Lower Limits on the Nucleosynthesis of $^{44}$Ti and $^{60}$Fe in the Dynamic Spiral-arm Cosmic-Ray Propagation Model

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Abstract

We have previously focused on studying the electron-capture isotopes within the dynamic spiral-arms cosmic-rays propagation model and empirically derived the energy dependence of the electron attachment rate using the observation of $^{44}$Ti/$^{49}$V and $^{51}$V/$^{53}$Cr ratios in cosmic rays. We have also shown how this relation recovers the energy dependence seen in the lab measurements. In this work, we use this relation to construct the $^{44}$Ti/$^{44}$Ca ratio and place a lower limit on the amount of $^{44}$Ti that is required for it to be nucleosynthesized at the source. The results also imply that the acceleration process of the radioisotopes cannot be much longer than a century timescale (or else the required nucleosynthesized amount has to be correspondingly larger). We also provide a similar lower limit on the source $^{60}$Fe by comparing to the recently observed $^{56}$Fe/$^{56}$Fe.

Key words: cosmic rays – diffusion – Galaxy: kinematics and dynamics

1. introduction

The composition of cosmic rays (CRs) has fascinated researchers for almost half a century: both the composition of CRs that reach the solar system and the primary composition, which is accelerated by supernova remnants (e.g., Ackermann et al. 2013, and references therein). In Benyamin et al. (2016), we studied the composition and propagation of two separate element groups: the “light” elements, Boron through Silicon; and the “heavy” elements, Scandium through Nickel. We found that the optimal primary composition for the “heavy” elements group that best fit the Ni/Fe ratio observation is 95% Iron and 5% Nickel.

In this paper, we continue our study of this group by focusing on two radioactive isotopes, $^{44}$Ti and $^{60}$Fe. We will show that our set of models cannot explain the observation of the two isotopes by only including secondary $^{44}$Ti and $^{60}$Fe, i.e., nuclei created as spallation products through collision with the interstellar medium (ISM) gas.1

The production of Iron group nuclei is through fusion in the last evolutionary phase of the progenitor stars or the supernova (SN) event itself. Indeed, $^{44}$Ti is spectrally detected in supernova remnants (SNRs) Cassiopeia A and SNR 1987A (Iyudin et al. 1994; The et al. 1996; Vink et al. 2001; Grebenev et al. 2012). Since $^{44}$Ti is produced through the reaction $^{40}$Ca($\alpha, \gamma$)$^{44}$Ti (The et al. 1998), its detection in remnants is evidence of a rich $\alpha$ particle supply in the supernova explosion, which exists inside the core-collapse supernova during the $\alpha$-rich freeze-out phase. However, if the acceleration process of the CR isotopes coming from the SNe is relatively long, then by the time the nuclei are accelerated those nuclei that are unstable through electron capture (EC) should decay. A short acceleration process will, however, strip the nuclei of their electrons and allow them to be long-lived CRs.

There is, however, another source of $^{44}$Ti in the CRs—CR nuclei are also created through spallation during their propagation in the galaxy. Since they are formed stripped, these EC unstable isotopes can survive as long as they remain at high energies. As a consequence, nuclei that decay through EC have a mean half-life time, which depends strongly on the energy. This can be seen with the Niebur et al. (2000) measurements that show how the $^{49}$Ti/$^{49}$V and $^{51}$V/$^{53}$Cr ratios decrease with energy, as expected from the longer decay time of the EC isotopes, $^{49}$V and $^{53}$Cr, at higher energies.

In Benyamin et al. (2014, 2016), we developed the first CR propagation code that includes dynamic spiral arms as the main source of the CRs in the galaxy and showed how changing the CRs source distribution from the “standard” azimuthal symmetry to a dynamic spiral-arms source distribution solves several “standard” model anomalies.

Within the Iron group nuclei (Scandium through Nickel), there are a few CR isotopes that are known to decay through EC in the lab, and these isotopes can provide an interesting fingerprint on the process of reacceleration (e.g., Strong et al. 2007, and references therein). In Benyamin et al. (2017), we focused on investigating these isotopes and showed that, in principle, they can also be used to constrain CRs propagation models, though present day uncertainties in the nuclear cross sections are a limitation.

Our model considers $^{44}$Ti, $^{49}$V, $^{51}$Cr, $^{53}$Mn, $^{55}$Fe, $^{57}$Co, and $^{59}$Ni as EC isotopes2 whose effective half-life can be governed by the electron attachment rate or radioactive decay. The timescale for stripping electrons by the ISM for these isotopes is roughly $\tau_{\text{stripping}} \approx 5 \times 10^{-3}$ Myr (Letaw et al. 1985). For the $^{44}$Ti, $^{49}$V, $^{51}$Cr, $^{55}$Fe, and $^{57}$Co, the decay timescale is on the order of several days to a few years, which is much smaller than $\tau_{\text{stripping}}$. This implies that we can neglect the stripping process for these isotopes and assume that they decay immediately after they attach to an electron from the ISM. However, the EC half-life time of $^{53}$Mn and $^{59}$Ni is 3.7 Myr and 0.076 Myr, respectively, which is much longer than $\tau_{\text{stripping}}$. Here, one can neglect the decay process and assume that these isotopes will become stripped of their electrons before being able to decay and can, therefore, be assumed to be stable. In Benyamin et al. (2017), we considered isotopes...
governed by the attachment timescale and empirically obtained the energy dependence of this process using the observation of $^{46}\text{Ti}/^{39}\gamma$ and $^{51}\nu/^{33}\text{Cr}$ ratios.

When an EC isotope is created through fusion, it has relatively low energy within the star or subsequent supernova. This leads to a very high electron attachment cross section, such that it will decay to its daughter isotope if produced. Several observations detected hard X-ray lines from supernova remnants, such as Cassiopeia A and SN 1987A, which are associated with the decay of $^{44}\text{Ti}$ to $^{44}\text{Sc}$ (through EC with a half-life time of about 60 years in the lab), 67.9 keV and 78.4 keV, and the decay of $^{44}\text{Sc}$ to $^{44}\text{Ca}$ through $\beta^-$ with a half-life time of about 4 hr in the lab), 1.157 MeV (OSSE, The et al. 1996; COMPTEL, Iyudin et al. 1994; BeppoSAX, Vink et al. 2001; and $\gamma$-rays, Grebenev et al. 2012). Since $^{44}\text{Ti}$ is an EC isotope with a half-life of 60 years, it implies two things. First, the $^{44}\text{Ti}$ should have been formed within this timescale preceding the supernova. Second, if this $^{44}\text{Ti}$ is to accelerate and become $^{44}\text{Ti}$ CRs, it should be accelerated through the SNR shocks, and get stripped, before being able to decay to its daughter isotope. Although there is no explicit acceleration timescale, there is one implicitly set by the decay timescale of $^{44}\text{Ti}$. Namely, any acceleration process, which will strip the daughter isotope. Although there is no explicit acceleration timescale, there is one implicitly set by the decay timescale of $^{44}\text{Ti}$. Namely, any acceleration process, which will strip the daughter isotope.

$^{44}\text{Ti}$ is produced through the $^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$ reaction (The et al. 1998), which requires a rich $\alpha$ particles supply, as is the case inside a core-collapse (Type II) supernova during the $\alpha$-rich freeze-out phase. The et al. (1998) also showed the importance of secondary reactions, such as $^{45}\text{V}(p,\gamma)^{46}\text{Cr}$, $^{44}\text{Ti}(\alpha,\gamma)^{44}\text{Ti}$, and $^{44}\text{Ti}(\alpha,\gamma)^{44}\text{Cr}$, on the rate of production and the amount of $^{44}\text{Ti}$ in the supernova explosion, but due to the unstable nature of these isotopes, it is hard to measure the reactions in the lab and provide meaningful constraints.

Woosley & Hoffman (1991) constrained the production of $^{44}\text{Ti}$ in SN 1987A using the $^{44}\text{Ca}/^{56}\text{Fe}$ ratio of CRs that reach the solar system. Given that $^{44}\text{Ca}$ is mainly produced by the decay of $^{44}\text{Ti}$, they concluded that the $^{44}\text{Ti}/^{56}\text{Fe}$ ratio at the source is about the same as the $^{44}\text{Ca}/^{56}\text{Fe}$ ratio in CRs that reach the solar system. In later work (Diehl et al. 2006, and references within), this result was recovered and extended for SN 1987A and Cas A.

The connection between $^{60}\text{Fe}$ (which decay through $\beta^-$ with half-life-time of about 2.6 million years) and $\gamma$-ray astronomy is extensively discussed in Diehl et al. (2011). The 1.173 MeV and 1.332 MeV lines associated with the decay modes of $^{60}\text{Fe}$ were detected by the space-based telescopes RH ESSI (Smith 2004) and International Gamma-Ray Astrophysics Laboratory/SPectrometer for INTEGRAL (INTEGRAL/SP; Harris et al. 2005), which give an instantaneous snapshot of the ongoing nucleosynthesis of this isotope in the Milky Way (Prantzos 2010; Diehl 2013).

The production of $^{60}\text{Fe}$ is associated with core-collapse supernovae, which is expected to be produced in two locations before the supernovae explosion—the neon shell and at the base of the helium shell. In the neon shell, $^{22}\text{Ne}$ and $^{52,56}\text{Mg}$ are mixed into the superheated neon burning region, which allows free neutrons to be captured by the $^{56}\text{Fe}$ seed. The seed itself is previously produced by the $s$-process during the helium burning phase, and then by the intermediate radioactive of $^{59}\text{Fe}$, to form $^{60}\text{Fe}$. At the base of the helium shell, $^{60}\text{Fe}$ is produced by mild $r$-process during explosive helium burning (Woosley & Weaver 1995). Meyer & Clayton (2000) calculated the nucleosynthesis production of the short-lived radioactive isotopes in massive stars, type Ia supernova, and neutron star disruption. In massive stars, they predicted that the ratio between $^{60}\text{Fe}$ to $^{56}\text{Fe}$ should be around $3 \times 10^{-5}$.

Recently, Binns et al. (2016) reported the observation of $^{60}\text{Fe}$ using the Advanced Composition Explorer-Cosmic Ray Isotope Spectrometer (ACE-CRIS) instrument in the energy range of 195 MeV to 500 MeV. They detected 15 $^{60}\text{Fe}$ nuclei, a total Fe number of $3.55 \times 10^5$, and calculated the $^{60}\text{Fe}/^{56}\text{Fe}$ and $^{60}\text{Fe}/^{58}\text{Fe}$ ratios to be $(4.6 \pm 1.7) \times 10^{-5}$ and $(3.9 \pm 1.4) \times 10^{-5}$, respectively. Using the leaky-box model, they concluded that the ratios at the source are $(7.5 \pm 2.9) \times 10^{-5}$ and $(6.2 \pm 2.4) \times 10^{-5}$, respectively.

We begin in Section 2 by briefly describing the model we developed and our nominal model parameters. In Section 3, we carry out an analysis of the model to find the amount of primary $^{44}\text{Ti}$ and $^{60}\text{Fe}$ required to explain the observations obtained by CRIS, using a more modern 3D model than the leaky-box model, namely, the dynamic spiral-arms model. The implications of these results are then discussed in Section 4.

### Table 1: Nominal Model Parameters

| Parameter | Definition | Model value |
|-----------|------------|-------------|
| $z_h$     | Half halo height | 250 pc       |
| $D_d$     | Diffusion coefficient normalization | $1.2 \times 10^{27}$ cm$^2$s$^{-1}$ |
| $\delta$  | Spectral index | 0.4          |
| $\tau_{arm}$ | Last spiral-arm passage | 5 Myr         |
| $i_1$     | 4-arms set’s pitch angle | 28°          |
| $i_2$     | 2-arms set’s pitch angle | 11°          |
| $\Omega_1$ | Angular velocity of the 4-arms set | $15 \text{ (km s}^{-1}\text{) kpc}^{-1}$ |
| $\Omega_2$ | Angular velocity of the 2-arms set | $25 \text{ (km s}^{-1}\text{) kpc}^{-1}$ |
| $f_{SN,4}$ | Percentage of SN in the 4-arms set | 48.4%         |
| $f_{SN,2}$ | Percentage of SN in the 2-arms set | 24.2%         |
| $f_{SN,CC}$ | Percentage of core-collapse SNe in the disk | 8.1%         |
| $f_{SN,II}$ | Percentage of SN Type Ia | 19.3%         |

3 The X-ray lines themselves imply the actual presence and decay of some $^{44}\text{Ti}$ in the SNRs. In our analysis, we will show that not only does it exist, but also that part of the $^{44}\text{Ti}$ also manages to accelerate before decaying to $^{44}\text{Sc}$.

### 2. The Numerical Model

In Benyamin et al. (2014), we developed a fully three-dimensional numerical code describing the diffusion of CRs in the Milky Way. The code is presently the only model to consider dynamic spiral arms as the main source of the CR particles. With the model, Benyamin et al. (2014) recovered the Boron to Carbon (B/C) ratio and showed how the dynamics of the arms is important for understanding the behavior of nuclei secondary to primary ratios, which, below 1 GeV/nuc., increase with the energy.

In Benyamin et al. (2016), we upgraded the code to be faster and more accurate and showed how a spiral-arms model, unlike a disk-like model, can explain the discrepancy between the grannage required to explain the B/C ratio and the sub-Fe/Fe ratio. The optimal parameters of the model are summarized in Table 1. The two main parameters that change when moving from a “disk-like” model to a spiral-arms model are the diffusion coefficient and the halo size, which are smaller by...
about a factor of 10 from the “standard” parameters. This change in the derived diffusion coefficient and halo size elucidate that the canonical values for the parameters that describe the CR diffusion were obtained under a given set of model assumptions. Once we change the underlying assumptions, we should reanalyze the various parameters accordingly and not assume that their canonical values still hold.

Our code is different from present day simulations (such as GALPROP, Strong & Moskalenko 1998; and DRAGON, di Bernardo et al. 2010), which solve the diffusion partial differential equations (PDE) that we use in a Monte Carlo methodology. It allows for more flexibility in adding various physical aspects to the code (such as the spiral-arm advection), though at the price of reduced speed. The full details of the code and of the model can be found in Benyamin et al. (2014, 2016).

In Benyamin et al. (2017), we focused on the EC isotopes and carried out a full parameter analysis of the electron attachment cross-section formula using measurements of $^{49}$Ti/$^{49}$V and $^{51}$V/$^{51}$Cr ratios in CRs. An empirical relation was derived from these results and is here applied to $^{44}$Ti, $^{49}$V, $^{51}$Cr, $^{55}$Fe, and $^{57}$Co isotopes. This relation is $\sigma(E, Z) = N(\zeta_0) \times Z^{4.5} \times (E/500 \text{ MeV})^{-1.8}$, with a normalization given by $N_{56}(\zeta_0, \tau_{\text{arm}}) = 7.98 \times 10^{-5} \text{ mb} / (\tau_{\text{arm}}/10 \text{ Myr})^{-0.278} \times (\zeta_0/1 \text{ kpc})^{0.230}$. The full details on the analysis can be found in Benyamin et al. (2017).

Many of the partial cross sections are poorly measured, and the values used are often the results of fits and extrapolations, giving rise to large uncertainties (Webber et al. 2003; Moskalenko 2011). The problem is aggravated below a few GeV/nuc., where the cross sections have larger energy dependences (Schwaller et al. 1979; Moskalenko & Mashnik 2003) and become more acute as $Z$ increases (e.g., see Appendix II in Garcia-Munoz et al. 1987; Sisterson & Vincent 2006; Titarenko et al. 2008). The same can be said about the attachment cross section, whose measurements were carried out half a century ago (Wilson 1978; Crawford 1979). The best that the analysis of Letaw et al. (1985) and our extrapolation of the data (Benyamin et al. 2017) could provide is that there is at least a 20% uncertainty on the attachment cross sections. With that in mind, we use the model itself to constrain the cross sections, which leads to model parameters appearing in the cross-section fits.

For $^{57}$Mn and $^{59}$Ni, the half-life time for the EC decay is 3.7 Myr and 0.076 Myr, respectively, which is much longer than $\tau_{\text{stripping}} \approx 5 \times 10^{-3}$ Myr (Letaw et al. 1985). Consequently, this allows one to neglect the decay process and assume that these isotopes will become stripped of their electrons before decaying and remain stable. For these isotopes, it is irrelevant to apply the above formula, as their identity will not change.

3. Results

3.1. Primary $^{44}$Ti

We begin by implementing the attachment rate formula to the EC isotopes, specifically to $^{44}$Ti. This allows us to predict the amount of $^{44}$Ti and compare it to its daughter isotope, $^{44}$Ca. The results are depicted in Figure 1. With our simulation, we find a ratio that is lower by about a factor of 2 from the observations. This can be explained by the fact that we did not include any $^{44}$Ti in the initial composition—any additional $^{44}$Ti

![Figure 1. $^{44}$Ti/$^{44}$Ca ratio. The green line represent the simulation where we did not include any primary $^{44}$Ti. As can be seen, the simulation is lower by a factor of 2 from the observations (ACE/CRIS; Scott 2005). The purple line is obtained after adding an amount of $^{44}$Ti/Fe = 0.4% to the initial composition, while the shaded area is the 1σ error in the prediction. All the simulations are compared with the correct solar modulation when compared with the observation (for solar minimum, $\phi = 513$ MV; and for solar maximum, $\phi = 923$ MV), but in the plot we show the simulation corrected to include the average solar modulation, $\phi = 718$ MV.](image)

3.2. Primary $^{60}$Fe

The next step is to estimate the amount of $^{60}$Fe in the initial composition. To do so, we carry out a similar analysis to the one described above for $^{44}$Ti and estimate the initial amount of $^{60}$Fe required to fit the recent CRIS results (Binns et al. 2016).

Figure 2 depicts the $^{60}$Fe/$^{56}$Fe ratio in our model, with and without the primary $^{60}$Fe. The optimal fit corresponds to an initial $^{60}$Fe/$^{56}$Fe ratio of $(4.5 \pm 0.5) \times 10^{-5}$. Our results agree with Meyer & Clayton (2000), who predict $^{60}$Fe/$^{56}$Fe $= 3 \times 10^{-5}$, and with Binns et al. (2016)'s estimate of $^{60}$Fe/$^{56}$Fe $= (7.5 \pm 2.0) \times 10^{-5}$.

Given the parameters in Table 1, the diffusion length of the $^{60}$Fe is only few hundreds pc’s, which is about the distance that $^{60}$Fe travels over its half-life time. Thus, the source of $^{60}$Fe, i.e.,
the spiral arm, is relatively local. This is consistent with the detections of \(^{60}\)Fe in deep-sea crusts in all major oceans of the world (Knie et al. 2004; Wallner et al. 2016), with detections of \(^{60}\)Fe in lunar samples (Fimiani et al. 2016, 2014, 2012), and with Benyamin et al. (2016, p. 680)’s conclusion that, “Our distance from the source of this nuclide cannot greatly exceed the distance that CRs can diffuse over this timescale, which is \(\lesssim 1\) kpc.”

4. Discussion and Summary

It is generally accepted that a bulk of the galactic CRs (whether in number or energy) are accelerated in supernova remnants (e.g., Ackermann et al. 2013, and references therein), while the production of iron group nuclei is through fusion in the last evolutionary phase of the progenitor stars or in the SN event itself. Indeed, \(^{44}\)Ti is spectrally detected in SNRs Cassiopeia A and SNR 1987A (Iyudin et al. 1994; The et al. 1996; Vink et al. 2001; Grebenev et al. 2012). Since \(^{44}\)Ti is produced through the reaction \(^{40}\)Ca\((\alpha, \gamma)^{44}\)Ti (The et al. 1998), its detection in remnants is evidence of a rich \(\alpha\) particle supply in the supernova explosion, which existed inside the core-collapse supernova during the \(\alpha\)-rich freeze-out phase. However, if the acceleration process of the CR isotopes coming from the SNe is relatively long, then by the time the nuclei are accelerated, those nuclei that are unstable through EC should decay. A short acceleration process will, however, strip the nuclei of their electrons and allow them to be long-lived CRs.

There is, however, another source of \(^{44}\)Ti in the CRs—CR nuclei are also created through spallation during their propagation in the galaxy. Since they are formed stripped, these EC unstable isotopes can survive as long as they remain at high energies. As a consequence, nuclei that decay through EC have a mean half-life time that depends strongly on the energy. This can be seen with the Niebur et al. (2000) measurements that show how the \(^{49}\)Ti/\(^{49}\)V and \(^{51}\)V/\(^{51}\)Cr ratios decrease with energy, as expected from the longer decay time of the EC isotopes (i.e., \(^{49}\)V and \(^{51}\)Cr) at higher energies.

In our previous analyses (Benyamin et al. 2014, 2016), we showed how our propagation model can be used to describe the CR propagation by fitting the secondary to primary ratios in the Beryllium–Oxygen and Scandium–Nickel elements groups.

Jones et al. (2001) and Niebur et al. (2001) suggested that a standard diffusion model cannot explain the behavior of EC isotopes and cannot explain the decrease in the ratios of the daughter EC isotopes to the EC isotopes: for example, the ratios \(^{49}\)Ti/\(^{49}\)V and \(^{51}\)V/\(^{51}\)Cr. Jones et al. (2001) and Niebur et al. (2001) were in agreement that nominal diffusion models cannot give a strong enough decrease as the energy increases. Their solution for the decrease of \(^{44}\)Ti/\(^{49}\)V and \(^{51}\)V/\(^{51}\)Cr was to add an ad hoc assumption to their propagation model on the reacceleration of the nuclei on their way to Earth in order to fit these observations.

In our previous work on EC isotopes (Benyamin et al. 2017), we suggested another explanation for the decrease in the ratio of \(^{49}\)Ti/\(^{49}\)V and \(^{51}\)V/\(^{51}\)Cr. We showed that a energy-dependent cross section for the attachment of electrons from the ISM can explain the observed behavior, without having to add any additional primary CRs at the source. When the isotope attaches an electron, it subsequently decays through EC. The fitted functional form for the electron attachment cross section that we obtained in Benyamin et al. (2017) is \(\sigma_s(E, Z) = N(z_h) \times Z^{4.5} \times (E/500\) MeV\(^{-1}\))\(^{18}\), with a normalization given by \(N_{03}(z_h, \tau_{arm}) = 7.98 \times 10^{-5}\) mb \(\times (\tau_{arm}/10\) Myr\)\(^{0.578}\) \(\times (z_h/1\) kpc\(^{-3}\)).

With the help of the empirical fit obtained in Benyamin et al. (2017), we simulated the \(^{44}\)Ti/\(^{44}\)Ca ratio here and found that the ratio is lower than the observations by a factor of about 2. This can be explained away by adding \(^{44}\)Ti to the list of injected isotopes, as is corroborated by the observations (Iyudin et al. 1994; The et al. 1996; Vink et al. 2001; Grebenev et al. 2012). We found out that the amount of \(^{44}\)Ti/\(^{56}\)Fe required to be injected as part of the initial composition is 0.44% ± 0.03% in order to match the CRS observations (Scott 2005). Our results agree with Diehl et al. (2006) and Woosley & Hoffman (1991), who predict it to be about the same as the \(^{44}\)Ca/\(^{56}\)Fe ratio measured in CRs reaching the solar system, which is about 0.5% ± 0.1% (Scott 2005).

Recently, Benyamin et al. (2016) reported the detection and measurement of \(^{60}\)Fe in CRs using the ACE-CRIS instrument. The ratios \(^{60}\)Fe/\(^{56}\)Fe and \(^{60}\)Fe/\(^{56}\)Fe found are \((4.6 \pm 1.7) \times 10^{-5}\) and \((3.9 \pm 1.4) \times 10^{-5}\) respectively. We found that we need to have an initial \(^{60}\)Fe/\(^{56}\)Fe ratio of \((4.5 \pm 2) \times 10^{-5}\) to the initial composition in order to fit the observed \(^{60}\)Fe/\(^{56}\)Fe. Our results also agree with Meyer & Clayton (2000), who predict \(^{60}\)Fe/\(^{56}\)Fe = 3 \times 10^{-5}\), and with Benyamin et al. (2016), who estimated a ratio of \(^{60}\)Fe/\(^{56}\)Fe = \((7.5 \pm 2.9) \times 10^{-5}\).

By noting the 25% difference between the spiral-arm and disk models, it is evident that these are the type of uncertainties in the prediction from the Galactic parameters. Moreover, together with the similarly large uncertainties in the spallation cross section, it implies that the predictions have an uncertainty of at least 40%. As a word of caution, one should emphasize that some of the EC radioactive isotopes could decay during the acceleration phase before escaping the SNR; thus, the amount of \(^{44}\)Ti/\(^{56}\)Fe = 0.44% ± 0.03% and of \(^{60}\)Fe/\(^{56}\)Fe = \((4.5 \pm 2) \times 10^{-5}\) that is required to add to the initial composition of CRs is actually only a lower limit on the nucleosynthesis of these isotopes. On top of that, if one wants to calculate the ratios before the acceleration, one needs also to consider that there might be a difference in the acceleration efficiencies (Meyer et al. 1997); thus, the actual ratios will be \(^{44}\)Ti/\(^{56}\)Fe\(_{\text{CR,source}}\) = \((^{44}\)Ti/\(^{56}\)Fe)\(_{\text{SN}}\) \times \epsilon_{\text{app}}/\epsilon_{\text{app}}\) and \(^{60}\)Fe/\(^{56}\)Fe\(_{\text{CR,source}}\) = \((^{60}\)Fe/\(^{56}\)Fe)\(_{\text{SN}}\) \times \epsilon_{\text{app}}/\epsilon_{\text{app}}\), with \(\epsilon\) denoting the acceleration efficiency.
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