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Lithium production in galactic flybys

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Abstract. Unlike ^{7}Li plateau which is expected but observed at a level that is difficult to explain, ^{6}Li observations in low-metallicity halo stars also reveal a plateau which is completely unexpected within the standard picture of ^{6}Li origin in galactic cosmic-ray (GCR) interactions. This indicates the existence of a new Li source, however all considered sources (e.g. supernovae, shocks due to structure-formation etc.) either completely fail to explain the observed abundance or require some fine-tuning. Here we present another possible source of lithium cosmic rays that arise due to galactic flybys. Gravitational interaction between two galaxies flying by each other could result in large-scale tidal shocks that would give rise to a new cosmic-ray population tidal cosmic rays. Such cosmic-ray population would increase the ^{6}Li (and ^{7}Li) abundance, but not be accompanied with increase in metallicity or gas content. The details, of course, depend on interacting galaxies. Our preliminary results presented here demonstrate that this could be an important source of lithium in some sites, such is the Small Magellanic Cloud which has experienced close encounters with the Large Magellanic Cloud and the Milky Way during its history.

Key words. Small Magellanic Cloud, cosmic rays, tidal shocks

1. Introduction

Unlike ^{7}Li which is created also during the big bang nucleosynthesis (BBN), light isotope ^{6}Li is created only in cosmic-ray interactions (Reeves 1970). However, recent hints of the ^{6}Li ”‘plateau”’ in low-metallicity halo stars (Asplund et al. 2006) have indicated the potential need for a new source of ^{6}Li. Though some solutions can be found within a non-standard BBN (Jedamzik et al. 2006), most conventional solutions are in the form of a new cosmic-ray population (see eg. Suzuki & Inoue 2002). Being that any cosmic ray population produces both lithium isotopes in ratio varying between ^{7}Li/^{6}Li $= 1.3 - 2$ depending on the cosmic-ray spectrum (Fields & Prodanović 2005), adding another CR source would also increase the severity of already existing discrepancy between primordial ^{7}Li abundance predicted from *WMAP* observations (Spergel et

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al. 2003) and under abundance of ^{7}Li observed in low-metallicity halo stars ("'Spite plateau"' Spite & Spite 1982), known as the "'lithium problem"' (Prodanović & Fields 2007; Cyburt et al. 2008). Another problem with finding a new, significant, cosmic-ray source of ^{6}Li is that it would usually be accompanied with overproduction of metals, or would require too much energy (Prantzos 2006). We present another possible source tidal cosmic rays (TCRs), accelerated in tidal shocks that would arise in a galaxy during close galactic flybys. Galactic mergers and close flybys give rise to large-scale shocks in the gas of interacting galaxies (Moore et al. 1996). Such shocks would inevitably accelerate cosmic rays which would not be directly accompanied with increase in metallicity. Our preliminary results demonstrate that these shocks have sufficient energy and could result in cosmic-ray fluxes high enough to, in some cases, produce significant amount of lithium. Whether or not the Asplund et al. (2006) ^{6}Li "plateau" is real (see e.g. Lind 2012), the question of cosmic-ray sources of lithium other than standard galactic cosmic rays remains important for understanding the magnitude of the lithium problem, because it would act as a contaminant - any observed ^{7}Li abundance would then be a mix of primordial and GCR-made ^{7}Li and ^{7}Li made in any other possible source. Recent observations of lithium abundance in the low-metallicity gas of the Small Magellanic Cloud are a direct probe of the lithium problem (Howk 2010, 2012) because they provide an independent measurement of the pre-galactic lithium abundance (Prodanović & Fields 2004), free of any uncertainty which accompanies lithium measurements in stellar spectra. However, in this work we demonstrate that lithium abundance in low-metallicity sites such is the Small Magellanic Cloud (SMC) which have experienced galaxy harassment in their history (Diaz & Bekki 2011), could have significantly been contaminated by the production from tidal cosmic rays.

2. Energy requirement

In order to produce significant amounts of lithium comparable to level expected from conventional sources (BBN, GCRs), any new cosmic-ray lithium source must first satisfy energy requirements. In the case of tidal cosmic rays, energy released in large scale tidal shocks, which arise from close flybys between galaxies, should account for the energy necessary to produce the level of lithium measured in those galaxies. Energy available from a galactic flyby event can be roughly estimated as the kinetic energy of the encounter for a satellite galaxy plunging towards the primary on a nearly radial orbit.

$$
\begin{aligned}
E_{\rm kin} &= \frac{q\,G\,M_1^2}{d} \\
&\approx 4\times10^{57}\,{\rm erg} \\
&\quad\times\left(\frac{q}{10^{-3}}\right)\left(\frac{M_1}{10^{12}M_\odot}\right)^2\left(\frac{d}{50\,{\rm kpc}}\right)^{-1} \qquad (1)
\end{aligned}
$$

This estimate corresponds to minor encounter of primary galaxy M_1 with small satellite galaxy M_2 at a distance d, where $q = M_2/M_1$. Simulations show that encounters with low q values are more damaging for the satellite galaxy (Callegari et al. 2011), where because of shallower potential well, gas of the satellite galaxy can be strongly shocked or tidally stripped. This is now maximal energy that could potentially be used for accelerating particles that would produce lithium. ^{6}Li is produced in cosmic-ray interactions, dominantly via the $\alpha\alpha \to {}^6$Li fusion channel, which places energy constraints on any cosmic-ray source. Energy required for ^{6}Li production via this channel is about 16 erg/nucleus (Prantzos 2006). Thus, the energy required to pollute the interstellar medium (ISM) gas $M_{\rm ISM}$ of a given satellite galaxy with lithium is then

$$
E_6 \approx 3\times10^{57}\,{\rm erg}\left(\frac{y_6}{y_{6,\odot}}\right)\left(\frac{M_{gas}}{10^9M_\odot}\right) \qquad (2)
$$

where lithium abundance is defined as $y_{6,} \equiv {}^6{\rm Li/H}$ with solar value taken $y_{6,\odot} = 1.53\times 10^{-10}$ (Anders & Grevesse 1989).

In the specific case of the SMC, with gas mass of $M_{gas}(r < 3{\rm kpc}) = 3\times10^8 M_\odot$ (Bekki & Stanimirović 2009), the energy required to pollute all gas with the lithium abundance at the level expected for the SMC metallicity 1/5 solar (Peimbert et al. 2000), would be $E_{6,\mathrm{SMC}} \sim 2\times10^{56}$erg. Taking the Milky Way as the primary galaxy which is causing the disruption, the energy available for particle acceleration and lithium production that comes from the MW-SMC interaction at a present day distance of $d = 61$ kpc (Hilditch et al. 2005), is thus $E_{kin,\mathrm{SMC-MW}} \sim 10^{58}$erg. Therefore, only about 2% of this energy would have to go into particle acceleration to account for all of the lithium produced assuming that the SMC gas phase has been uniformly polluted by lithium everywhere.

3. Cosmic rays: Tidal vs. Galactic

Tidal shocks that would arise from close galactic flybys would inevitably accelerate particles and give rise to the a new cosmic-ray population within a given galaxy. These cosmic rays can be a potentially important source of lithium at some sites if they can produce Li in comparable amounts to what GCRs have produced over history. Since GCRs are constantly accelerated in supernova remnants (SNR) while TCRs arise only during isolated flyby events, for TCRs to be as efficient in producing lithium as GCRs, they have to be accelerated in a much larger volume to have sufficiently high fluxes. Though mechanisms are different, the assumption is that the underlying physics of cosmic-ray acceleration for both CR populations is similar. Thus, assuming that TCRs are accelerated by diffusive shock acceleration just like the standard GCRs do (Bell 1978; Blandford & Ostriker 1978), we estimate the amount of gas that has to be shocked in order to produce sufficiently large TCR flux, which would within a give timescale result in significant lithium production.

We now estimate the fraction of the gas in the galaxy that has to be shocked in a single satellite flyby, to give rise to a TCR flux sufficient to produce the amount of lithium comparable to that produced by the GCR population over the satellite's history.

$$\frac{M_{T,swept}}{M_{gas}} \approx 8\left(\frac{0.2M_\odot}{M_{\mathrm{Fe,SN}}}\right)\left(\frac{y_{\mathrm{Fe}}}{y_{\mathrm{Fe},\odot}}\right)\left(\frac{10^9\mathrm{yr}}{\tau_{TCR}}\right)$$
$$\times\left(\frac{n_{ISM}}{1\mathrm{cm}^{-3}}\right)\left(\frac{R_{SNR}}{10\mathrm{pc}}\right)^3\left(\frac{\eta_{GCR}}{\eta_{TCR}}\right) \qquad (3)$$

Here y_{Fe} is the iron abundance (metallicity) of the satellite system, $M_{\mathrm{Fe,SN}}$ is the average supernova iron yield (all SN types) where the fiducial value is taken to be $M_{\mathrm{Fe,SN}} = 0.2M_\odot$ (Pagel 2009), τ_{TCR} is the assumed lifetime of tidal cosmic-ray population (timescale of the flyby event), n_{ISM} is the number density of the ISM around supernova remnants, R_{SNR} is the maximal supernova remnant radius within which it is efficiently accelerating particles (Berezhko & Völk 2004), while η is the dimensionless particle injection efficiency parameter. Note that the absolute injection efficiency does not have to be assumed - the only relevant thing is the relative particle injection efficiency between supernova and tidal shocks. The result presented in equation (3) tells us that in order for TCRs to produce as much lithium as GCRs have produced up to given epoch, the entire ISM gas of a given system (at solar metallicity!) must be shocked 8 times, if fiducial values of our parameters are adopted. For a specific case of SMC, which is at a metallicity of 1/5 of solar, and with other parameters taken at fiducial values, we get $M_{T,swept}/M_{gas} \sim 2$, i.e. the entire SMC gas has to be tidally shocked only about twice to allow for enough TCRs to be accelerated to produce as much lithium as GCRs did over the history. If we assume that all gas gets tidally shocked only once per one galactic flyby, then one such encounter could produce half the lithium that GCRs make, which, at the SMC metallicity, would result in the lithium isotopic ratio of $^7\mathrm{Li}/^6\mathrm{Li} \sim 13$, while two such encounters would decrease this ratio to $^7\mathrm{Li}/^6\mathrm{Li} \sim 10$. This isotopic ratio would be anomalously low compared to ratio expected at such metallicity. However, new lithium observations in the SMC gas indicate isotopic ratio of $^7\mathrm{Li}/^6\mathrm{Li} \sim 8$ (Howk 2010, 2012), consistent with our result.

4. Conclusions

Close flybys between galaxies can result in large scale shocks in the galactic gas which would inevitably result in particle acceleration and give rise to a population of tidal cosmic rays. This would especially be important for interactions between a major galaxy such is the Milky Way and a minor satellite galaxy where these shocks would arise, such is the Small Magellanic Cloud which has already suffered galaxy harassment by the Milky Way and Large Magellanic Cloud as well. Consequently, presence of any new cosmic ray population (other than standard cosmic rays accelerated in SNRs) would lead to extra production of both lithium isotopes. Our preliminary results show that energy of the interaction between MW and SMC is sufficient to produce significant amount of lithium. Moreover, our first estimate shows that gas of the SMC would have to be tidally shocked only about twice in order for TCRs to produce as much lithium as GCRs have produced over history. This would lead to anomalously low ^{7}Li/^{6}Li ratio in systems such is the SMC, possibly consistent with most recent observations of lithium in the gas phase of the SMC (Howk 2010, 2012). Finally, we note that our estimate was done under the assumption that the entire SMC gas was uniformly polluted by lithium everywhere to the observed value. However, if pollution driven by flybys is confined to certain regions of SMC (as opposed to whole SMC), then only one flyby may be sufficient to enrich the gas to the observed level. In that sense, the requirement for two episodes of tidal shocking is an upper limit on the number of flybys.

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