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On the contribution of classical novae to the ^{26}Al content of the Galaxy

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A comparative analysis of the various scenarios proposed to explain the ^{26}Al content of the galaxy, as observed through its characterisitc γ-ray line at 1.8 MeV, is presented. We include some suggestions about how theoretical yields should be handled, accounting for the influence of the initial metallicity of the corresponding star, which depends not only on its mass but also on its location in the galaxy. A code of chemical evolution of the galaxy is used to derive the temporal evolution of metallicity along the galaxy, the necessary tool to determine the initial metallicity of any stellar source of ^{26}Al. The contribution of each scenario (AGB stars, massive stars and classical novae) and its range of uncertainty are described.

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1. Introduction

The radioactive nucleus ^{26}Al was the first cosmic radioactivity ever detected, through its γ-ray emission at 1.809 MeV, with the HEAO-3 satellite (Mahoney et al. 1984). This detection of live ^{26}Al is not the unique way to observe this long-lived isotope (lifetime 10^6 years); it can also be traced through excesses of its daughter nucleus ^{26}Mg in presolar meteoritic grains. 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 (Lee et al. 1977).

After the pioneering detection with the HEAO-3 satellite, other γ-ray instruments, either on balloon flights or onboard satellites, have detected the 1.8 MeV line from ^{26}Al. The excellent results from the COMPTEL (*COM*PTON *TEL*escope) instrument onboard the Compton Gamma-Ray Observatory (CGRO), active from 1991 until 1999, have been specially relevant. An all-sky map of the diffuse emission from ^{26}Al in the galactic interstellar medium was obtained (Diehl et al. 1995), 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 (*SP*ectrometer of *I*NTEGRAL) instrument onboard the INTEGRAL (*INTE*rnational *G*amma-*RA*y *L*aboratory) satellite (launched in october 2002) 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 (Smith 2003, Diehl et al. 2003), 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 (Naya et al. 1996). In addition, blue and red shifted emission have been carefully detected, along the galactic spiral arms, in perfect agreement with what is expected from galactic rotation (Diehl et al. 2006). All these observational results point to an origin of bulk ^{26}Al in the galactic plane, and not in foreground sources closer to us. In spite of all this recent progress, however, it is not yet still clear how much each one of the potential ^{26}Al sources contributes: massive stars (including both the ejecta during the WR phase and after core collapse supernova explosion), AGB stars and classical novae (Prantzos & Diehl, 1996).

In this paper we make a critical analysis of the contribution of the different scenarios proposed to explain the ^{26}Al (and ^{60}Fe) galactic content, paying special attention to some important aspects that should be taken into account when computing the relevance of each particular source.

2. Influence of metallicity at birth

The first step to evaluate the contribution of any stellar source to the global galactic content of a particular isotope is to adopt some particular yields (i.e., mass ejected to the interstellar medium), relying on theoretical calculations. Theoretical yields are given in the literature for sets of masses and metallicities, for each scenario. Since there is broad interest in interpreting observed abundances in old stars, there has been a large effort in computing yields for low initial metallicites (Z), even Z=0. However, there is not a parallel 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, as we will show below (see also the discussion in Prantzos, 2004).

It is important to remind that the lifetime of ^{26}Al and ^{60}Fe is very short as compared to the timescale of galactical evolution, so that they must be continuously produced: they are the proof of ongoing nucleosynthesis in the galaxy. A correct evaluation of the contribution of any scenario to the global ^{26}Al (^{60}Fe) galactic content, needs a good knowledge of the metallicity at birth of the corresponding stars. Stars contributing to the current observed ^{26}Al and ^{60}Fe should have died just around 10^6 years ago, but they were born either very recently, if they were massive, or long ago if their mass was small. Therefore, metallicity at birth and mass are not independent variables ($t_{birth}(M) = t_{gal} - t_{ms}(M)$, where $t_{ms}(M)$ is the main sequence mass lifetime). We need Z(t) (ideally at each galactic region), so that we can derive $Z(t_{birth}(M))$, or shortly Z(M).

We have developed a code of chemical evolution (de Séréville, 2006), based on the same premises as Alibés et al. (1991): an initial mass function (IMF) from Kroupa (1993), a double infall from Chiappini et al. (1997), star formation rate from Dopita & Ryder (1994). This combination of hypotheses gives a very good fit to the observed age-metallicity relation (AMR) in the solar neighborhood, as well as a good metallicity distribution for the G-dwarfs, two classical tests for any galactic chemical evolution code. In addition to the solar neighborhood properties, our code also reproduces quite well the gradients of metallicity for galactocentric radii larger than $\sim$4 kpc (a good treatement of the bulge is not included yet). Here we have adopted the Anders & Grevesse (1989) value for $Z_\odot$, to be revised downwards according to recent work (see for instance Asplund, this volume).

From the age-metallicity for various galactocentric radii, we get Z(M). It is worth noticing that for all radii except the largest one studied (10.5 kpc), the metallicity now is larger than the solar value (metallicity of the sun at birth). For massive stars, which have very small main sequence lifetimes, metallicity at birth is equal to current galactic metallicity, i.e., larger than solar (except for very large distances from the galactic center). For AGB stars, the situation is more complicated, since there is a broad range of masses; therefore, the metallicity at birth will depend not only on position in the galaxy, but also on mass. We will detail these aspects in the two following sections.

3. AGB stars

All stars with masses between ~ 1 M$_\odot$ and $\sim$ 9-10 M$_\odot$ go through the so-called asymptotic giant branch phase (a brief period as compared to the main sequence phase) and end their lifes as white dwarfs (CO or ONe). AGB stars are good candidates for ^{26}Al production, since they burn hydrogen through Mg-Al "chains", at temperatures larger than 35×10^6 K (low-mass AGB stars, with mass smaller than around 4 M$_\odot$) or 50×10^6 K for massive AGB stars (see Mowlavi & Meynet, 2000). In principle, AGB stars are not major producers of ^{60}Fe, although they host the production of s-process elements, involving neutron captures which eventually could lead to some production of ^{60}Fe. As mentioned in section 2, we need Z(M) (ideally at each galactocentric radius, assuming cylindrical symmetry) for each AGB mass to well compute the ^{26}Al yields of this population. Following the results of our galactic chemical evolution code, we have derived Z(M) for various galactocentric radii (4.5, 7, 8.5 and 10.5 kpc), corresponding to the galactocentric distances for which an estimated flux of the 1.8 MeV ^{26}Al line exists, from CGRO/COMPTEL data (Knödlseder, 1997). These Z(M) correspond to AGB stars dying now, with t_{gal}=13 Gyr and $t_{ms}(M) = 10(M/M_\odot)^{-3.5}$ Gyr (see figure 1, left panel); turn-off mass is 0.93 M$_\odot$ for 13 Gyr. As expected, there is a steep dependence of Z at birth on M for small masses, around 1 $M_\odot$, since for them t_{ms} is quite large. For larger masses, in contrast, a flat profile Z(M) is obtained, since t_{ms} gets very small (a few % of t_{gal}) and so t_{birth} becomes practically equal to t_{gal}, i.e., present time ($Z=Z_{\text{“now”}}$). This plot is, of course, also valid for massive stars (WR and core collapse supernovae).

Once we know Z(M) at various galactocentric radii (R) we can derive the correct yield of ^{26}Al for each mass, at a given R, through interpolation of the yields found in the literature (we have used here those from Karakas and Lattanzio, 2004). In figure 1 (right panel), we show these ^{26}Al yields for the four galactic annuli mentioned. We have been obliged to extrapolate in Z, since to our knowledge there are no yields available at metallicities larger than solar, which are the metallicities at birth corresponding to masses larger than 1 $M_\odot$ for R<10.5 kpc (or even to smaller masses for R$\sim$ 10.5 kpc), as shown in figure 1 (left panel). So yields for metallicites lower than solar are only useful for AGBs with masses lower than $\sim$1.5 $M_\odot$ or for all masses when R is equal or larger than 10.5 kpc. We have also extrapolated to masses smaller than 1 $M_\odot$ (down to the turn-off mass, i.e., the mass of a star born at t=0 and dying now, 0.93 $M_\odot$ for t_{gal}=13 Gyr and our t_{ms}(M)). We show for comparison the yields versus mass when solar metallicity at birth is adopted, which is the approximation usually made. It is clear that yields of AGB stars with initial metallicites larger than solar (up to $\sim 1.5 Z_\odot$) are required for all masses, together with yields for masses $\sim$0.9 $M_\odot$, with all initial metallicites, to avoid risky extrapolations.

The following step to evaluate the AGB's contribution to galactic ^{26}Al is to perform a IMF-weighted average of $Y_{^{26}Al}(M)$. We adopt 6-6.5 $M_\odot$ as a preliminary upper limit in mass, awaiting for yields for larger masses from the same authors mentioned; as lower limit we take the turn-off mass (see figure 1, right panel). We get (with a Salpeter IMF and yields from Karakas & Lattanzio) $<Y(^{26}Al)>=$ 4.9, 6.5, 7.3 and 9.0 $\times 10^{-8}$ $M_\odot$, for galactocentric radii R=4.5, 7.0, 8.5 (solar) and 10.5 kpc, respectively. These average yields are smaller than the one obtained with the usual assumption that all AGB stars were born with solar metallicity (as expected since ^{26}Al yields scale inversely with metallicity), independently of their mass and location in the galaxy, which is (for the same set of theoretical yields and the same integral limits) 1.4 $\times 10^{-7}$ $M_\odot$. A very preliminary estimate of the global contribution of AGB stars to the galactic ^{26}Al is $\sim 7 \times 10^{-2}$ $M_\odot$, if the last number is taken as representative of the $\sim$ 480000 AGB stars in the galaxy (see Mowlavi & Meynet 2000).

4. Massive stars

Massive stars (M larger than 9-10 $M_\odot$) do not go through the AGB phase, but end their lifes as core collapse supernovae. We do not deal in this paper with Wolf-Rayet (WR) stars, i.e. massive stars that ultimately explode as core collapse supernovae, but prior to that experience strong stellar winds that enrich the interstellar medium in ^{26}Al (see the recent paper by Palacios et al. 2005, which deals in detail with the contribution of WR stellar winds to the galactic ^{26}Al: they estimate that winds of WR stars can contribute to at least 20-50% of the global ^{26}Al in the galaxy). In fact, ^{26}Al produced during the WR phase should be added to the ^{26}Al synthesized by the same star when it explodes.

The two radioactive isotopes ^{26}Al and ^{60}Fe are synthesized in massive stars, both during hydrostatic and explosive burning phases (see Chieffi, this volume). Explosive nucleosynthesis in

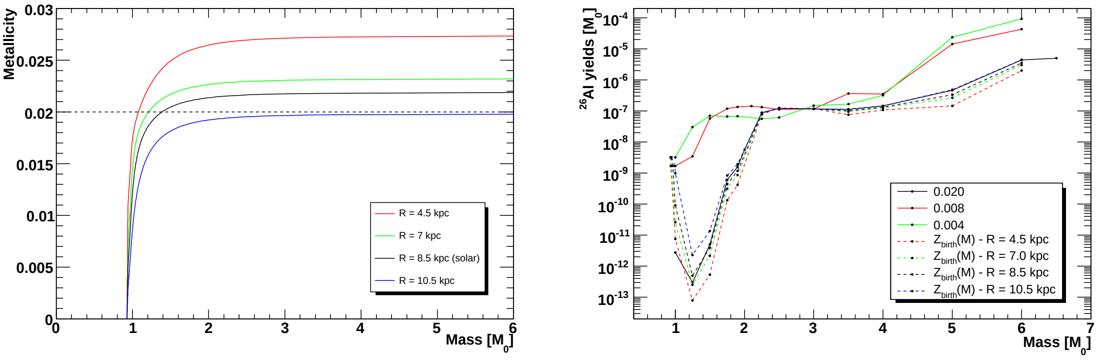

Figure 1: Left panel: Metallicity at birth versus mass, for various galactocentric radii R, and t_{gal}=13 Gyr. Right panel: ^{26}Al yields versus M, evaluated with the correct metallicity at birth, which depends on R (see text), are displayed as dotted lines. Solid lines correspond to fixed metallicites, for which yields are available. Notice that ^{26}Al yields scale inversely with metallicity.

massive stars for a grid of stellar masses (from 11 to 40 $M_\odot$) and metallicities (Z from 0 to $Z_\odot$) was performed 10 years ago by Woosley & Weaver (1995; hereinafter WW95). The initial prediction of the ^{60}Fe/^{26}Al ratio, based on these yields, if cc-SNe were the only producers of ^{26}Al and ^{60}Fe, was 0.16 (Timmes et al. 1995), in very close agreement with the recently observed value (Smith 2003, Harris et al. 2005). However, those yields were revised later on (for instance because of changes in some crucial reaction rates; see Rauscher et al. 2002), but the topic is not yet settled. Other groups have presented large computational sets as well (i.e., Chieffi & Limongi 2004). All these new nucleosynthetic results give ^{60}Fe/^{26}Al ratios much larger than observed (Prantzos 2004 and this volume; Diehl, this volume).

Our purpose here is to highlight again the importance of a correct handling of the yields, by adopting a correct metallicity at birth Z(M) (see section 2). With the same strategy applied to AGBs (see section 3), we compute the ^{26}Al and ^{60}Fe yields for the Z(M) from figure 1. We adopt the WW95 yields; even if obsolete, these are a complete set, with respect to M and Z, very useful for our illustrative purposes. We have been obliged to extrapolate in Z, since, as mentioned before, Z at birth for massive stars is $Z_{\text{“now”}}$, which is larger than solar except for large galactocentric radii. We assume that the yields do not depend much on Z ($\propto Z^{0.8}$) for ^{26}Al and that they depend linearly on Z for ^{60}Fe (Prantzos 2004). The IMF-averaged yields of ^{26}Al and ^{60}Fe for the four radii adopted are: <Y(^{26}Al)>= 9.2, 8.0, 7.7 and 7.1 $\times 10^{-5}$ $M_\odot$, and <Y(^{60}Fe)>= 5.2, 4.5, 4.2 and 3.8 $\times 10^{-5}$ $M_\odot$, for galactocentric radii R=4.5, 7.0, 8.5 (solar) and 10.5 kpc, respectively. The average yields obtained with the usual assumption that all massive stars were born with solar metallicity, independently of their mass and location in the galaxy, is 4.0 $\times 10^{-5}$ $M_\odot$ (^{26}Al) and 2.2 $\times 10^{-6}$ $M_\odot$ (^{60}Fe). A global contribution of cc-SNe to ^{26}Al derived from the IMF-averaged ^{26}Al yields, assuming 3 cc-SNe per century now is 1.2 $M_\odot$ (if 4.0 $\times 10^{-5}$ $M_\odot$ is adopted as representative), again a number subject to changes by a factor of even 10 depending on which yields are adopted.

These numbers are in some way obsolete, since new yields are becoming available which are in principle more correct (at least from the point of view of input physics, as mentioned above); however, in WW95 it was already clear that a range of yields, differing by a factor of 10 or more, can be obtained with the same input physics, but changing the explosion conditions (we have adopted here models A, but Timmes et al. (1995) adopted models B, differing in the kinetic energy at infinity). For set B, a ratio ^{60}Fe/^{26}Al=0.16 was found. As a conclusion of this analysis, we want to stress that a range of values for the global ^{26}Al content of the galaxy coming from cc-SNe, as well as for their ^{60}Fe/^{26}Al flux ratio, is obtained with the available theoretical yields; so the comparison with observations should be made carefully, accounting for spatial locations and corresponding metallicities of sources.

5. Classical novae

The production of ^{26}Al by classical novae occurs mainly in ONe novae (see José & Hernanz 1998 for details). It is important to stress, that (ONe) novae with low mass white dwarfs are more prolific producers of ^{26}Al than massive novae. Therefore, the evaluation of the global contribution of novae to the ^{26}Al content in the Galaxy is not straightforward, but a crude estimate can be made. Let's assume that all novae contribute with the same amount of ^{26}Al, $M_{\rm ejec}(^{26}{\rm Al})$. Then the Galactic mass of ^{26}Al coming from novae would be (Weiss & Truran 1990, José et al. 1997)

$$M(^{26}{\rm Al}) = M_{\rm ejec}(^{26}{\rm Al})(M_\odot)\,\tau R_{\rm nova}({\rm novae/yr})\, f_{\rm ONe} = 0.12\,\frac{M_{\rm ejec}}{10^{-8}M_\odot}\,\frac{R_{\rm nova}}{35{\rm novae/yr}}\,\frac{f_{\rm ONe}}{0.33}$$

where $R_{\rm nova}$ is the total galactic nova rate, $f_{\rm ONe}$ is the proportion of ONe novae and τ is ^{26}Al lifetime. But the ^{26}Al typical yield of novae is not easy to know. According to José & Hernanz (1998) and José et al. (1999), expected yields are 13, 2.1, 1.2 and 0.32 $\times 10^{-8}$ $M_\odot$, for $M_{\rm WD}$=1.0, 1.15, 1.25 and 1.35 $M_\odot$. Adopting 2×10^{-8} $M_\odot$, the contribution of novae to galactic ^{26}Al can be estimated as $\sim$0.2 $M_\odot$, around a factor of 10 below the observed mass.

An improvement to this "back of the envelope" calculation needs two things. First of all, a better determination of the ^{26}Al yields, i.e., the fraction of ^{26}Al novae's ejecta plus the amount of ejected mass; for the first part, recent improvements in the knowledge of the crucial reaction rates playing a role in the ^{26}Al synthesis in novae (see for instance Ruiz et al., this volume) have alleviated previous uncertainties (discussed in detail in José et al. 1999). Regarding the ejected mass, a long-standing problem of nova theory, still a factor of 10 uncertainty (at most) remains: this does not mean at all that theoretical values are always underestimated, but it is known that for certain well observed novae ejected masses are larger than predicted (however, determinations of observed ejected masses suffer from large uncertainties). A second improvement would come from an appropriate "weight" given to each nova, based on its mass. Here we can not apply the IMF, since we are not dealing with single stars but with white dwarfs in binaries, which explode as novae, once a set of conditions is fulfilled; these conditions depend not only on the mass of the white dwarf, but also on its chemical composition and luminosity, on the mass accretion rate and on the accreted matter's content of hydrogen and other elements (CNO). A selection function has been derived in the literature (Ritter et al. 1991; Gil-Pons et al. 2003), which gives the white dwarf mass distribution in classical novae, accounting for the envelope ignition mass (mass accreted before explosion) and other aspects, like the effect of binarity on the final composition of the white dwarf (Gil-Pons et al. 2003). Following these prescriptions, we would obtain a weight $P(M_{\rm wd})$=0.03, 0.06, 0.16 and 0.75 for masses $M_{\rm wd}$=1.0, 1.15, 1.25 and 1.35 $M_\odot$, which would mean that the contribution of the 1.0 and 1.15 $M_\odot$ ONe white dwarfs would be irrelevant as compared to that of the more massive of 1.25 and, specially, 1.35 $M_\odot$. The representative nova yield of ^{26}Al would then be 0.6×10^{-8} instead of 2×10^{-8} $M_{\odot}$! A deeper study of this selection function together with the analysis of the spatial distribution of the 1.8 MeV emission for all the different scenarios is in progress.

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