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LITHIUM IN SMALL MAGELLANIC CLOUD: IMPLICATIONS FOR NEW PHYSICS

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Abstract. One of the main tests of the standard hot Big Bang model comes from predictions of abundances of primordial element, which have been synthesized during the epoch of the Big Bang nucleosynthesis. Though there is a general agreement, there is one more and more pressing disagreement that has not yet been resolved predicted primordial lithium abundance is about 4 times higher than what is observed in atmospheres of MilkyWay halo stars at wide range of low metallicities. To test this issue lithium was observed in the interstellar medium in the Small Magellanic Cloud. The measured abundance was found to be barely consistent with the predicted primordial value, but only very little lithium was made in the cosmic-ray interactions. However, unlike the Milky Way, the Small Magellanic Cloud has suffered a significant tidal disruption due to close galactic fly-bys. We point out that in those cases, tidal shocks can give rise to a population of cosmic rays in addition to standard galactic cosmic rays accelerated in supernova shocks. We demonstrate that significant amount of lithium can be produced in such a scenario where a small galaxy is tidally disrupted in close galactic interactions. In the specific case of the Small Magellanic Cloud, this could potentially be sufficient to make its lithium abundance also inconsistent with the predicted primordial value, leaving the new physics as the only remaining solution to this discrepancy.

1. INTRODUCTION

There are many ways to search and probe the physics beyond the standard model: hoping to see the unexpected in accelerator experiments, hoping to directly detect dark matter, or interpreting the actual detection of the unexpected as a signature of non-standard physics. An example of the "unexpected" would be the recent detection of the gamma-ray excess from the galactic center, which can be interpreted as a dark matter signal (Daylan et al. 2014), though more conventional solutions are also still possible (see e.g. Petrović et al. 2014a,b). Another way to test the non-standard physics is to search for the anomalies in the abundances of primordial elements.

Abundances of the primordial elements- hydrogen, helium and lithium-7, directly depend on the physical conditions of the early Universe and the physics that drives the big bang nucleosynthesis (BBN). The competition between the expansion rate of the Universe and rate of nuclear reactions, eventually comes down to one number that controls primordial element abundances- the baryon-to-photon ratio, or the baryon density. The WMAP (Wilkinson Microwave Anisotropy Probe) high-precision observations (Dunkley et al. 2009) of the cosmic microwave background (CMB) have marked the beginning of the era of precision cosmology because of the precision with which the baryon density is determined from the CMB, from which then primordial element abundances are determined. However, when theoretically predicted and CMB calibrated primordial abundances are compared to observations of these abundances in low-metallicity systems where the composition should be close to pristine, large discrepancies are found in some cases. Even though observations of helium, and especially deuterium abundance in low-metallicity systems match well with their predicted abundances, this is not the case for lithium. Namely, as we can see in Fig. 1, the primordial lithium abundance (7Li/H)p = $(4.79 \pm 0.96) \times 10^{-10}$ (Cyburt 2013) predicted by the standard BBN models with baryon density set by Planck (Planck Collaboration 2013), was found to be ≈4 times higher than lithium observed in low-metallicity halo stars where abundances show a trend in the form of the so-called "Spite plateau" (Spite & Spite 1982) at the level $(7\mathrm{Li/H})_{obs} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (Ryan et al. 2000). This has been known as the "lithium problem".

2. "LITHIUM PROBLEM" ISSUES

In order to understand the issues around the lithium problem we first must know its origin. Lithium-7 is made in the big bang nucleosynthesis process but is also made in neutrino process in type II supernovae, and together with its light isotope ^{6}Li, in cosmic-ray interactions (Reeves 1970) through fusion channel $\alpha + \alpha \rightarrow ^{6,7} Li + ...$ and spallation reactions on heavier nuclei $p, \alpha + CNO \rightarrow Li, Be, B + ...$ As we can see, the spallation process also results in production of other light nuclei beryllium and boron, but due to necessary presence of CNO, this process is important at higher metallicities. It is also important to note here that unlike its heavy version, light isotope ^{6}Li is only made in cosmic-ray interactions. Pre-galactic lithium abundance that is supposed to reflect the primordial value, is observed in atmospheres of old, warm metal-poor halo dwarf stars. In their famous paper Spite & Spite 1982 have shown that lithium abundance observed in many of these stars over the range of low-metallicities does not change and forms a plateau value with very little scatter. The existence of the plateau is expected for all primordial elements, if observations are made at a sufficiently low metallicity with sufficient statistics. However, as it became evident, the observed plateau is by a factor of 4 lower than the expected primordial lithium abundance. Furthermore, more observations have also found that the plateau in fact has a slight slope and also it breaks down, i.e. shows large scatter at very low metallicities.

The solution to the lithium problem is either in correcting the observed abundances by changes in stellar modeling, by accounting for some stellar or pre-stellar destruction of lithium, or in changing the prediction of primordial lithium abundance due to any non-standard physics. One of the main issue in destroying lithium in stars (due to e.g. deep mixing) is how to do it uniformly over a large range of metallicities so that

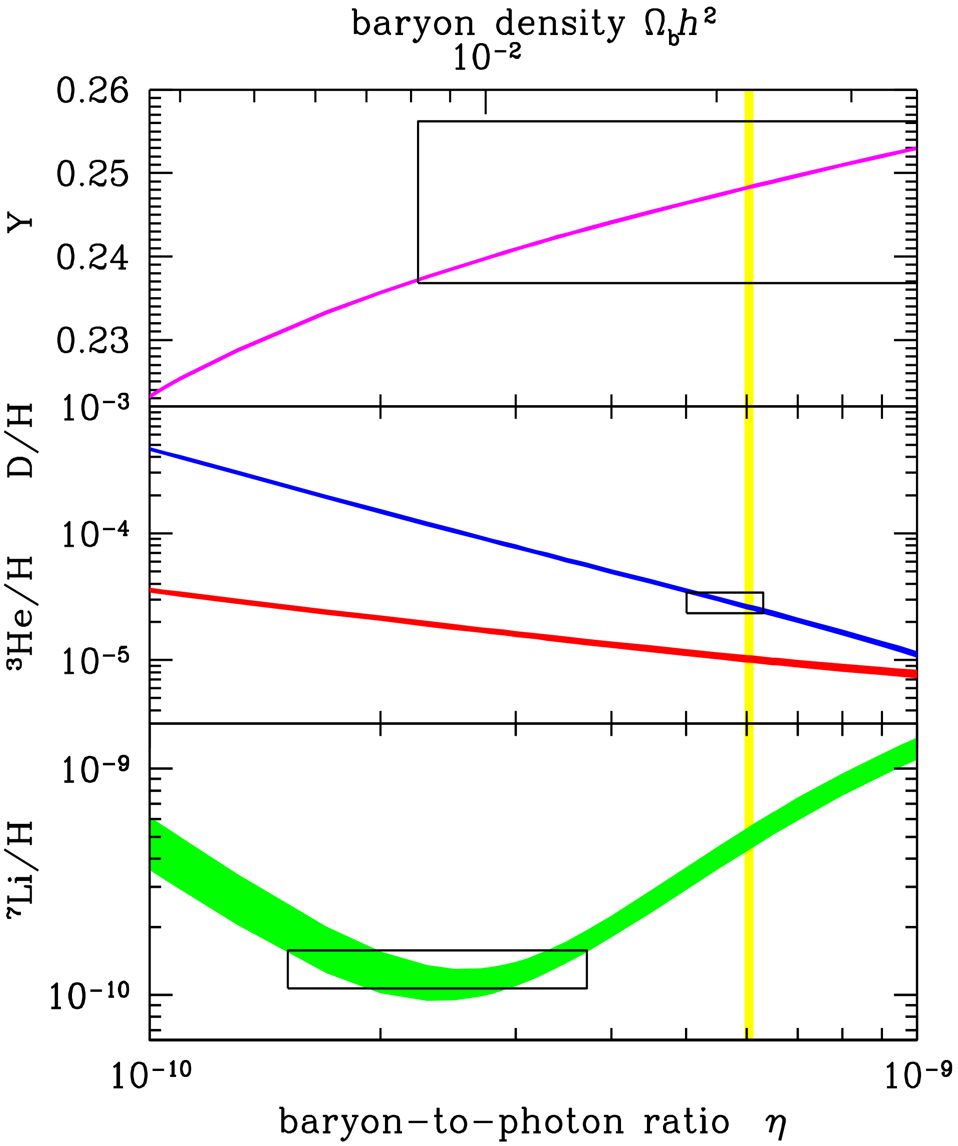

Figure 1: The so-called Schramm plot of primordial element abundances as a function of baryon-to-photon ratio and compared to abundances obtained from observations in low-metallicity systems presented as boxes (Cyburt 2013). The yellow band represents baryon density as determined by Planck Collaboration 2013.

very little scatter remains, especially when looking at the upper abundance envelope. Another issue is a worry that even this low lithium abundance observed in low-metallicity halo stars could have been contaminated (Suzuki & Inoue 2002) by post-BBN production of lithium in various processes such as for example interactions of cosmological cosmic rays accelerated during the large-scale formation process (Prodanović & Fields 2007). If there is any post-BBN and pre-galactic production of lithium that extra abundance will add to the lithium content in halo stars and must be corrected for when comparing it to the primordial lithium abundance. Given that the observed abundance is already lower than the primordial one, any additional lithium production channel would only make the problem worse. One way to constrain lithium production by any cosmic-ray population is to look into gamma rays since there is a unique and direct connection between expected gamma-ray emission and lithium production due to cosmic ray interactions (Fields & Prodanović 2005). Extragalactic gamma-ray emission due this cosmological cosmic-ray population was recently constrained (Dobardžić & Prodanović 2014) and can thus be used to constrain pre-galactic lithium production by this cosmic-ray population, which is now, due to lower level of the extragalactic gamma-ray background detected by Fermi-LAT lower than previous estimates (Prodanović & Fields 2007) but still allows for significant fraction of the lithium plateau to be made by cosmological cosmic rays (Dobardžić & Prodanović 2015).

3. NEW SITES FOR PRIMORDIAL LITHIUM OBSERVATIONS

One of the most useful tests of the nature of the lithium problem would be to measure lithium in the gas phase, rather than is stellar atmosphere, in some low-metallicity system. One such potentially suitable target system was suggested to be the high velocity cloud Complex C (Prodanović & Fields 2004). Unfortunately it turned out that there is no suitable line of sight along which lithium can be measured in this gas cloud, and the search for another site where lithium can be measured in gas phase has continued. Recently, Howk et al. 2012, have made the first observation of extragalactic gas-phase lithium. They have observed lithium in the Small Magellanic Cloud at metallicity ≈1/5 of solar. The abundance they measured was found to be consistent with prediction of primordial lithium abundance. However, in the system at fifth of solar metallicity, significant post-BBN production of lithium should have happened due to galactic cosmic-ray nucleosynthesis, and thus, the found lithium abundance is in tension with galactic chemical evolution models. Moreover, isotopic ratio of $^6\mathrm{Li}/^7\mathrm{Li}$ was found to be anomalously high, at the level of $^6\mathrm{Li}/^7\mathrm{Li} \approx 0.13$ (Howk et al. 2012). Given that $^6\mathrm{Li}$ is only made in cosmic-ray interactions, high isotopic ratio implies a non-standard cosmic-ray history of the system.

However, it has been known that the Small Magellanic Cloud (SMC) has experienced close galactic fly-bys and tidal disruptions (Diaz & Bekki 2011). Galactic interactions can cause large scale tidal shock waves (Cox et al. 2006), which would in turn, result in particle acceleration and in a population of tidal cosmic rays (TCRs). As mentioned, any cosmic-ray population, additional to standard galactic cosmic rays (GCRs) accelerated in supernova remnants, would be contaminant when lithium abundance measured in low-metallicity systems is compared to its expected primordial abundance. Besides lithium, cosmic-rays also produce beryllium and boron, however at low-metallicities, spallation channel would be suppressed compared to fusion channel, so lithium would be affected most.

4. LITHIUM PRODUCTION BY TIDAL COSMIC RAYS

In Prodanović et al. (2013) we have explored the possibility of extra production of lithium by tidal cosmic rays, especially in the case of the Small Magellanic Cloud where lithium has recently been measured. The main question we tried to answer is whether it is possible energy-wise and sufficient flux-wise for close galactic fly-bys between the SMC and Large Magellanic Cloud and/or Milky Way to result in such tidal cosmic ray flux which would make comparable amount of lithium as standard GCRs have made over the history of the SMC. We have shown that the kinetic energy between SMC and the Milky Way at their current separation, is about 50 times higher than the energy needed to produce all lithium observed in the SMC. Continuing further, we have made a toy model comparing tidal shock that would arise due to a close galactic fly-by to a large-scale supernova shock. The main difference between cosmic rays accelerated in tidal shocks and supernova shocks then comes from the scale of the shock itself and from occurrence frequency where tidal shocks would arise due to a few episodes of close encounter while supernova shock are constantly occurring throughout the history of the SMC as long as there is ongoing star-formation.

As the result of our toy-model we have shown that in order for TCRs to produce same amount of lithium in isolated close fly-by events as GCRs have accumulated over the history of the system, the fraction of the entire gas of the system that needs to be shocked (so that particles get accelerated!) is a function of

$$M_{TCR}/M_{gas} \propto M_{Fe,SN}^{-1} y_{Fe} \tau_{TCR}^{-1} n_{ISM} R_{SNR} \tag{1}$$

mass of iron ejected by one supernova $M_{Fe,SN}$, metallicity y_{Fe} and density n_{ISM} of the system, radius R_{SNR} of the supernova remnant up to which GCRs are efficiently accelerated (note here that we have assumed the same efficiency in accelerating TCRs as well as GCRs), and the lifetime timescale of tidal cosmic-ray population τ_{TCR}. We have further found that for a system at solar metallicity it would be sufficient to shock the entire gas of the system 8 times in order for TCRs to produce as much lithium as GCRs have produced, while in the case of the SMC which is at 1/5 of solar metallicity, the entire gas of the SMC would need to be shocked only 2 times to achieve this, and we know that SMC has suffered at least 2 interactions with the LMC and one with Milky Way. Thus, production of lithium via TCRs can potentially be very important, especially in the case of the SMC where the first gas-phase measurement of lithium abundance outside our own galaxy has recently been made in order to test the lithium problem. In order to test this, one must first test all of the underlying assumptions. While some of our assumptions were reasonable and are not expected to change much, the main caveat comes from the TCR lifetime timescale assumption which can vary by an order of magnitude and can the shocked gas mass ratio. This has to be tested in numerical models and will be the topic of the followup work.

One other way to test any additional production of lithium would be to look into the isotopic ratio. As already mentioned, the isotopic ratio detected in the SMC was found to be anomalously high. Namely, isotopic ratio was observed to be at the level ^{6}Li/^{7}Li $\approx$ 0.13 (Howk et al. 2012), which is consistent with the isotopic ratio of ^{6}Li/^{7}Li = 0.1 (Prodanović et al. 2013) that would be expected if 50% of total lithium abundance was made by TCRs, as opposed to the expected isotopic ratio of ^{6}Li/^{7}Li = 0.06 where only lithium production by GCRs is included. Another observational way to test for the presence of TCRs would be to look into interacting systems of galaxies, especially into the smaller of the galaxies, and search for anomalously high non-thermal emission in radio frequencies that is inconsistent with that galaxies star-formation rate. Later on, tidal disruptions could trigger star-formation and result in an episode of enhanced star-formation in the smaller of the galaxies, but prior to that, TCRs should be accelerated resulting in enhanced synchrotron emission. Though further investigation is needed, our first estimates indicate that this might be true in the case of M51.

5. CONCLUSION

The discrepancy between expected primordial abundance of lithium and that observed in low-metallicity halo stars is an outstanding problem that can have important consequences for our understanding of the big bang nucleosynthesis and cosmology in general. One of the main issues related to the origin and nature of this problem is the fact that lithium has only been observed in stellar environment, where results depend on stellar modeling. The only measurement of lithium in a different low-metallicity environment was recently done in the interstellar medium of the SMC metallicity 1/5 of solar. Although observed SMC lithium abundance was found to be consistent with expected primordial abundance, this is only true if there was very little post BBN production of lithium in cosmic-ray nucleosynthesis and other processes, which is in strong tension with chemical evolution models of the SMC. Moreover, as we have pointed out in Prodanović et al. (2013), SMC is a system that has experienced a few close galactic fly-bys, which could have given rise to tidal shock waves in the SMC. Consequently this would lead to cosmic-ray acceleration and additional lithium production, and we have shown that in the case of the SMC, the entire gas of the SMC would have to be shocked only twice for TCRs to produce as much lithium as GCRs have produced. Even though our results come from a simple, but instructive toy model, we have shown that the existence of a tidal cosmic ray population might be important for smaller interacting galaxies.

If indeed significant fraction of the lithium in the SMC comes from an additional source like TCRs, this would mean that SMC lithium measurement is also inconsistent with predicted primordial abundance and consistent with lithium observed in low-metallicity halo stars, implying that the solution to the lithium problem should be sought in the form of the new physics which would either result in a lower primordial lithium abundance or would destroy lithium at very low metallicity, before halo stars were born. Furthermore, enhanced non-thermal emission due to a population of cosmic rays, which is not related to supernova rate would impact the far infrared-radio correlation (see e.g. Lacki et al. 2010), determinations of star-formation rates and have other important consequences. Thus, this is an issue that has to be further investigated in more detail, both numerically and by looking at surveys of interacting systems in different wavelengths.

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