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Lithium in the closest satellite of our Milky Way

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Abstract. Recently, we studied the chemical evolution of lithium in the thin disc of the Milky Way. We found that the best agreement with the observed Li abundances in the thin disc is obtained considering novae as the main source of lithium. We assumed a delay time of ≈1 Gyr for nova production and an effective ^{7}Li yield of 1.8(± 0.6)x10^5 $M_\odot$ over the whole nova lifetime. The possibility to check our detailed assumptions on lithium production on other stellar systems, such as the satellites of our Milky Way, is seriously hampered by their distance from us. In these systems dwarf stars (where the original lithium can be measured) are too faint to detect lithium lines. However, thanks to the Gaia mission, it was recently possible to disentangle the stars of a disrupted dwarf galaxy in the Galactic halo (called Enceladus or Galactic sausage). Adopting a chemical evolution model tuned to match the metallicity distribution function of Enceladus stars, we present our predictions for the lithium abundance of the stars of this disrupted galaxy.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: abundances

1. Introduction

In the last decades, kinematical and chemical surveys of the stars of the Galactic halo revealed streams and structures belonging to different stellar groups.

The Gaia survey has revealed a component in the inner halo showing a peculiar velocity and with metallicities $Z \approx Z_\odot/10$ which are relatively more metal-rich than the Galactic halo (Helmi et al. 2018).

This structure called Gaia-Enceladus or also Gaia Sausage (Belokurov et al. 2018), likely represents a disrupted dwarf galaxy after a major collision with the Milky Way which happened more than 10 Gyr ago. In the Galactic halo, a population of stars showing low-[α /Fe] stellar component was already identified and this was explained as stars possibly accreted from dwarf galaxies.

Gaia-Enceladus offers an unique opportunity to study the chemical abundances of chemical elements in a dwarf galaxy which is normally hampered by their large distance from us. A detailed chemical analysis of these stars was carried out in (Vincenzo et al. 2019). Here, we focus on ^{7}Li in dwarf stars which are normally out of reach in dwarf galaxies of the local group.

2. Chemical evolution model for Gaia-Enceladus

In this Section, we describe the main characteristics of a generic chemical evolution models; moreover, we describe how we set its parameters to match the particular chemical evolution of Gaia-Enceladus; with this model we intend predict the Li abundance in the Gaia-Enceladus. The infall law is:

$$A(t) = M_{Enc} Gauss(\sigma_{Enc}, tau_{Enc}) \qquad (1)$$

where Gauss is a normalised Gaussian function, τ_{Enc} is time of the center of the peak and σ_{Enc} the standard deviation; M_{Enc} is the total amount of the gas accreted into Gaia-Enceladus. The star formation rate (SFR) is:

$$\psi(t) = \begin{cases} \nu_{Enc}\Sigma(t)^k & t \leq T_{Enc} \\ 0 & t > T_{Enc} \end{cases} \qquad (2)$$

where ν_{Enc} is the efficiency of the star formation, $\Sigma(r)$ is the surface mass density, and the exponent, k, is set equal to 1.5 (Kennicutt 1989); T_{Enc} is the time when Gaia-Enceladus stops forming star, due to the interaction with the Galaxy. A galactic wind is considered as follows:

$$W(t) = \begin{cases} \nu^{wind}_{Enc}\psi(t) & t \geq T^{wind}_{Enc} \\ 0 & t < T^{wind}_{Enc} \end{cases} \qquad (3)$$

where T^{wind}_{Enc} is when the galactic wind in Gaia-Enceladus starts due to interaction with the Galaxy and ν^{wind}_{Enc} is the wind efficiency. Seven parameters - ν_{Enc}, M_{Enc},τ_{Enc}, σ_{Enc} T_{Enc}, T^{wind}_{Enc} and ν^{wind}_{Enc} - determine the equations of the chemical evolution model for Gaia-Enceladus. These parameters are obtained by minimise the results of the model and the chemical properties of the kinematically selected stars of Gaia-Enceladus measured by the APOGEE survey (Helmi et al. 2018) and in particular the metallicity distribution function (MDF); more details will be available in (Cescutti et al. 2020) The best parameters are summarised in Tab 1. The MDF obtained with the best parameters is compared to the observational MDF of Gaia-Enceladus stars in Fig. 1. We obtain as best parameter for the surface mass density of Gaia-Enceladus (M_{Enc}) 2 $\mathrm{M}_{\odot}/pc^2$.

Table 1. Best parameters for the chemical evolution of Gaia-Enceladus.

parameter	best value
ν_{Enc} (star formation efficiency)	1.3 Gyr^{-1}
M_{Enc} (surface mass density)	2.0 $\mathrm{M}_{\odot}/pc^2$
τ_{Enc} (peak of the infall law)	550 Myr
σ_{Enc} (SD of the infall law)	1408 Myr
ν^{wind}_{Enc} (galactic wind efficiency)	5.0
T^{wind}_{Enc} (start of the galactic wind)	2919 Myr
T_{Enc} (end of the star formation)	5767 Myr

This value is ≈1/30 of the Galaxy, assuming as typical value the solar vicinity with 50-60 $\mathrm{M}_{\odot}/pc^2$. However, only 30% of the total mass is turned into stars during the evolution of Gaia-Enceladus. Thus, a rough estimate of the total stellar mass of Gaia-Enceladus should be approximately $<10^9$ $\mathrm{M}_{\odot}$. We also compare the predicted [α/Fe], with the abundances measured by APOGEE. These data were not used to establish the best parameters. As it is shown in Fig. 2, the predictions of the model in the [α/Fe] vs [Fe/H] plane are in excellent agreement with the data from the APOGEE survey. A minimise procedure was adopted also by Vincenzo et al. (2019) to determine the chemical evolution model for Gaia-Enceladus. The main difference is that Vincenzo et al. (2019) used the data in the [α/Fe] vs [Fe/H] to constrain the parameters of the chemical evolution model, whereas in our approach the results of the model in [α/Fe] vs [Fe/H] are a prediction. Moreover, the galactic wind in our Gaia-Enceladus model is due by the interaction with the Galaxy and so T^{wind}_{Enc} is a parameter. In Vincenzo et al. (2019), it is determined by number of supernovae explosions and the gravitational potential of Gaia-Enceladus (Lanfranchi et al. 2006).

3. Lithium evolution model results in Gaia-Enceladus

In Fig. 3, we show the predictions for ^{7}Li in Gaia-Enceladus of our theoretical model, based on the assumptions on the nucleosynthesis described in Cescutti & Molaro (2019) and the parameters of chemical evolution for Gaia-Enceladus derived in Sect. 2. The sample

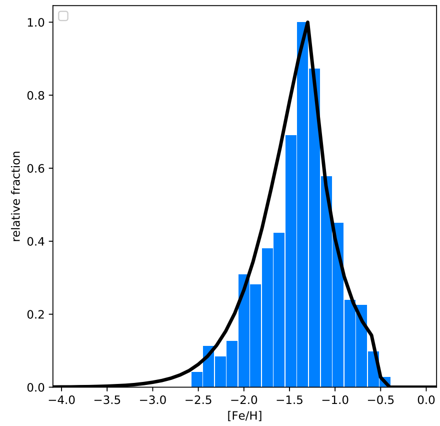

Fig. 1. Metallicity distribution function for Gaia-Enceladus. The histogram represents the observational data, the black line shows the model results.

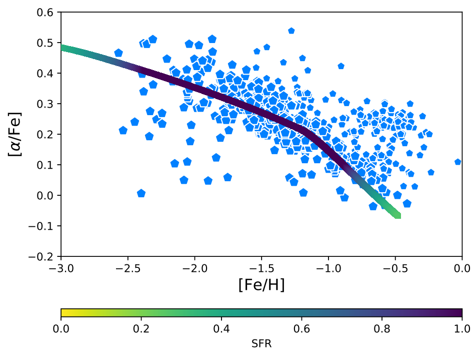

Fig. 2. [α/Fe] as a function of [Fe/H]. The cyan pentagons are stars measured by APOGEE, which belong to Gaia-Enceladus according to Helmi et al. (2018). The model is shown as a line and it is colour-coded according to the SFR (see colorbar).

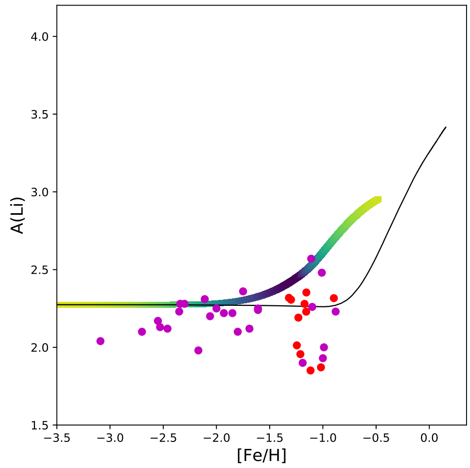

Fig. 3. Log(Li/H) vs [Fe/H]. Theoretical model results are presented with the observational data. The model is shown as a line colour-coded according to the SFR. For comparison we show with a black solid line the model results for the thin disc presented in Cescutti & Molaro (2019). The observational data are shown as solid circles. They are dwarf stars (logg>3.65) and Gaia-Enceladus members. Red circles are stars from the GALAH survey, magenta dots from literature.

of Gaia-Enceladus stars was obtained by cross-matching the sample of 4644 confirmed Gaia-Enceladus member stars (Helmi et al. 2018) with the GALAH survey (Buder et al. 2018) and literature data (for details, see Molaro et al. 2020). The model predicts lithium abundances for Gaia-Enceladus stars which rise from the Spite plateau at [Fe/H]~ -1.8. On the other hand, the best model for the Milky Way shows a similar increase, but at [Fe/H]~ -1. Therefore, the model predicts for the Gaia-Enceladus stars higher lithium abundances compared to the genuine stars of the Milky Way of in the metallicity range $-1 <$[Fe/H]< -0.5. Clearly, this holds only for those stars that still maintain their lithium original abundances (so dwarf stars with T>5700K). The predicted overabundance is at maximum of 0.5 dex, but in most cases is within the observation uncertainties. Still, it should be feasible to assess this difference, and in the future with surveys measuring a large number of stars in this metallicity region, a statistical approach can be used to test our results. At present, most of the Gaia-Enceladus stars have similar behavior the one of the Milky Way stars. Nevertheless, two stars present an enhancement of lithium precisely on the model results predicted for Gaia-Enceladus.

4. Discussion

Recently several efforts have been made to measure *extragalactic* ^{7}Li abundance. Li measured belonging to Gaia-Enceladus are robust "extragalactic " measurements of Li. Omega Centauri (ω Cen) is a globular cluster-like stellar system characterised by a wide range of metallicities and probably ages. Usually, it is thought as the stripped core of a dwarf galaxy. Monaco et al. (2010) found that dwarf stars in ω Cen display a constant Li abundance and this is observed among stars spanning a wide range of ages and metallicities overlapping with the Spite plateau. Mucciarelli et al. (2014) were able to derive for the first time the initial lithium abundance in the globular cluster M54 in the nucleus of the Sagittarius dwarf galaxy. Sagittarius galaxy is located at 25 Kpc and its main sequence stars are too faint ($\sim$22 mag) to be studied at high resolution. The only possibility in this case are stars in the red giant branch (RGB). However, the ^{7}Li abundance in RGB stars was modified by stellar evolution and corrections are needed to account for the post main sequence dilution. By considering this dilution, Mucciarelli et al. (2014) have established an initial Li abundance of this stellar system of A(Li)= 2.29$\pm$ 0.11 (2.35$\pm$ 0.11 considering atomic diffusion, too). The analysis of the Gaia-Enceladus stars confirms the findings in Sagittarius and ω Cen: the Li problem seems to be a universal problem, regardless of galaxy. Therefore, the solution must work both in the Milky Way and other galaxies, with different origins and star formation histories. As noted by Mucciarelli et al. (2014), it seems unlikely that the scenario proposed by Piau et al. (2006), requiring that at least one third of the Galactic halo has been processed by Population III, massive stars, can work in the same way in smaller systems like Gaia-Enceladus. According to our chemical evolution model results, we expect that lithium will rise from the Spite plateau at a metallicity lower in Gaia-Enceladus than in the thin disc of the Galaxy. Future observations aiming to relative hot dwarf stars of Gaia-Enceladus will determine the correctness of this prediction.

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