can only be judged through comparisons with detailed numerical simulations.

(b) Results and Discussion

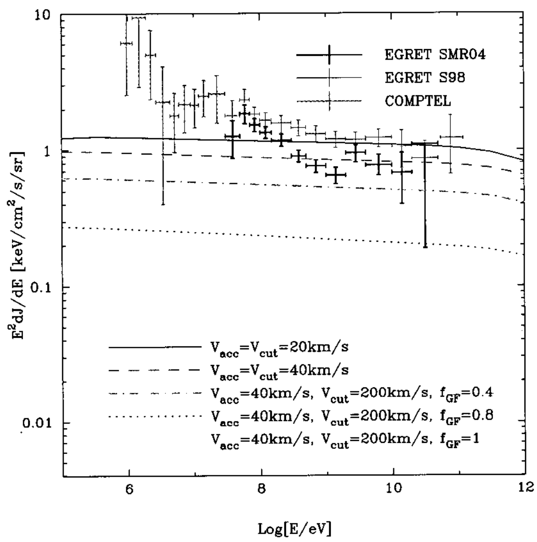

Fig. 1.— Cosmic gamma-ray background for different values of V_{acc}, V_{cut} and f_{GF} as indicated in the legend, compared with COMPTEL and EGRET (both S98 and SMR04) data.

Fig.1 shows our results of the SF shock contribution to the CGB for different values of V_{acc}, V_{cut} and f_{GF}. To be compared are CGB data from COMPTEL (Weidenspointner et al. 2000) and EGRET, including both the old Sreekumar et al. (1998; S98) and new Strong, Moskalenko & Reimer (2004; SMR04) determinations.

We first take $V_{acc} = V_{cut} = 20$ km/s, corresponding closest to the situations treated in numerical simulations, where the sole non-gravitational effect is a temperature floor of $T = 10^4$ K (Miniati 2002, Keshet et al. 2003). The result accounts for almost all of the S98 CGB, and in fact exceeds the new SMR04 CGB, indicating either that this case does not represent reality or that ξ_e is significantly less than the fiducial value 0.05. Although this is quantitatively in more agreement with the result of Miniati (2002) than of Keshet et al. (2003), here we reserve a judgement, given the approximate nature of our formulation.

For this and all other cases discussed here, the end result is dominated by minor merger shocks, with accretion shocks amounting to at most 1% of the S98 CGB. Keeping $V_{acc} = V_{cut}$ (i.e. no condensation into stars), a larger value decreases the merger component and hence the total CGB, while slightly increasing the accretion component; for smaller values, vice-versa. Taking $f_{GF} = 1$ (complete condensation in the cooling regime) with $V_{acc} = 40$ km/s fixed, varying V_{cut} has a dramatic effect, with the CGB being suppressed by more than an order of magnitude as $V_{cut} = 200$ km/s is approached. This can be understood as removing larger and larger galaxy-scale objects, which can potentially produce strong shocks in minor mergers with cluster-scale objects. Our fiducial set of $V_{acc} = 40$ km/s, $V_{cut} = 200$ km/s leads to ~ 10 % of the S98 CGB, consistent with the results of GB03.

Obviously, when condensation occurs only for a fraction f_{GF} of objects in the cooling regime, the reduction is less, and one gets a CGB somewhere between 10 to 100 % of the S98 CGB. Recalling the above-mentioned connection between f_{GF} and f_{cond}, the current uncertainty in $f_{cond} \simeq 0.1 - 0.4$ allows a range $f_{GF} = 0.4 - 0.9$, and the CGB due to SF shocks cannot be reliably predicted to within an order of magnitude. However, this points to an interesting possibility of constraining f_{cond} and hence f_{WH} if the SF shock contribution to the CGB can be observationally determined. In practice, this requires removing other contributions (e.g. blazars) to the CGB with good precision, which may not be an easy task.

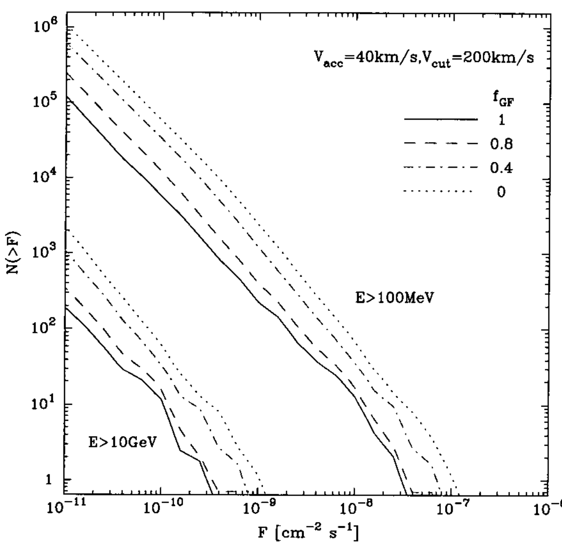

Fig. 2.— Gamma-ray source counts at >100 MeV and >10 GeV for different values of f_{GF}.

A more promising way to constrain f_{WH} with gamma-rays may be through the statistics of source counts. Fig.2 displays the cumulative source counts due to SF shocks at energies $>$ 100 MeV and $>$ 10 GeV, for fixed fiducial values of V_{acc} and V_{cut} and different f_{GF}. Again, differences of an order of magnitude can be seen, depending on how much minor merger shocks are suppressed. For $f_{GF} = 0.9$ ($f_{cond} \simeq 0.25$, $f_{WH} \simeq 0.25$), ~ 100 and ~ 10 sources should be observable by GLAST at >100 MeV and >10 GeV, respectively, while none exists above the EGRET sensitivity at >100 MeV. For $f_{GF} = 0.4$ ($f_{cond} \simeq 0.1$, $f_{WH} \simeq 0.4$), the respective numbers are $\sim$ 400 and $\sim$ 40 at >100 MeV and >10 GeV for GLAST, whereas a few are expected for EGRET. The fact that EGRET actually saw no emission associated with clusters (Reimer et al. 2003) may point to either $f_{GF} > 0.4$ or $\xi_e < 0.05$. This underlies the need for the electron injection effiency to be pinned down, preferably through detailed observations of individual sources where the kinetic energy can be estimated independently. Once this is done, SF gamma-rays can provide an indirect but very valuable probe of the unknown fraction of baryons in the WHIM. In fact, a close connection between SF gamma-rays and the WHIM is not surprising at all, as they both arise from the same large-scale shocks. However, the quantitative correspondence is a nontrivial one involving the reduction of strong, minor merger shocks by condensation into stars.

The present work is an example of nonthermal phenomena due to SF shocks where semi-analytic, PS-based methods can be applied effectively, allowing the exploration of physical effects in a simple way which is not always the case with numerical simulations. However, in view of the numerous approximations in our formulation, further studies with simulations are warranted, both to confirm the qualitative trends found here and to make predictions that are quantitatively more robust.

III. COSMIC RAY PRODUCTION OF ^{6}LI BY STRUCTURE FORMATION SHOCKS IN THE EARLY GALAXY

Apart from ^{7}Li, the bulk of the light elements Li, Be and B in the universe are believed to have originated through nonthermal nuclear reactions induced by cosmic rays (CRs; see Vangioni-Flam, Cassé & Audouze 2000, Prantzos 2004 for reviews). To date, most models of light element evolution in the Galaxy have focused on strong shocks driven by supernovae (SNe) as the principal CR sources. Observations of metal-poor halo stars (MPHS) in our Galaxy show a linear relation between [Fe/H] and Be/H (Boesgaard et al. 1999) or B/H (Duncan et al. 1997), which can be well explained as resulting from spallation of CRs enriched with CNO from fresh SN ejecta while impinging on interstellar H or He atoms (Vangioni-Flam et al. 2000, Ramaty et al. 2000, Suzuki & Yoshii 2001, hereafter SY and references therein).

The origin of ^{6}Li in MPHS is more mysterious. Part of the problem lies in the observational difficulty of measuring ^{6}Li via the weak isotopic shift feature relative to the much stronger ^{7}Li line, requiring very high resolution and high S/N spectroscopy. Reliable measurements for an adequate sample of stars have become possible only very recently through dedicated programs with the Very Large Telescope UV Echelle Spectrograph (VLT/UVES) by Asplund et al. (2001, 2004, in prep.; see also Lambert 2004), as well as with the Subaru High Dispersion Spectrograph (HDS) carried out by ourselves (Aoki et al. 2004, Inoue et al. in prep.). Both HDS and UVES have confirmed beyond doubt the high abundance of ^{6}Li in the star HD84937, previously indicated by lower quality observations. Furthermore, new ^{6}Li measurements in other stars at various [Fe/H] reveal a striking trend, shown in Fig.III: high ^{6}Li abundances are seen in some stars including ones with [Fe/H] $\lesssim -3.0$, suggesting a plateau-like behavior in ^{6}Li vs [Fe/H] (notwithstanding upper limits for some other stars; see below). This includes the UVES detection of LP815-43 ([Fe/H=-3.0]), as well as our tentative HDS detection in G64-12 ([Fe/H]=-3.2; not shown in Fig.III).

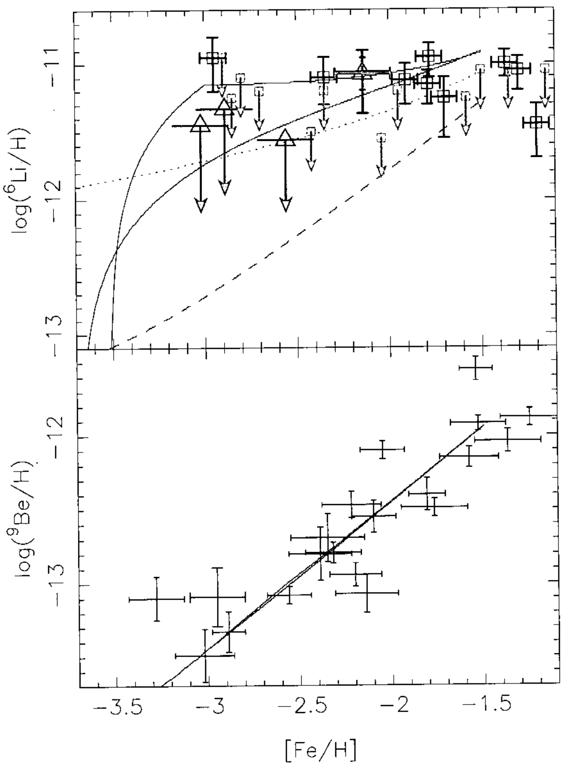

Fig. 3.— Top: Latest observational data on ^{6}Li/H vs. [Fe/H] from HDS (triangles) and UVES (squares). Overlayed are ^{6}Li production model curves for: SN CRs (dashed); SF CRs with $\tau_{SF} = 0.1$Gyr, $t_{SF} = 0.12$Gyr (upper solid) and $\tau_{SF} = 0.5$Gyr, $t_{SF} = 0.1$Gyr (lower solid), SF CRs with mass growth history guided by Abadi et al. (dotted). Bottom: Current data for Be/H, compared with model curves for SN CRs only (lower) and SN+SF CRs (upper) with parameters for the upper solid curve in the top panel.

A peculiar aspect of Li is that in addition to CNO spallation, the fusion process of CR α particles with ambient He atoms can be effective and should dominate Li production at low metallicities. (Note that while both ^{7}Li and ^{6}Li are synthesized in comparable amounts, the CR-produced ^{7}Li is generally overwhelmed by the "Spite plateau" from primordial nucleosynthesis in the metallicity range under consideration; e.g. Ryan et al. 2001.) Although SN CR models of light element production can give a good account of the Be and B observed in MPHS, they already faced a challenge in explaining the high ^{6}Li/H in HD84937, being forced into additional, rather implausible and/or contrived assumptions (Ramaty et al. 2000; SY). Furthermore, log^{6}Li/H vs. [Fe/H] in such models can never be much flatter than linear. Thus the new observations are on the verge of ruling out SN CR models for ^{6}Li at low metallicities.

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 SF shocks, i.e. shocks driven by the gravitational infall and merging of sub-Galactic 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 (Rees & Ostriker 1977, White & Rees 1978). (However, we mention that doubts have been raised as to whether the shocks occur at the virial radius as in the standard picture (Birnboim & Dekel 2003, Keres et al. 2004); see §(c)).) We discuss below a number of testable predictions and important implications expected in our scenario for understanding the formation of our Galaxy, as well as the potential relevance to some fundamental issues in cosmology and structure formation on sub-galactic scales (see also Suzuki & Inoue 2004).

(a) Formulation

The basic formulation regarding SN CRs is the same as in SY and SI and will not be repeated here. We highlight below the main features of light element production by SF CRs, and also describe a somewhat more realistic model than those presented in SI.

A guide to how structure formation may have proceeded in our Galaxy, particularly for the Galactic halo, is offered by recent high resolution numerical simulations of disk galaxy formation by Abadi et al. (2003a, 2003b; see also Bekki & Chiba 2001, Samland & Gerhard 2003). It is expected that sub-Galactic structures eventually merge into a single entity in the central region at redshift $z \sim 2$ in a "final major merger", whereby the majority of the infall kinetic energy is virialized. The total energy dissipated at this main SF shock can be evaluated from the virial temperature of the merged system. The virial temperature T_v for a halo of total mass M_t virializing at redshift $z \sim 2$ is $k_B T_v = \mu m_p G M_t / 2 r_v \simeq 0.26\mathrm{keV}\left(M_t/3 \times 10^{12}\mathrm{M}_\odot\right)^{2/3}$, where r_v is the virial radius, and we have assumed a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$. The specific energy dissipated at the SF shock is thus $\epsilon_{\rm SF} \sim 3k_BT_v/2 \simeq 0.4$ keV per particle, if we adopt $M_t = 3 \times 10^{12} M_\odot$ (Sakamoto, Chiba & Beers 2003). This is higher by a factor of $\simeq 3$ than that estimated for SNe in the early Galactic halo, $\epsilon_{\rm SN} \simeq 0.15$ keV per particle (see SI). As the SF CR injection efficiency should not be too different from that for SNe (e.g. Miniati et al. 2001), SF CRs should be at least as important as SN CRs, and may well dominate at early epochs. (Fields & Prodanović have also pointed out that the pion decay gamma-rays from SF CRs may give an interesting contribution to the CGB.) For both SN and SF CRs, we take the injection efficiency to be $\xi = 0.15$ of the kinetic energy. The spectral index $\gamma_{\rm SF}$ for SF CRs may be either as hard as that for SNe $\gamma_{\rm SN} \simeq 2$ or steeper, depending on the temperature of the preshock gas.

SF CRs are markedly different from SN CRs in a number of important ways. First and foremost, SF shocks do not synthesize 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 spallation, and are only efficient at spawning Li via $\alpha - \alpha$ fusion. Another distinction from SNe is that the SF CR flux should not entail any direct dependence on the metallicity. This is in fact an obstacle to predictive modeling, since the time evolution of star formation and chemical enrichment relative to that for structure formation is not specified in our chemical evolution model. SI opted for a simple, toy model description, parameterizing the time evolution of SF CRs by t_{SF}, the main epoch of Galactic SF relative to halo chemical evolution, and τ_{SF}, the main duration of SF.

Here we also consider a slightly more realistic form for the mass growth history, based on the numerical simulation results of Abadi et al. (2003a). Fig. 4 in their paper shows that the mass of dark matter within the virial radius grows rapidly at a rate $\dot{M} \simeq 2 \times 10^{11} M_\odot {\rm Gyr}^{-1}$ until the final major merger at $z \sim 2$, after which $\dot{M}$ levels off dramatically and there is relatively little mass increase. Such a merger history should be more or less generic to disk galaxies; most of the dark halo mass must have been assembled before the thin, fragile disk can be formed slowly and gently. With such a mass growth history in mind, we posit that our halo chemical evolution begins when a mass $M = 4 \times 10^{11} M_\odot$ is in place, followed by infall at a rate $\dot{M} \simeq 1.8 \times 10^{11} M_\odot {\rm Gyr}^{-1}$ until a final mass of $M = 3 \times 10^{12} M_\odot$ (Sakamoto et al. 2003) is reached. Note that the simulations of Abadi et al. were not intended as a model specific to our Galaxy and should only be taken as a guide.

(b) Results and Discussion

Plotted in Fig.III are model curves (solid) for two parameters sets in the SI model: $\tau_{SF} = 0.1$Gyr, $t_{SF} = 0.12$Gyr, and $\tau_{SF} = 0.5$Gyr, $t_{SF} = 0.1$Gyr, as well as the model described above, guided by Abadi et al.'s simulations (dotted). In all cases, $\gamma_{\rm SF} = 3$ has been assumed. The following salient points are to be noted. First, we can confirm that with the 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 $\epsilon_{\rm SF}$, $\xi_{\rm SF}$ and $\gamma_{\rm SF}$, production by SF CRs may be capable of explaining the latest ^{6}Li detections quite adequately. This mainly owes to two facts: (1) SF CRs are more energetic than (or at least as energetic as) SN CRs, (2) SF CRs can generate ^{6}Li at early epochs independently of the metallicity.

Regardless of the particular evolutionary parameters, the following abundance trends are characteristic of SF CR production and should serve as distinguishing properties of the scenario. Going from high to low metallicity: a plateau or a very slow decrease in log^{6}Li/H vs. [Fe/H], followed by a steeper decline in some range of [Fe/H] corresponding to the main epoch of SF; 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 not expected in SN CR models. Distinction from any production processes in the early universe (e.g. Jedamzik 2004, Kawasaki et al. 2004) should also be straightforward, as they predict a true plateau down to the lowest [Fe/H], in contrast to an eventual decrease for SF CR models.

(c) Implications

Besides the ^{6}Li-detected stars which show the plateau-like ^{6}Li-Fe/H behavior, the new observations have also produced strong upper limits for some other stars (Fig.III), possibly indicating different amounts of ^{6}Li production at different sites with similar [Fe/H] (except for HD140283 where stellar depletion effects may be at work; Aoki et al. 2004). This is of interest with regard to a further, unique expectation of the SF CR picture: systematic correlations between the ^{6}Li abundance and stellar kinematical properties. On the one hand, ^{6}Li production arises through gravitational shock heating, which is also the principal gas dissipation mechanism, so that ^{6}Li provides a measure of dissipative dynamical processes in the early Galaxy. On the other, the kinematical properties of MPHS reflect the dynamical state of their parent gas clouds (Chiba & Beers 2000, Freeman & Bland-Hawthorn 2002), whose dynamics should both affect and be affected by dissipative effects Thus, important correlations should exist between the two.

For example, according to Chiba & Beers (2000), dissipative processes may have been more important in forming the inner, flattened and rotating part of the Galactic halo compared to the the outer, spherical and non-rotating part. If this was true, stars belonging to the inner halo may show systematically higher ^{6}Li/H than those in the outer halo, even for similar [Fe/H]. On the other hand, the results of Abadi et al. (2003b) may suggest a wholly opposite trend: in their simulated galaxy, most of the outer halo stars originate in the main dissipative merger event, while an important fraction of inner halo stars are formed in dissipationless mergers with late infalling satellites. Our new Subaru HDS results may actually favor the latter, with strong upper limits for two inner halo stars, and a tentative detection in G64-12, an extreme outer halo star. Although the current sample is too small for a conclusive statement, it is a remarkable possibility that further observations of ^{6}Li in MPHS may provide us with such kinds of important information regarding the origin of dynamical structure in our Galactic halo.

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 efficiency and location of SF shocks as commonly assumed on sub-galactic scales has recently been brought into question (Birnboim & Dekel 2003, Keres et al. 2004), with significant 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. (2) 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. (3) 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 subgalactic 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.

Thus the SF CR model for ^{6}Li bears important implications for understanding how our Galaxy formed. If the above mentioned trends are observationally firmly established, it would not only confirm the SF CR origin of ^{6}Li, but may potentially point to new studies of "^{6}Li Galactic archaeology", whereby extensive observations of ^{6}Li in MPHS in conjunction with detailed chemo-dynamical modeling can be exploited as a robust and clear-cut probe of dissipative dynamical processes that were essential for the formation of the Galaxy.

IV. SUMMARY

Two topics were discussed regarding nonthermal effects due to structure formation shocks, with emphasis on what important things we may learn from such phenomena about the structure formation process itself.

First, we investigated inverse Compton gamma-rays from electrons accelerated in large scale structure formation shocks, employing a semi-analytic formulation that self-consistently treats merger and accretion shocks. Non-gravitational effects such as radiative cooling and photoionization heating were shown to have significant effects, with the predicted cosmic gamma-ray background contribution and gamma-ray source counts uncertain by an order of magnitude depending on the fraction of baryons condensing into stars. This in turn implies that such gamma-rays may in the near future serve as an indirect "baryometer" of the universe and probe the "missing" fraction of baryons in the warm-hot intergalactic medium, which is very difficult to observe directly.

Second, we discussed the production of ^{6}Li by structure formation cosmic rays during the formation of our Galaxy, which dominate over supernova cosmic rays at early epochs and entail no direct correlations with the metallicity evolution. New observational measurements of ^{6}Li in metal-poor halo stars with the Subaru HDS and VLT/UVES instruments reveal striking trends thay may be consistent with the scenario. 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.

ACKNOWLEDGEMENTS

The authors are very grateful to M. Chiba, S. G. Ryan and S. Kawanomoto for a fruitful ongoing collaboration on Subaru observations of ^{6}Li in halo stars. M. Nagashima and T. K. Suzuki are supported by the JSPS Research Fellowships for Young Scientists.

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