Cosmic rays, lithium abundance and excess entropy in galaxy clusters

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\begin{abstract}
We consider the production of $^6\text{Li}$ in spallation reactions by cosmic rays in order to explain the observed abundance in halo metal-poor stars. We show that heating of ambient gas by cosmic rays is an inevitable consequence of this process, and estimate the energy input required to reproduce the observed abundance of $^6\text{Li}/\text{H} \sim 10^{-11}$ to be of order a few hundred eV per particle. We draw attention to the possibility that this could explain the excess entropy in gas in galaxy groups and clusters. The evolution of $^6\text{Li}$ and the accompanying heating of gas is calculated for structures collapsing at the present epoch with injection of cosmic rays at high redshift. We determine the energy required to explain the abundance of $^6\text{Li}$ at $z \sim 2$ corresponding to the formation epoch of halo metal-poor stars, and also an increased entropy level of $\sim 300$ keV cm$^2$ necessary to explain X-ray observations of clusters. The energy budget for this process is consistent with the expected energy output of radio-loud AGNs, and the diffusion length scale of cosmic-ray protons responsible for heating is comparable to the size of regions with excess entropy. We also discuss the constraints imposed by the extragalactic gamma-ray background.

\textbf{Key words:} Cosmology: Early Universe, Nucleosynthesis, Abundances, Stars: Abundances, ISM: Cosmic Rays, Gamma Rays:Theory
\end{abstract}

\section{INTRODUCTION}

The primordial abundance of lithium as predicted from the big bang nucleosynthesis (BBN) poses a puzzle when compared with observed abundance in our Milky Way halo. Since lithium, along with other light elements such as beryllium and boron, are not produced during stellar nucleosynthesis, the study of their abundance offers a unique probe of the conditions in the early universe. The agreement between recent WMAP determination of the cosmic baryon density (Spergel et al 2003), and the BBN prediction from observed deuterium and $^4\text{He}$ abundances (Cyburt et al 2005) has been encouraging, pushing one to study other light elements. The predicted abundance from BBN using the WMAP baryon density of $\Omega_b h^2 = 0.0224 \pm 0.0009$ is $^7\text{Li}/\text{H} \approx 4.26^{+0.92}_{-0.86} \times 10^{-10}$ (Cyburt et al 2005). A wealth of data on $^7\text{Li}$ abundance among halo metal-poor stars ([Fe/H] $\leq -1.5$) has accumulated since the original discovery of a plateau in the $^7\text{Li}$ abundance by Spite & Spite (1982). Current measurements find the $^7\text{Li}$ abundance to be a factor $\sim 3-4$ lower than this prediction (Asplund et al 2005; Cyburt 2004; Coc et al 2004; Serpico et al 2004). Cyburt et al (2005, and references therein) have recently discussed the roles of several process including stellar destruction and new physics to account for this discrepancy.

$^6\text{Li}$, on the other hand, is difficult to detect owing to the small difference in its mass from the predominant isotope of $^7\text{Li}$, making lines from these two isotopes blend easily. Until recently it was measured in only three stars with metallicity [Fe/H] $\leq -1.3$. Recent high resolution studies have significantly expanded this dataset to 24 metal-poor halo stars (Lambert 2004; Asplund et al. 2005), revealing a plateau at log($^6\text{Li}/\text{H}$) + 12 = 0.8 for metallicities [Fe/H] $\leq -2.5$. This is $\sim 1000$ times the predicted abundance from BBN, $^6\text{Li}/\text{H}_{\text{BBN}} \approx 10^{-14}$ (Thomas et al. 1993; Vangioni-Flam et al 1999). The observed $^6\text{Li}$ abundance therefore poses a challenge in understanding its origin.

The mismatch between the predicted and observed abundance of $^6\text{Li}$ remains puzzling even when one considers other possible production mechanisms. $^6\text{Li}$ can be synthesized after BBN epoch by spallation (e.g., $p + O \rightarrow \text{fragments}$) and fusion ($\alpha + \alpha \rightarrow ^6\text{Li}$ and $^7\text{Li}$) reactions, when high-energy cosmic-ray particles collide with ambient gas particles. Spallation reactions would also produce B and Be in addition to lithium, and the pioneering work by Reeves et al. (1970) matched the abundances of $^6\text{Li},$
Be and $^{10}$B with solar system abundances. Current models of Galactic cosmic-ray spallation predict a $^6$Li/H abundance that is roughly proportional to the stellar metallicity (Fe/H), with $^6$Li/H $\sim 10^{-11}$ for [Fe/H] $\sim -2$ and lower abundance for lower metallicities (Fields & Olive 1999a, 1999b; Vangioni-Flam et al 1999; Ramaty et al 2000; Alibés et al 2002). The measured $^6$Li plateau in stars with metallicities [Fe/H] $\sim -2.5$ therefore cannot be explained by Galactic cosmic-ray spallation (Lambert 2004), and requires a different origin. In this context, Suzuki & Inoue (2002) have studied the gamma ray background also Ramaty et al 2000; Fields et al. 2001). Fields & Prodanović (2005) have discussed the energy requirements for these processes (see also Rollinde et al 2005). Rollinde et al. 2005). Fields & Prodanović (2005) have studied the gamma ray background that would ensue from the same cosmic-ray population that is expected to produce $^6$Li. Recently Jedamijk (2004) and Kawasaki et al. (2005) have invoked decaying relic particles to explain the $^6$Li discrepancy. Reeves (2005) has suggested that the early massive metal-poor Population III stars considered responsible for the reionisation of the universe injected via their winds the low-energy cosmic rays that generated $^6$Li/H via spallation in the intergalactic medium (see also Rollinde et al 2005).

In spallation reactions by cosmic rays, it is the low-energy $\alpha$-particles (with kinetic energy per nucleon $E \leq 100$ MeV) that contribute most to the production of $^6$Li as the cross-section decreases sharply with increasing energy (Mercer et al. 2001). Low energy cosmic rays also deposit a large fraction of their energy into the ambient medium through Coulomb interactions (e.g., Mannheim & Schlickeiser 1994). Cosmic rays as a source of heating of the intergalactic gas have been previously studied by Ginzburg & Ozernoi (1966) and Nath & Biermann (1993). Moreover an important source of $^6$Li is via $\alpha + \alpha$ spallation, and hence independent of metallicity. It is then expected that the production of $^6$Li from spallation cosmic rays could be accompanied by substantial heating of the pregalactic gas.

X-ray observations of galaxy groups and clusters indeed suggest that the gas in these objects has been preheated by some non-gravitational process. The gas entropy ($S \equiv T/n_e^2/3$) in galaxy groups appears to be in excess of expectations from gravitational interactions of gas with dark matter, and this excess entropy makes the gas less luminous than expected (Ponman et al. 2003, and references therein). The proposals to explain this entropy floor include energy input from supernovae (e.g., Wu et al. 2000), warm-hot intergalactic medium (Valageas et al. 2003), radiative cooling (e.g., Voit & Bryan 2000), accretion shocks (e.g., Tozzi & Nulsen 2001), and AGN heating (e.g., Roychowdhury et al. 2004). It has been estimated that to reproduce the observed density and temperature profiles, entropy must be injected into the gas at a level of $S \sim 300$ keV cm$^{-2}$ (McCarthy et al. 2002).

In this paper, we assess the possibility of cosmic rays simultaneously producing the observed abundance of $^6$Li and preheating the ambient gas to explain X-ray observations of galaxy clusters. All results shown below assume a ΛCDM cosmology with $h = 0.7$, $\Omega_m = 0.29$, $\Omega_\Lambda = 0.71$ and $\Omega_b h^2 = 0.02$.

### 2 COSMIC RAY HEATING AND $^6$Li ABUNDANCE

We assume that the cosmic-ray injection spectrum for protons is a power-law in momentum, of the form

$$n_{cr,p}dE \approx A_{cr}(E + E_0)[E(E + 2E_0)]^{(-\alpha+1)/2}dE,$$  \(1\)

where $E$ is kinetic energy per nucleon, $E_0 = 939$ MeV is the nucleon rest energy, and $A_{cr}$ is the normalization factor. This form of cosmic-ray spectrum is expected from shock acceleration theories (e.g., Blandford & Eichler 1987). We normalize the spectrum in terms of the energy density in cosmic-ray particles, $\epsilon_{cr}$ (erg cm$^{-3}$) assuming a lower limit to the kinetic energy $E_i$. The heating rate due to Coulomb interactions of a fully ionized gas with cosmic-ray particles with charge $Ze$ is given by (Mannheim & Schlickeiser 1994, eq. 4.22),

$$\Gamma = \int_{E_i}^{\infty} n_{cr,p}(E) \frac{dE}{dt}(\beta) dE$$

$$\approx 1.72 \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-3} \left(\frac{\epsilon_{cr}}{\text{erg cm}^{-3}}\right) \left(\frac{n_e}{\text{cm}^{-3}}\right),$$  \(3\)

for $E_i = 30$ MeV, and $\alpha = 2.5$. This can be compared with the rate at fixed proton energy $E_i$ from Ginzburg & Ozernoi (1966), $\Gamma \sim 6 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-3} \left(\epsilon_{cr}/\text{erg cm}^{-3}\right) \left(E_i/30 \text{MeV}\right)^{-3/2}$, which therefore provides an upper limit to the true heating rate for a distribution of proton energies.

The cross-section for the production of $^6$Li by $\alpha - \alpha$ interactions is given by (Mercer et al 2001), $\sigma \sim 66 \exp(-0.016E_\alpha/\text{MeV})$ mb, where $E_\alpha$ is the total kinetic energy of the cosmic-ray $\alpha$-particle. This reaction has a threshold of $\sim 10$ MeV per nucleon. For the abundance of $\alpha$-particles in cosmic rays, we use,

$$n_{\alpha cr}(E) = K_\alpha n_{cr,p}(E)dE,$$  \(4\)

where, again, $E$ is the kinetic energy per nucleon, and $K_\alpha \sim 0.08$ is the abundance factor for $\alpha$-particles. We also use an abundance of helium in the ambient gas of $n_H/n_\alpha \sim 0.08$. The production rate of $^6$Li per proton is then written in terms of the CR energy density as,

$$\frac{d(^6\text{Li}/H)}{dt} = \int_{E_i}^{\infty} \sigma \beta c K_\alpha n_\text{He}/n_H n_{cr,p}(E)dE$$

$$\approx 1.05 \times 10^{-16} \text{s}^{-1} \left(\frac{\epsilon_{cr}}{\text{erg cm}^{-3}}\right),$$  \(5\)

where we have used $\alpha = 2.5$ and $E_i = 30$ MeV for the second equality. Eliminating the cosmic-ray energy density from equations \(3\) and \(5\), we find that the production of
lithium via fusion reaction is accompanied by the deposition in the ambient gas of the following amount of energy per particle:

\[ \Delta E \sim 16.5 \text{ erg} \Delta (\text{Li/H}) \]  

\[(6)\]

(again for \( \alpha = 2.5 \) and \( E_t = 30 \text{ MeV} \)). This estimate can be somewhat larger for a spectrum flatter than \( \alpha = 2.5 \) [e.g., \( \Delta E \sim 20.4 \text{ erg} \Delta (\text{Li/H}) \) for \( \alpha = 2 \)], or for a spectrum with a higher low-energy cutoff \( \Delta E \sim 56.1 \text{ erg} \Delta (\text{Li/H}) \) for \( E_t = 50 \text{ MeV} \) and \( \alpha = 2.5 \)]. Clearly, an abundance of \( (\text{Li/H}) \sim 10^{-11.2} \) through fusion reaction should be accompanied by the deposition of \( \sim 100 \eta \text{ eV} \) per particle, where \( \eta \sim 1-5 \) is a factor that describes the uncertainty in the cosmic-ray spectrum. The production of \(^6\text{Li}\) would not have been pervasive in the intergalactic medium, as cosmic rays must have been accelerated within (or in the vicinity of) bound structures (note that, even if this energy deposition had a large volume filling factor, it would occur too late to cause a large Compton distortion of the cosmic microwave background). Interestingly, the above estimate of the heating associated with \(^6\text{Li}\) production is comparable to the energy needed to explain X-ray observations of groups and clusters, which require about 0.5–1 keV per particle (Cavaliere et al. 1999; Borgani et al. 2002). Therefore the production of \(^6\text{Li}\) through spallation reactions can have important implications in the evolution of gas in galaxy groups and clusters.

3 EVOLUTION OF ENTROPY AND \(^6\text{Li}\) ABUNDANCE

We next calculate the evolution of gas entropy and \(^6\text{Li}/\text{H}\) abundance as a function of time. We have already mentioned X-ray data requiring gas in groups and galaxy clusters that collapse at the present epoch to be endowed with an entropy \( \sim 300 \text{ keV cm}^2\). For the lithium abundance observed in metal-poor stars, the constraint on the redshift of enrichment is somewhat uncertain. The ages of halo stars are estimated to be in the range 12.5 ± 3 Gyr (e.g., Cowan et al. 2002). In the adopted cosmology, these correspond to a formation redshift \( z \geq 1.6 \). In the following, we require that the \(^6\text{Li}/\text{H}\) abundance must grow to \( 10^{-11.2} \) by \( z \sim 2 \), and that the sources of cosmic rays are confined within structures that decouple from the Hubble flow at some point in the past and collapse at the present epoch. We thus calculate the growth of \(^6\text{Li}/\text{H}\) abundance and gas heating within such structures. In the spherical top-hat model, the equation of motion of a bound shell of matter is

\[ \ddot{r} = -\frac{GM}{r^2} + \frac{A\tau}{3}, \]  

\[(7)\]

where \( A = 3\Omega_\Lambda H_0^2 \). Since the term with \( A \) becomes smaller than the first term once the overdensity is larger than \( \sim (2\Omega_\Lambda - 1) = 0.4 \), we neglect it for simplicity, and use the parametric solution \( r = 2v_{\text{vir}}(1 - \cos \theta)/2 \), \( t = t_c[(\theta - \sin \theta)/2\theta] \). Here, \( v_{\text{vir}} \approx \tau_{\text{max}}/2 = \sqrt{[(2GM/c^2)/(\pi^2)]}^{1/3} \tau_{\text{vir}} \) is the radius at virialization, and \( t_c \) is the age of the universe at collapse, which is taken to be the present age of the universe. The density of gas after virialization is assumed to be constant and fixed by the overdensity expected in the spherical top-hat model. The overdensity for virialization in a \( \Lambda \text{CDM} \) universe is given by \( \Delta_c \approx 18\pi^2 + 82x - 39x^2 \) with \( x \equiv \Omega_m(z) - 1 \) (Bryan & Norman 1998). This overdensity is \( \approx 100 \) for \( z = 0 \). We assume the gas fraction to be \( \Omega_g/\Omega_m \sim 0.14 \).

For simplicity we assume the injection of cosmic rays occurs in a burst at a redshift \( z_{\text{in}} \) with an energy density \( \epsilon_{\text{cr}}(z_{\text{in}}) \). The gas is assumed to be ionized with an initial temperature of \( 10^4 \text{ K} \) and an initial BBN abundance of \(^6\text{Li}/\text{H} = 10^{-14} \). The volume dilution factor of cosmic-ray particles is calculated using the above mentioned scaling for radius. We calculate the energy losses of cosmic-ray protons and \( \alpha \)-particles according to equation 2, with an additional term \( d\beta/\beta = (d\nu/\nu)\beta(1 - \beta^2)/(1 + z) \) until the turnaround epoch (when \( r = r_{\text{max}} \)) to account for the losses of momentum due to the Hubble expansion. We also calculate the continuous depletion of \( \alpha \)-particles in the cosmic rays due to fusion of \(^6\text{Li}\). We do not calculate the accompanying production of \(^7\text{Li}\) since the production rates of \(^6\text{Li}\) and \(^7\text{Li}\) are similar and the additional production of \(^7\text{Li}/\text{H}\) due to cosmic rays (\( \sim 10^{-11} \)) is negligible compared to the BBN value of \(^7\text{Li}/\text{H} \sim 10^{-10} \) (Rollinde et al. 2005).

The free parameters in the calculations are the cosmic-ray spectral index \( \alpha \), the low-energy cutoff \( E_1 \), and the cosmic-ray energy density at injection, \( \epsilon_{\text{cr}}(z_{\text{in}}) \). We find that one can reproduce the required \(^6\text{Li}/\text{H}\) abundance at \( z \sim 2 \) and the entropy of cluster gas at \( z \sim 0 \) with different combinations of \( \alpha, E_1 \) and \( \epsilon_{\text{cr}}(z_{\text{in}}) \). Values of \( \alpha \) and \( z_{\text{in}} \) in the range \( \alpha = (2.2-2.7) \) and \( z_{\text{in}} = 3-6 \) require \( E_1 = (50-75) \text{ MeV} \) and \( \epsilon_{\text{cr}}(z_{\text{in}}) \sim 10^{-12.2} - 10^{-11.8} \text{ erg cm}^{-3} \). The requirement \( E_1 \sim 50-70 \text{ MeV} \) can be succinctly expressed in terms of the quantity of matter (grammage) the cosmic rays need to traverse before suffering large ionization losses. Equation 2 can be rewritten in terms of the grammage (\( \sim n_m\delta t \)) as \( \Delta \beta/\beta \approx 6.5 \times 10^{-5}(1 - \beta^2)^{3/2}/\beta^4 \times \text{grammage} \), which shows that a 60 MeV proton (\( \beta \sim 0.341 \)) will lose most of its energy after a grammage of \( \sim 2.5 \text{ g cm}^{-2} \). For comparison, the grammage inferred for GeV cosmic rays inside the Milky Way is \( \sim 10 \text{ g cm}^{-2} \) (e.g., Brunetti & Codino 2000). We note that observed ionization rates in diffuse clouds in our Galaxy imply \( E_1 \sim 30-60 \text{ MeV} \) for \( \alpha \sim 2.7 \) (Nath & Biermann 1994).

4 DISCUSSION

Figure 1 shows the evolution of the \(^6\text{Li}/\text{H}\) abundance, gas temperature and entropy with redshift, for various values of \( z_{\text{in}} \) and \( \epsilon_{\text{cr}}(z_{\text{in}}) \). The latter have been chosen in order to produce an abundance of \(^6\text{Li}/\text{H} \sim 10^{-11.2} \) at \( z \sim 2 \) and to reach \( S \equiv T/n^{2/3} \sim 300 \text{ keV cm}^{-2} \) at \( z \sim 0 \). The required cosmic-ray energy density is also plotted. We have used \( \alpha = 2.5 \) and the appropriate values of \( E_1 = (50-75 \text{ MeV} \) for \( z_{\text{in}} = 3-6 \)). The rate of production of \(^6\text{Li}\) falls rapidly after the redshift of injection \( z_{\text{in}} \) because of the dilution of cosmic-ray energy density by the Hubble expansion, as was first noted by Montmerle (1977). The abundance of \(^6\text{Li}\) therefore reaches a plateau soon after \( z_{\text{in}} \). Unlike the production of \(^6\text{Li}\), the effect of gas heating peaks at much later epochs. This happens because (1) as protons lose energy in Coulomb interactions (and also initially due to momentum losses from

\footnote{For simplicity we have assumed the same low-energy cutoff for both protons and \( \alpha \)-particles, although in principle they could be different (Nath & Biermann 1994).}
Figure 1. The evolution of the $^6$Li/H abundance (top left panel), gas temperature (in Kelvin, top right panel) and entropy (in keV cm$^2$ kg$^{-1}$, bottom left panel) with redshift is shown for a few cases with different $z_{in}$. The values of cosmic-ray energy density at injection, $\epsilon_{cr}(z_{in})$, have been chosen to satisfy the observational constraints of lithium abundance and gas entropy and are shown (in physical coordinates) in the bottom right panel.

the Hubble expansion), the fraction of energy deposited into the ambient gas increases (as shown by eq. 6 for $\beta > x_n$), and (2) $\alpha$-particles lose energy faster (because of the $Z^2$ factor in eq. 8) and sink below the threshold of $E \sim 10$ MeV per nucleon for fusion reactions. The timescale over which a cosmic-ray proton loses all its energy is long, $t_{cr} \sim 9 \times 10^9 (E/10 \text{ MeV})^{1.5} (n/10^{-5}\text{ cm}^{-3})^{-1}$ yr. The sharp rise in the temperature at very low redshift as seen in Figure 1 is mostly due to adiabatic compression after turn-around (at $z \sim 0.25$). The modest rise in entropy seen at low redshift is due to residual cosmic-ray protons.

We can estimate the extent of the region heated by cosmic rays from the distance travelled by energetic protons before ionization losses, which depends on the diffusion coefficient. Studies of radio observations of the Coma cluster suggest that the diffusion coefficient of GeV particles in a magnetic field of $B \sim 2 \mu$G is $D \sim (1–4) \times 10^{29}$ cm$^2$ s$^{-1}$ (Schlickeiser et al. 1987). The diffusion coefficient is proportional to the mean free path, which in turn depends on the spectrum of turbulence in the ambient medium. If the turbulence has a Kolmogorov spectrum, then the diffusion coefficient for scattering off the magnetic irregularities scales as $D \propto r_g^{-2/3} \propto (E + E_0)^{2/3} B^{-1/3}$, where $r_g$ is the gyration radius, $E$ and $E_0$ are kinetic and rest energy of particles (Biermann & Strittmatter 1987; Berezinsky et al. 1997). For cosmic-ray protons responsible for heating, $E \sim E_0$. We can estimate the diffusion coefficient of these protons for $B \sim 10^{-9}$ G as $D \sim 2.5 \times 10^{38} (B/10^{-9} \text{ G})^{-1/3}$ cm$^2$ s$^{-1}$. The distance travelled in $t \sim 10^{10}$ yr is then $r \sim \sqrt{(6Dt)} \sim 0.7(B/10^{-9} \text{ G})^{-1/6} (t/10^{10} \text{ yr})^{1/2}$ Mpc. Although the scalings with magnetic field and particle energy are somewhat uncertain, we can compare this length scale with the scale of structures considered in this paper.

X-ray observations of galaxy clusters indicate that gas entropy is enhanced in the central region, with $r \sim 0.1 r_{200}$, where $r_{200} \sim 0.9–1.9$ Mpc for a cluster of mass $M \sim 10^{14–15} M_{\odot}$ is the radius within which the mean overdensity is 200 times the ambient density, although there may be some evidence for enhanced entropy out to $r_{200}$ ($\sim 0.5–1.2$ Mpc for $M \sim 10^{14–15} M_{\odot}$, Ponman et al 2002). We therefore conclude that cosmic rays can heat gas in these regions in $\sim$ a few Gyr.

The required cosmic-ray energy density in this scenario is (from Figure 1) $\epsilon_{cr} \sim 6 \times 10^{-15}$ erg cm$^{-3}$ at $z \sim 3$, so that the comoving energy density is $\sim 9.4 \times 10^{-15}$ erg cm$^{-3}$. If the cosmic rays fill structures corresponding to groups and clusters, with a volume filling factor $f \sim 10^{-3}$ (for structures with $M \geq 10^{14} M_{\odot}$ in a $\Lambda$CDM universe), then the comoving energy density is $\sim 9.4 \times 10^{-18} (f/10^{-3})$ erg cm$^{-3}$. If the efficiency of accelerating cosmic rays is $\eta \sim 0.15$ then this requires an energy density of $6.3 \times 10^{-17} (\eta/0.15)^{-1} (f/10^{-3})$ erg cm$^{-3}$.

According to Chokshi & Turner (1992) and Yu & Tremaine (2002), the integrated energy density in radiation from quasars is $\sim 1.3 \times 10^{-15}$ erg cm$^{-3}$ at $z = 0$; for quasars at $z \geq 2$, the energy density is $\sim 6.5 \times 10^{-16}$ erg cm$^{-3}$. Radio-loud AGNs possibly deposit comparable mechanical energy in outflows as in radiation (Furlanetto & Loeb 2001), but only a fraction $\sim 0.1$ of AGNs are radio-loud. The available energy density in outflows from radio galaxies $z \geq 2$ is therefore estimated to be $6.5 \times 10^{-17}$ erg cm$^{-3}$, comparable to the requirement in the present scenario. We then find that the energy budget in this scenario is consistent with the energy available from radio-loud AGNs, and the diffusion length scale of cosmic-ray protons responsible for heating is comparable to the size of the region with enhanced entropy in clusters. Cosmic-ray particles would also be accelerated by supernovae responsible for the enrichment of the intracluster medium. Berezinsky et al. (1997) estimated the cosmic-ray energy in a cluster of total mass $M \sim 2 \times 10^{14} M_{\odot}$ to be $\sim 4.4 \times 10^{60}$ erg, which corresponds to an energy density $\sim 3.5 \times 10^{-14}$ erg cm$^{-3}$ for a region of size $\sim 1$ Mpc. This is smaller than the energy density $\sim 5 \times 10^{-13}$ erg cm$^{-3}$ required in our scenario, but if produced within a smaller region, supernovae also could be an important source of cosmic rays if produced early ($z \geq 2$).

Recent observations (Croston et al 2004) have shown that although gas in groups with currently active radio galaxies has high entropy, even groups with radio-quiet AGNs deviate somewhat from the scaling relation between the X-ray luminosity and temperature extrapolated from rich clusters. It is conceivable that past activity of radio galaxies could have raised the entropy in these systems (Roychowdhury et al 2005). This observation is consistent with the present model since the AGNs responsible for gas heating may have been active in the past, at $z \geq 2$, and be inactive today. The synchrotron life time of cosmic-ray electrons with $\sim 10$ GeV electrons, which can radiate at $\sim 600$ MHz for $B \sim 1 \mu$G, is $\sim 1.4(E/10 \text{ GeV})^{-1} (B/1 \mu$G)$^{-2}$ Gyr: this emission might be detectable in future continuum observations at low radio frequencies.

In the context of the lithium abundance in the halo stars of our Galaxy, our scenario would require a pregalactic
generation of cosmic ray sources that might plausibly be associated with intermediate mass black holes or miniquasars. These objects are likely precursors to the supermassive black holes observed at present in our Galaxy and in M31.

The cosmic-ray protons responsible for gas heating would also interact with ambient protons to produce pions which would eventually decay to produce gamma-ray photons. It is therefore important to study the consequences of our scenario for the production of high-energy photons. We first estimate the emissivity of gamma radiation above a certain photon energy $\epsilon_0$, using the analytical fit to the differential emissivity provided by Pfrommer and Enßlin (2004). For cosmic rays with a power-law index $\alpha = 2.5$, we estimate the gamma-ray emissivity in the ambient gas to be (in the units of photons $s^{-1}$ proton$^{-1}$)

$$f(\epsilon_0) \approx 1.2 \times 10^{-28} \left(1 + \frac{\epsilon_0}{0.2 \text{ GeV}}\right)^{-1.45} \left(\frac{\epsilon_{cr}}{10^{-12} \text{ erg cm}^{-3}}\right).$$

The photon number density $n_{\gamma, Li}$ expected to accompany the fusion of $^6\text{Li}$ can then be written as,

$$n_{\gamma, Li}(\epsilon_0) \approx 1.16 \times 10^{-8} \left(1 + \frac{\epsilon_0}{0.2 \text{ GeV}}\right)^{-1.45} \left(\text{Li/H} \times 10^{-11}\right),$$

where we have used equation (4) to eliminate the dependence on cosmic-ray energy density and time.

Prodanović and Fields (2004, eq. 3) provide a convenient fit to the observed extragalactic gamma-ray background. We integrate it to estimate the flux above $\epsilon_0$ to be

$$F_{\gamma}(\epsilon_0) \approx 5 \times 10^{-6} \left(\epsilon_0/0.2 \text{ GeV}\right)^{-1.2} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},$$

for $0.05 \text{ GeV} < \epsilon_0 < 1 \text{ GeV}$. Following Silk and Schramm (1992), and using the present-day mean proton density $n_{p,0} \approx 1.9 \times 10^{-7} \text{ cm}^{-3}$, we can write the observed gamma-ray flux as

$$\frac{n_{\gamma, Li}(\epsilon_0)}{n_{p,0}} \approx 1.1 \times 10^{-8} \left(\epsilon_0/0.2 \text{ GeV}\right)^{-1.2}.$$  

We then find that a fraction $\approx 0.15 - 0.2$ of the extragalactic gamma ray background between $0.1 - 1 \text{ GeV}$ could have been produced by cosmic rays responsible for the cosmological production of $^6\text{Li}$.

5 SUMMARY

We have drawn attention to the connection between the possible origin of $^6\text{Li}$ in halo metal-poor stars and the excess entropy in galaxy clusters as indicated by X-ray observations. Spallation reactions and heat losses by cosmic rays can reproduce the observed abundance of $^6\text{Li}/\text{H} \sim 10^{-11.2}$ by $z \approx 2$ and raise the entropy of cluster gas to $\sim 300 \text{ keV cm}^2$ by $z \approx 0$. The required energy budget is consistent with that expected from radio-loud AGNs. The size of the region heated by cosmic-ray protons ($\sim 0.7 \text{ Mpc}$) is comparable to the observed scales of gas with excess entropy. The expected gamma-ray flux from pion decay is a fraction $0.15 - 0.2$ of the observed extragalactic background at $0.1 - 1 \text{ GeV}$. The scenario described in this paper then ties together two apparently disparate sets of observations – of enhanced $^6\text{Li}$ abundance in metal-poor stars and of enhanced entropy in gas in galaxy groups – with a population of cosmic rays that may have originated from AGN activity at early times.

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