The Origin of the Galactic ^{26}Al and ^{60}Fe

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Abstract The radioactive nucleus ^{26}Al (1 Myr lifetime) was the first cosmic radioactivity ever detected, through its gamma ray emission line at 1.809 MeV, with the HEAO-3 satellite in the 80's. More recently, COMPTEL instrument onboard CGRO made the first all-sky map of its diffuse emission in the Galaxy, which revealed that 1.8 MeV photons trace the massive star population, but with room to other potential important producers like AGB stars and novae. The SPI instrument of the current ESA mission INTEGRAL has corroborated the detection of the ^{26}Al line with excellent spectroscopic resolution, and has also detected the two lines at 1.173 and 1.333 MeV of ^{60}Fe (2 Myr lifetime), yielding an observed ^{60}Fe/^{26}Al gamma ray flux ratio which can not be reproduced with current theoretical determinations based solely on massive stars. We will discuss the contribution of the different stellar scenarios to the global ^{26}Al and ^{60}Fe content of the Milky Way and give an interpretation of the recent INTEGRAL observations.

1 Introduction

After the pioneering detection with the HEAO-3 (High Energy Astrophysics Observatory) satellite [11, 12], other γ-ray instruments, either on balloon flights or onboard satellites, have detected the 1.8 MeV line from live ^{26}Al. However, this is not the unique way to observe it; excesses of its daughter nucleus ^{26}Mg in presolar meteoritic grains can trace its existence. Enhanced ^{26}Mg/^{24}Mg ratios found in Ca/Al rich inclusions of the Allende meteorite were in fact the first evidence for live ^{26}Al in the early solar system [9].

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The excellent results from the COMPTEL (COMPTON TELescope) instrument onboard the Compton Gamma Ray Observatory (CGRO) have been specially relevant. An all-sky map of the diffuse emission from ^{26}Al in the galactic interstellar medium was obtained [3], which revealed that 1.8 MeV photons mainly trace the massive star population, but with room to other potential important producers like asymptotic giant branch (AGB) stars and novae. More recently, the SPI (SPectrometer of INTEGRAL) instrument onboard the INTEGRAL (INTErnational Gamma-RAy Laboratory) satellite has also detected ^{26}Al, with excellent spectroscopic resolution. It has been settled now both by RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) and by INTEGRAL that the ^{26}Al line is narrow [20, 4], in contradiction with a previous claim of a broad ^{26}Al line from observations with GRIS (Gamma-Ray Imaging Spetrometer), a balloon-borne high-resolution γ-ray spectrometer with Ge detectors [13]. In addition, blue and redshifted emission have been carefully detected, along the galactic spiral arms, in perfect agreement with what is expected from galactic rotation [5]. All these observational results point to an origin of bulk ^{26}Al in the galactic plane, and not in foreground sources closer to us.

The long awaited detection of the ^{60}Fe characteristic γ-ray lines at 1.173 and 1.332 MeV has been possible thanks to RHESSI and INTEGRAL satellites. Observations with both satellites have provided ^{60}Fe/^{26}Al line flux ratios in very good agreement with each other: 0.097 ± 0.039 with RHESSI [21], 0.11 ± 0.03 with INTEGRAL/SPI [6], and 0.148 ± 0.06 in a more recent analysis of a larger data set from SPI [23].

Radioactive ^{60}Fe is expected to be produced only in core collapse supernovae (ccSNe), which may also synthesize most of the galactic ^{26}Al. With this assumption and adopting the yields of WW95 [25], a ^{60}Fe/^{26}Al flux ratio of 0.16 was predicted [22], in very good agreement with the recently observed value. However, updated models of nucleosynthesis with revised cross sections of nuclear reaction rates [18, 2] predicted larger flux ratios. Shortly afterwards, it was claimed that a possible way to solve this apparent discrepancy is to include other contributors to the galactic ^{26}Al [16], as the winds of Wolf-Rayet (WR) stars, an idea that has been repeatedly proposed since then [15, 7]. In addition, there is still room for other potential ^{26}Al sources, such as AGB stars and classical novae. However, it is not yet clear how much each one of the scenarios contribute to ^{26}Al [17]. The latest models of massive stars come back to smaller values of the flux ratio, in closer agreement again with the observations [10, 24].

2 ^{60}Fe/^{26}Al flux ratio

Under the assumption that ^{26}Al and ^{60}Fe are mainly produced in massive stars, they should have a similar spatial distribution in the Galaxy [22], which has important implications on the observed ^{60}Fe/^{26}Al γ-ray flux ratio. To derive the theoretical flux ratio, we first define the mean yield $\overline{Y}$ of a given species produced by stars in the mass range $[M_{low}, M_{up}]$:

$$\overline{Y} = \frac{\int_{M_{low}}^{M_{up}} Y(M)\phi(M)dM}{\int_{M_{low}}^{M_{up}} \phi(M)dM} \quad (1)$$

where we average the yields $Y(M)$ by the initial mass function $\phi(M)$ (IMF) (we adopt Salpeter's prescription [19]). Since the flux of the γ-ray emission of a given isotope is proportional to the number of nuclei, i.e., to the ratio of the averaged yield and its mass number, the flux ratio FR of ^{60}Fe to ^{26}Al turns out to be:

$$FR = \frac{26}{60}\frac{\int_{M_{low}}^{M_{up}} Y_{60}(M)\phi(M)dM}{\int_{M_{low}}^{M_{up}} Y_{26}(M)\phi(M)dM} \quad (2)$$

We consider two different possibilities for the yields: WW95 [25] and LC06 [10]. The former takes a range of masses between $11M_{\odot}$ and $40M_{\odot}$ and metallicities up to the solar value. The latter has improved physics and revised nuclear reaction rates, but only for solar metallicity stars. However, a range of progenitor masses up to $120M_{\odot}$ allows them to include the WR phase.

As a first approximation, we determine mean yields and flux ratios using data for solar metallicity (see Table 1). With WW95 yields, we have obtained a FR of 0.19; this value is in very good agreement with Timmes et al. [22], who used the same input data and determined a flux ratio of 0.16 from the integration along the galactic plane of the injection rates of ^{26}Al and ^{60}Fe. These are two independent ways to obtain the flux ratio, giving similar results; therefore, the method proposed here is robust and consistent with previous works.

Table 1 Flux ratio using the solar metallicity yields from WW95 and LC06. Note that the mass ranges are different, so the former does not include the contribution of WR stars.

Authors	M_{low} - M_{up} ($M_{\odot}$)	Y_{26} ($10^{-5}M_{\odot}$)	Y_{60} ($10^{-5}M_{\odot}$)	Flux ratio
WW95	12-40	8.48	3.80	0.19
LC06	11-120	9.75	6.90	0.31

3 The influence of initial metallicity

The flux ratio obtained with the LC06 set of yields (Table 1) is larger than the value deduced from observations. In order to solve this discrepancy, we perform a more careful analysis taking into account that massive stars were born with metallicities different from solar. Actually, ^{26}Al and ^{60}Fe yields depend not only on the mass but also on the metallicity at birth of the star, which in turn depends on its location in the Galaxy (defined from its galactocentric radius R): $Y_{26(60)}(M, Z_{\rm birth}) = Y_{26(60)}(M, R)$. Since the lifetimes of ^{26}Al and ^{60}Fe are much shorter than the age of the Galaxy (t_{Gal}), we should take into account only stars exploding now as ccSNe and/or undergoing the WR phase, i.e., stars dying now. Furthermore, since we are dealing with massive stars, we can safely assume that their lifetimes are short as compared to t_{Gal}, and thus their original metallicities are the current ones at their birth location.

We use a code of chemical evolution of the Galaxy based on the prescriptions of Alibés et al. [1] to determine the metallicity of stars born now at any R. The model is valid for the galactic disk and reproduces the observed age-metallicity relation in the solar neighborhood and the metallicity distribution of G-dwarf stars. Assuming t_{Gal} = 13 Gyr, the metallicity of the Milky Way at two different radii is: 0.036 at 2.5 kpc, and 0.022 at 8.5 kpc, both larger than solar and well inside the range of observed values.

There has not been much effort to compute yields for stars with metallicites larger than solar, which are crucial for a correct evaluation of the ^{26}Al and ^{60}Fe content in the Galaxy. This lack of yields has obliged us to adopt a theoretical prescription to obtain yields at large metallicities. The simplest way to proceed is to take the power law suggested by Prantzos [16], as well as by Palacios et al. [15]: $Y_{26(60)} = Y_{26(60),\odot} \cdot (Z/Z_\odot)^{\beta_{26(60)}}$. Either by chance or not, yields really follow a power law tendency for metallicities smaller than solar, and this is the metallicity range we have used to extract the slopes $\beta_{26} = 0.7$ and $\beta_{60} = 2.0$. Although yields strongly depend on mass loss and convection, both influenced in a non linear way by metallicity (see LC06), our purpose is to use orientative values in order to determine the expected range of the flux ratio. A summary of the flux ratios obtained for a range of metallicities (related to different R) and slopes of the IMF is displayed in Figure 1. The values are larger than those computed with solar metallicities, because the increase with metallicity of the ^{60}Fe yields is larger than that of ^{26}Al. Therefore, the disagreement between theory and observations becomes more severe than in the solar case.

Results with WW95 yields are the closest to observations, but their nuclear network is obsolete [24]. In this sense, LC06 provide the best yields since the problems in nuclear reactions are solved and they include the contribution of WR winds. However, the agreement between LC06's theoretical values and observations is far from being satisfactory, once the effect of metallicity at birth is included. A flux ratio of

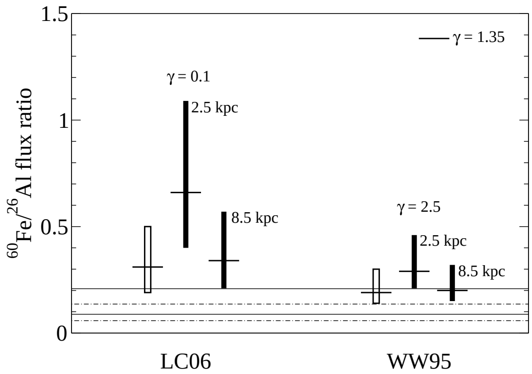

Fig. 1 Range of validity of the ^{60}Fe/^{26}Al flux ratio. Empty boxes result from the computations with solar metallicity yields, while solid boxes indicate the use of yields with corresponding metallicities at 2.5 kpc and 8.5 kpc. The horizontal black dashes refer to the flux ratio determined by $\gamma = 1.35$ and the labels at the top of each box refer to the value of γ giving the upper limit of the flux ratio. Solid lines represent the range of the flux ratio obtained with INTEGRAL observations, while dashed lines belong to the RHESSI limits.

0.66 is obtained, even more distant from the observed value than the previous determination, since the yields of LC06 present an enhancement of the ^{60}Fe production. As stated in LC06, the mass loss rate is still one of the main uncertainties concerning the evolution of a star. The fact that the authors adopt Nuggis & Lammers [14] mass loss recipe for the WNE+WNO phases may drive an excessive ejection of ^{60}Fe, and therefore unexpected high amounts of this isotope in the ISM are obtained. As a consequence, the flux ratio turns out to be too large.

4 Discussion and conclusions

A simple prescription for the determination of the theoretical ^{60}Fe/^{26}Al gamma-ray line flux ratio has been derived, based on the definition of mean yield for a given stellar population. We have checked that this recipe gives results fully consistent with previous theoretical FR determinations [22], when the same conditions and input data are adopted. We then emphasize that theoretical values of the flux ratio depend on the metallicity at birth of stars. This effect translates into a radial dependence of the FR, related to the current metallicity distribution in the Galaxy, which has been computed with a code of chemical evolution. The yields have been inferred following the suggestions of Prantzos [16] and Palacios et al. [15]. The derived theoretical FRs in the central Galaxy are much larger than observed, and only extremely large IMF slopes and/or small M_{up} can alleviate the discrepancy.

The large ^{60}Fe/^{26}Al flux ratio obtained points towards the need of either extra sources of ^{26}Al in addition to massive stars and/or stronger mass loss rates in order to enhance the production of ^{26}Al with respect to the ^{60}Fe one and thus reproduce the observed flux ratio more faithfully. Only a better knowledge of the radial dependence of the observed flux ratio, together with a good knowledge of the yields at metallicities larger than solar, will permit to do a proper comparison between theory and observations based on the recipe presented here, and use it to put constraints on the models.

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