PROCEEDINGS OF SCIENCE

Nucleosynthesis and gamma-ray lines

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Astrophysical gamma-ray spectroscopy is an invaluable tool for studying nuclear astrophysics, supernova structure, recent star formation in the Milky Way and mixing of nucleosynthesis products in the interstellar medium. After a short, historical, introduction to the field, I present a brief review of the most important current issues. Emphasis is given to radioactivities produced by massive stars and associated supernova explosions, and in particular, those related to observations carried out by INTEGRAL: short-lived ^{44}Ti from CasA and long-lived ^{26}Al and ^{60}Fe from massive stars. The observed 511 keV emission from positron annihilation in the Galaxy and the role of stellar radioactivity and other potential positron sources are also discussed.

8th INTEGRAL Workshop The Restless Gamma-ray Universe- Integral2010,
September 27-30, 2010
Dublin Ireland

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1. Historical background

Gamma-ray line astronomy with cosmic radioactivities was essentially founded with the landmark paper of Clayton, Colgate and Fishman (1969). That work clarified the implications of the production of ^{56}Ni (a doubly magic, and yet unstable nucleus) during explosive Si-burning in supernovae (SN). In particular, it opened exciting perspectives for γ-ray line astronomy, by suggesting that any supernova within the local group of galaxies woud be detectable in the characteristic γ-ray lines resulting from the radioactive decay of ^{56}Ni (lifetime τ_{Ni-56}=8.8 d) and its daughter nucleus ^{56}Co (τ_{Co-56}=0.31 y).

In the 70's D. Clayton identified most of the radionuclides of astrophysical interest (i.e. giving a detectable γ-ray line signal); for that purpose, he evaluated their average SN yields by assuming that the corresponding daughter stable nuclei are produced in their solar system abundances[1]. Amazingly enough (or naturally enough, depending on one's point of view) his predictions of average SN radionuclide yields (Table 2 in Clayton 1982) are in excellent agreement with modern yield calculations, based on full stellar models and detailed nuclear physics (see Fig. 1 in Prantzos 2004a). Only the importance of ^{26}Al (τ_{Al-26}=1.04 10^6 y) escaped Clayton's (1982) attention, perhaps because its daughter nucleus ^{26}Mg is mostly produced in its stable form, making the evaluation of the parent's yield quite uncertain. That uncertainty did not prevent Arnett (1977) and Ramaty and Lingenfelter (1977) from arguing that, even if only 10^{-3} of solar ^{26}Mg is produced as ^{26}Al, the resulting Galactic flux from tens of thousands of supernovae (during the $\sim$1 Myr lifetime of ^{26}Al) would be of the order of 10^{-4} cm^{-2} s^{-1}.

In the case of ^{26}Al nature appeared quite generous, providing a γ-ray flux even larger than the optimistic estimates of Ramaty and Lingenfelter (1977): the HEAO-3 satellite detected the corresponding 1.8 MeV line from the Galactic center direction at a level of 4 10^{-4} cm^{-2} s^{-1}(Mahoney et al. 1984). That detection, the first ever of a cosmic radioactivity in γ-rays, showed that nucleosynthesis is still active in the Milky Way; however, the implied large amount of galactic ^{26}Al ($\sim$2 M$_\odot$ per Myr, assuming steady state) was difficult to accomodate in conventional models of galactic chemical evolution if SN were the main ^{26}Al source (Clayton 1984), since ^{27}Al would be overproduced in that case; however, if the "closed box model" assumption is dropped and *infall* is assumed in the chemical evolution model, that difficulty is removed, as subsequently shown by Clayton and Leising (1987).

Another welcome mini-surprise came a few years later, when the ^{56}Co γ-ray lines were detected in the supernova SN1987A, a $\sim$20 M$_\odot$ star that exploded in the Large Magellanic Cloud. On theoretical grounds, it was expected that a SNIa (exploding white dwarf of $\sim$1.4 M$_\odot$ that produces $\sim$0.7 M$_\odot$ of ^{56}Ni) would be the first to be detected in γ-ray lines; indeed, the large envelope mass of massive exploding stars ($\sim$10 M$_\odot$) allows only small amounts of γ-rays to leak out of SNII, making the detectability of such objects problematic. Despite the intrinsically weak γ-ray line emissivity of SN1987A, the proximity of LMC allowed the first detection of the tell-tale γ-ray line signature from the radioactive chain ^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe (Matz et al. 1988); this confirmed a 20-year old conjecture, namely that the abundant ^{56}Fe is produced in the form of radioactive ^{56}Ni.

[1]For a vivid account of the history and foundations of γ-ray line astronomy (and astronomy with radioactivities in general) see Chapter 2, written by D. D. Clayton, in the recent monograph edited by Diehl, Hartmann and Prantzos (2010).

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Those discoveries laid the observational foundations of the field of γ-ray line astronomy with radioactivities. The next steps were made in the 90ies, thanks to the contributions of the Compton Gamma-Ray Observatory (CGRO). First, the *OSSE* instrument aboard CGRO detected the γ-ray lines of ^{57}Co (τ_{Co-57}=1.1 y) from SN1987A (Kurfess et al. 1992); the determination of the abundance ratio of the isotopes with mass numbers 56 and 57 offered a unique probe of the physical conditions in the innermost layers of the supernova, where those isotopes are synthesized (Clayton et al. 1992). Second, the *COMPTEL* instrument mapped the Miky Way in the light of the 1.8 MeV line and found irregular emission along the plane of the Milky Way and prominent "hot-spots" in directions approximately tangential to the spiral arms (Diehl et al. 1995), which suggests that massive stars (SNII and/or WR) are at the origin of galactic ^{26}Al (as pointed out in Prantzos 1991, 1993) and not an old stellar population like e.g. novae or low mass AGB stars.

Furthermore, *COMPTEL* detected the 1.16 MeV line of radioactive ^{44}Ti (τ_{Ti-44}=89 y)in the Cas-A supernova remnant (Iyudin et al 1994). That discovery offered another valuable estimate of the yield of a radioactive isotope produced in a massive star explosion (although, in that case the progenitor star mass is not known, contrary to the case of SN1987A). On the other hand, it also created some new problems, since current models of core collapse supernova do not seem able to account for the yield inferred from the observations (see Sec. 2 and Fig. 1).

After the CGRO mission, another important discovery was made in the field: the RHESSI experiment detected the characteristic decay lines of ^{60}Fe (Smith 2004), another long-lived isotope (τ_{Fe-60}=3.8 10^6 y). The ^{60}Fe lines were also detected by *SPI*/INTEGRAL after 5 years of observations, and the observed ^{26}Al/^{60}Fe flux ratio appears compatible with theoretical expectations, which are however subject to large uncertainties yet (see Sec. 3).

Finally, in the past few years, the study of the 511 keV emission from positron annihilation in the galaxy attracted particular attention from astronomers and particle physicists. It is the oldest (Johnston et al. 1972) and brightest γ- ray line detected from outside the solar system, but despite more than 30 years of study, the origin of the annihilating positrons remains unknown yet (Sec. 4; see also the recent extensive review of Prantzos et al. 2010).

In the following I shall focus on the radioactivities produced by massive stars and associated supernova explosions, and in particular, those related to observations carried out by INTEGRAL. Recent reviews of similar scope are provided in Leising and Diehl (2009) and Diehl (2009), while a monograph on "Astronomy with Radioactivities", covering all topics related to γ-ray line astronomy, appeared recently (Diehl, Hartmann and Prantzos 2010).

2. ^{56}Ni and ^{44}Ti from core collapse supernovae (CCSN)

Both ^{56}Ni and ^{44}Ti are produced in the innermost layers of core collapse SN, through explosive Si-burning. Their yields (and those of other Fe-peak nuclei) are extremely difficult to evaluate from first principles, at least in the framework of current models of CCSN. The layers undergoing explosive Si-burning are very close to the "mass-cut", that fiducial surface separating the supernova ejecta from the material that falls back to the compact object (after the passage of the reverse shock). Since no consistent model of a core collapse supernova explosion exists up to now (e.g. Magkotsios et al. 2010 and refences therein), the position of the mass-cut is not well constrained.

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The presence of ^{56}Ni in SN1987A has been unambiguously inferred from the detection of 847 keV and 1238 keV γ-ray lines of the decay of its daughter nucleus ^{56}Co. Their early appearance ($\sim$6 months earlier than expected from spherically symmetric stratified models, from e.g. Gehrels et al. 1987) suggested that the SN ejecta were asymmetric, with ^{56}Co being driven close to the surface by hydrodynamic instabilities. The yield of ^{56}Ni has been estimated from the extrapolation of the early optical lightcurve to the origin of the explosion (precisely known thanks to the neutrino signal, see Arnett et al. 1989 and references therein); the derived value, 0.07 $M_{\odot}$, is often taken as a "canonical" one for CCSN, e.g. in studies of galactic chemical evolution. It turns out, however, that CCSN display a wide range of ^{56}Ni values, spanning a range of at least one order of magnitude; it also appears that there is a clear correlation between the amount of ^{56}Ni and the energy of the explosion (Hamuy 2003) probably because a shock of larger energy heats a larger amount of material to NSE conditions.

SN1987A was a "once in a lifetime"event and it is improbable that another CCSN will be seen in the light of the ^{56}Co lines in the next decades. Eriksen et al. (2009) constrained recently the ^{56}Ni yield of CasA, by estimating the extinction toward Casa and the iron mass from X-ray observations; the derived value (0.058-0.16 $M_{\odot}$) is comparable to the one of SN1987A. Observational prospects are better for thermonuclear supernovae (SNIa), although none has been seen up to now (see discussion in Leising and Diehl 2009, and references therein). Such a detection, combined with an optical one, would allow an unambiguous identification of the ^{56}Ni yield. Probing the physics of the explosion will require observations of the γ- ray lightcurve, in particular during the period when the SN envelope becomes optically thin (see Horiuchi and Beacom 2010 for an updated discussion of the perspectives for such detections).

^{44}Ti has not been directly detected in SN1987A up to now. Modelling of the late lightcurve of that supernova and of the infrared emission lines of the ejecta suggests that it may be powered by 1-2 10^{-4} $M_{\odot}$ of ^{44}Ti (Fransson and Kozma 2002, Motizuki and Kumagai 2004). The expected flux in the high energy 1157 keV line is $\sim$5 10^{-6} ph/cm^2/s, i.e. considerably lower than the $\sim$2 10^{-5} ph/cm^2/s sensitivity of *SPI* for an exposure of 1 Ms; it will undoubtedly constitute a major target for the next γ-ray satellite in the MeV range.

The γ-ray lines of ^{44}Ti have been detected in the $\sim$340 yr old CasA supernova remnant, located at a distance of $\sim$3.4 kpc from Earth. Both the high energy line at 1.157 MeV and the low energy ones, at 68 and 78 keV, have been detected: the former by *COMPTEL* (Iyudin et al. 1994) and the latter by Beppo-SAX (Vink et al. 2001) and by *IBIS*/INTEGRAL (Renaud et al. 2006). In contrast, the 1.157 MeV line was not detected by *SPI*/INTEGRAL; taking into account the aforementioned detections and the energy resolution of *SPI*, the non-detection by *SPI* constrains the velocity dispersion of the Ti-rich ejecta to $>$500 km/s (Martin et al. 2009). The detected flux of 3.3$\pm$0.6 10^{-5} ph/cm^2/s from *COMPTEL*, points to a ^{44}Ti yield of $\sim$1.7 10^{-4} $M_{\odot}$. Similar values, i.e. 1-2 10^{-4} $M_{\odot}$, are obtained through a study of the combined fluxes of the low energy lines (Vink et al. 2001, Renaud et al. 2006), although the modelisation of the underlying continuum spectrum makes the analysis somewhat uncertain. Note that the CasA yield of ^{44}Ti also suffers from uncertainties related to the ionization stage of the CasA remnant. ^{44}Ti decays by orbital electron capture and an ionized medium could slow down its decay (Mochizuki et al. 1999). Depending on the degree and the epoch of ionization, this effect could affect considerably the derived yield of ^{44}Ti. An early ionization preserves most of ^{44}Ti and produces higher than normal gamma-ray flux today, leading

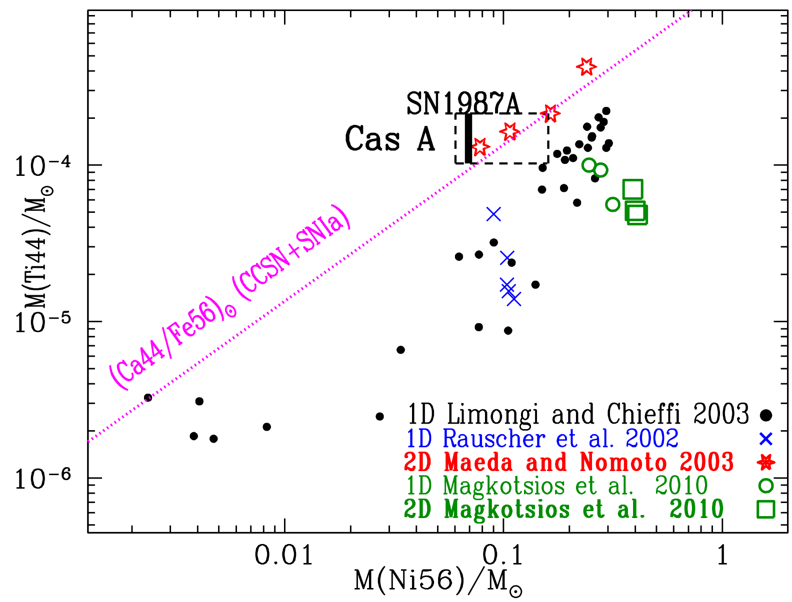

Figure 1: Yield of ^{44}Ti vs yield of ^{56}Ni, from models and observations. Model results are from Limongi and Chieffi (2003, filled circles, with large variations in yields due to variations in both stellar mass - from 15 to 35 M$_{\odot}$ - and explosion energy), Rauscher et al. (2002, crosses, for stars in the 15 to 25 M$_{\odot}$ range and explosion energies of 10^{51} ergs), Maeda and Nomoto (2003, asterisks, for axisymmetric explosions in 25 and 40 M$_{\odot}$ stars, producing high ^{44}Ti/^{56}Ni ratios) and Magkotsios et al. (2010, open circles for 1D and open squares for 2D models). Estimated amounts of ^{56}Ni and ^{44}Ti detected in CasA appear within the box limits (dashed) (assuming that its decay rate has not been affected by ionisation in the CasA remnant). The amount of ^{44}Ti in SN1987A is deduced from its late optical lightcurve. The diagonal dotted line indicates the solar ratio of the corresponding stable isotopes (^{44}Ca/ ^{56}Fe)$_{\odot}$.

to an overestimate of the ^{44}Ti yield, whereas a late ionization just reduces the flux of the little ^{44}Ti left today and leads to an underestimate of the true yield[2] (see also Motizuki and Kumagai 2004).

In summary: from observations we have a wide range of values for the ^{56}Ni yields of core collapse SN, a precise value of 0.07 M$_{\odot}$ for SN1987A and a range of 0.058-0.16 M$_{\odot}$ for CasA; and for ^{44}Ti yields we have similar values, i.e. 1-2 10^{-4} M$_{\odot}$, for both SN1987A (indirectly, through the modelisation of the UVOIR light) and for CasA (directly, through γ-ray lines, albeit with a systematic uncertainty resulting from poorly constrained ionisation effects). How do these observations compare to theory ?

The results of recent calculations are plotted as ^{44}Ti yield vs ^{56}Ni yield in Fig. 1, where the solar ratio of the corresponding stable isotopes is also displayed as a diagonal line. With one exception (to be discussed below) none of the theoretical results matches the SN1987A value of the ^{44}Ti/^{56}Ni ratio. In fact, those results are $\sim$3 times lower than the solar ratio of (^{44}Ca/^{56}Fe)$_{\odot}$ $\sim 10^{-3}$. This implies that such explosions cannot produce the solar ^{44}Ca, since ^{56}Fe would be overproduced in that case (e.g. Timmes et al. 1996). Moreover, there is another important source of Fe, SNIa, which produce about 0.5-0.65 of solar ^{56}Fe, but very little ^{44}Ca; this makes the defficiency of ^{44}Ca from CCSN even more serious than appearing in Fig. 1, since it implies that CCSN *should*

[2] I am grateful to J. Vink for a quantitative illustration of the ionization effects on the inferred ^{44}Ti yield of CasA.

produce a ^{44}Ti/^{56}Ni ratio *at least twice* solar in order to compensate for the ^{56}Fe production of SNIa (Prantzos 2004a).

In the case of CasA, the indirectly derived ^{56}Ni yield is comparable to the one of SN1993J (Krause 2008), a rather bright SNIIb, and the corresponding ^{44}Ti/^{56}Ni ratio is substantially higher than obtained in most models. It has been argued that such high ratio may be obtained in multi-dimensional, aspherical, models of energetic explosions of rotating massive stars (hypernovae): material along the jet (rotation) axis undergoes higher temperatures and entropies (i.e. lower densities) than material in normal spherical explosions, resulting in the production of large ^{44}Ti amounts and ^{44}Ti/^{56}Ni ratios (Nagataki et al. 1998, Maeda and Nomoto 2003). However, recent hydrodynamic simulations for rotating CCSN do not confirm that finding (Magkotsios et al. 2010 and Fig. 1). Thus, although there is observational evidence for asphericity in both SN1987A (Wang et al. 2002) and CasA (Schure et al. 2008 and references therein), it is not clear whether this property helps with the ^{44}Ti/^{56}Ni ratio.

The difficulty of present day CCSN nucleosynthesis models to produce sufficiently high ^{44}Ti/^{56}Ni ratios also bears to another issue: searches of the Milky way with HEAO-3, SMM, COMPTEL and INTEGRAL failed to detect ^{44}Ti sources other than CasA up to now, although a few sources are expected on the basis of inferred ^{44}Ti yields and Galactic CCSN frequency (The et al. 2006, Renaud et al. 2006). This may suggest that the main source of ^{44}Ca in the Galaxy may be a rare type of SN of high ^{44}Ti yield ($\sim 10^{-3}$ M$_\odot$), e.g. He-triggered SNIa of low mass (Woosley et al. 1986). A variant of that scenario, the double-detonation sub-Chandrasekhar model for SNe Ia, was recently investigated by Fink et al. (2010), who find indeed high ^{44}Ti yields and ^{44}Ti/^{56}Ni ratios for some values of the relevant parameter space.

3. ^{26}Al and ^{60}Fe from massive stars

^{26}Al is the first radioactive nucleus ever detected in the Galaxy through its characteristic gamma-ray line signature, at 1.8 MeV (Mahoney et al. 1984). Since its lifetime of $\sim$1 Myr is short w.r.t. galactic evolution timescales, its detection convincingly demonstrates that nucleosynthesis is still active in the Milky Way (Clayton 1984).

The morphology of the 1.8 MeV emission, as established by *COMPTEL*/CGRO and confirmed by *SPI*/INTEGRAL clearly suggests a young population at the origin of ^{26}Al, since it is concentrated along the plane of the Galactic disk. The degree of the irregularity ("patchiness") of that emission is not well established yet, since it depends on the method of analysis (i.e. Plüschke et al. 2001 vs Knödlseder 1999). Although it is tempting to identify some of the "hot-spots" seen in the COMPTEL map with tangents to the spiral arms (as predicted in Prantzos 1991, 1993) only the star forming regions of Cygnus (Knödlseder 2000) and Sco-Cen (Diehl et al. 2010) are unambiguously identified up to now.

For several years, progress has been hampered by the difficulty to evaluate distances to the regions of the 1.8 MeV emission, which could be dominated by nearby sources. The high resolution Ge spectrometer of *SPI* allowed for the first time to measure Doppler shifts and derive radial velocities of the emitting regions (a technique widely used in radioastronomy to map 21 cm emission of HI): the result is consistent with expectations from large scale rotation of the galactic disk (Kretschmer et al. 2010) and implies that most of ^{26}Al is moving as the average ISM. This allows,

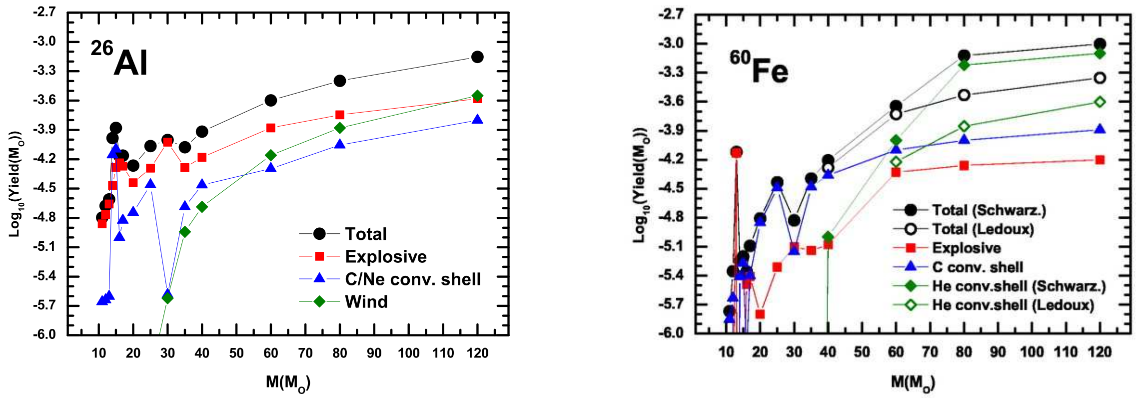

Figure 2: Yields of ^{26}Al (right) and ^{60}Fe (left) from massive, mass losing stars of solar metallicity, according to Chieffi and Limongi (2006). ^{26}Al yields are dominated by explosive nucleosynthesis, while those of ^{60}Fe by hydrostatic production in the He-shell.

in turn, to use geometrical models of the large scale distribution of the ISM (normalised to the mesured 1.8 MeV flux), to derive the total mass of ^{26}Al, which is 2.7$\pm$0.7 M$_\odot$ according to Wang et al. (2009) or somewhat smaller (Diehl et al. 2010). Moreover, the observed broadening of the 1.8 MeV line is consistent with expectations from Galactic rotation and suggests that ^{26}Al is at rest with respect to the ISM (at least in the plane of the disk).

The most plausible sources for the inferred $\sim$2 M$_\odot$/Myr of ^{26}Al (assuming a steady state between its production and radioactive decay in the ISM) are massive stars[3]. The roles of their winds (expelling ^{26}Al from hydrostatic H-burning) and explosions (expelling ^{26}Al from subsequent nuclear burning phases) remained unclear for two decades. Chieffi and Limongi (2006), using non-rotating models of mass losing stars of solar metallicity, found that explosive yields always dominate (Fig. 2 left). One should keep in mind, however, that substantial uncertainties (related to convective mixing or nuclear reaction rates, e.g. Tur et al. 2010) still affect the ^{26}Al yields, while rotation and higher metallicities (as appropriate for the inner Galaxy) might affect the relative importance of hydrostatic vs explosive yields.

The original aims of γ-ray line astronomy, as formulated in e.g. Clayton (1982) concerned the study of nucleosynthesis and SN structure, through observations requiring high energy resolution. The spatial resolution of satellite instruments made it possible to address new questions related to large scale star formation (in stellar associations or the whole Galaxy) and mixing of nucleosynthesis products in the ISM. Thus, Diehl et al. (2006) used the total Galactic ^{26}Al flux, combined to theoretical ^{26}Al yields, to infer a rate of 1.9$\pm$1.1 CCSN in the Galaxy (consistent with more conventional estimates), while Martin et al. (2010) and Voss et al. (2010) studied recently ^{26}Al production and evolution in Cygnus and Orion, respectively, with population synthesis models. On the other hand, preliminary constraints on the vertical extent of the ^{26}Al distribution in the Galaxy (and, thereof, on the existence of galactic "fountains"or "chimneys") can be obtained from the study of the latitude extent of the 1.8 MeV emission, which suggests a scaleheight of 130 pc (Wang et al.

[3]Massive AGB stars (5-8 M$_\odot$) cannot be excluded, but their ^{26}Al yields are difficult to evaluate and appear small.

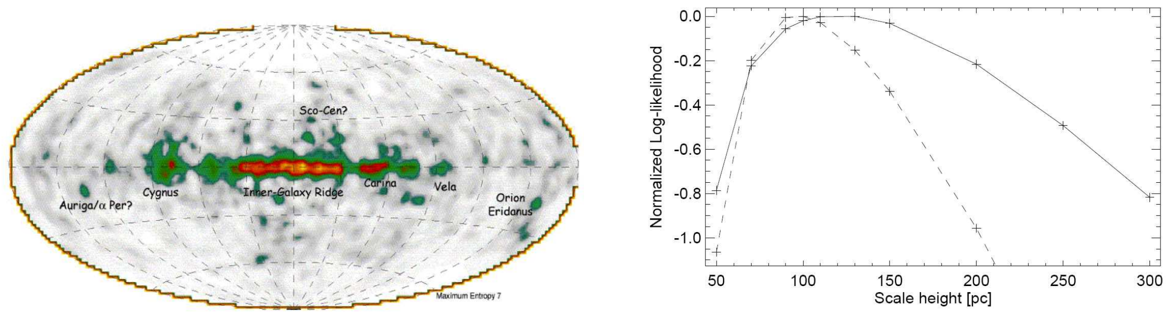

Figure 3: Right: COMPTEL map of Galactic ^{26}Al(from Plüschke et al. (2001). Left: Evaluation of the scaleheight of the ^{26}Al distribution of the Galaxy, from the estimated latitude extent of the 1.8 meV emission (from Wang et al. 2009).

2009, see Fig. 3, right).

Clayton (1982) pointed out that SNII explosions produce ^{60}Fe, a radioactivity, with a lifetime comparable to the one of ^{26}Al[4]. The gamma-ray line flux ratio of ^{60}Fe/^{26}Al in the Galaxy (assuming both radioactivities in steady state) would provide then a "clean" probe of stellar nucleosynthesis, independent from e.g. absolute values of CCSN rates. Based on calculations from Woosley and Weaver (1995, with models having no mass loss or rotation) Timmes et al. (1995) found that the expected ratio of ^{60}Fe/^{26}Al from CCSN (for each of the two lines of ^{60}Fe) is 0.16.

The ^{60}Fe lines were detected by RHESSI (Smith 2004) and subsequently confirmed by *SPI*/INTEGRAL (Harris et al. 2005; Wang et al. 2007, see Fig. 4 left). The reported *SPI* flux ratio is ^{60}Fe/^{26}Al=0.14±0.06, but potentially important systematic effects (from nearby instrumental lines) cannot be excluded. Taken at face value, the reported ratio is in astonishingly good agreement with original predictions. However, in the meantime, refined theoretical models predicted substantially higher ^{60}Fe/^{26}Al values, (more ^{60}Fe and less ^{26}Al) as pointed out in Prantzos (2004b). The most recent works in the field (Woosley and Heger 2007, Chieffi and Limongi 2006) still predict values on the high side of the *SPI* result, at least for plausible values of various physics inputs (e.g. Fig. 4 right).

It is clear, however, that substantial uncertainties still remain in stellar and nuclear physics, both for ^{26}Al and ^{60}Fe. The latter is produced mostly by hydrostatic burning in the He- and C- layers[5], through neutron captures on Fe-seed nuclei (Fig. 2 right). Convection (still a major unknown in stellar evolution calculations) plays a key role in determining the sizes of convective shells, but other factors, like mass loss (for the most massive stars, above 50 $M_\odot$) or rotation also turn out to be important. Besides, uncertainties on nuclear reaction rates, including reactions which are not directly involved in production/destruction of ^{60}Fe, like e.g. the 3-alpha or ^{12}C$(\alpha,\gamma)^{16}$O rates, may greatly affect the final yield of ^{60}Fe (see Tur et al. 2010). This leaves a lot of theoretical issues unsettled yet and underscores the importance of γ-ray line observations in the Galaxy, both at large scale and at smaller scales (to determine any gradient of the ^{60}Fe/^{26}Al ratio, or its value in young star forming regions like Cygnus, presumably too young to be affected from the action of CCSN).

[4]The most recent measurements of ^{60}Fe lifetime give τ_{Fe-60}=3.78±0.06 Myr (Rugel et al. 2009), a value almost twice as large as previously thought.

[5]Notice that a large fraction of ^{60}Fe in the bottom of the He-layer is produced *after* central O-burning, which implies that virtualy all stages of stellar evolution are important for ^{60}Fe production (Tur et al. (2010).

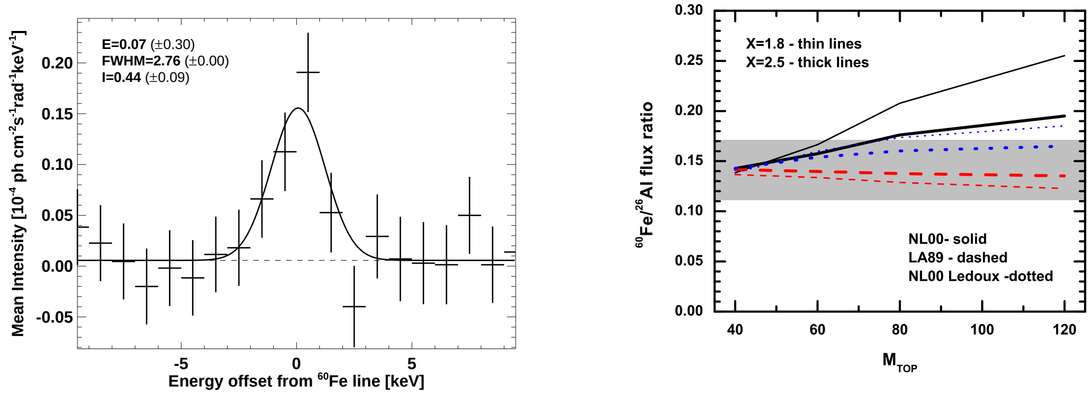

Figure 4: Left: ^{60}Fe line profile from SPI/INTEGRAL observations of the inner Galaxy (from Wang et al. 2007). Right: theoretical estimates of the ^{60}Fe/^{26}Al ratio as a function of the upper mass limit of the stellar initial mass function (curves, based on various assumptions abouth the physics of massive stars) compared to observations (shaded aerea), from Chieffi and Limongi (2006).

4. Positron annihilation in the Galaxy

The first γ-ray line ever detected outside the solar system was the 511 keV line of electron-positron annihilation (Johnson et al. 1972). Observations by various instruments in the 90's established that the line is not variable (at least in a $\sim$10 year period), that its spatial distribution is apparently dominated by a bulge-like component and that the overall spectrum suggests that most positrons annihilate after formation of the bound state of *positronium* (positronium fraction of 0.93, see Kinzer et al. 2001 and references therein). The 511 keV flux attributed to the central Galactic sterad was found to be $\sim 10^{-3}$ ph/cm^2/s, corresponding to a steady state production rate of 10^{43} e$^+$ s^{-1}.

Observations in the 2000s with *SPI*/INTEGRAL confirmed the abnormally high bulge/disk ratio of the 511 keV emission (larger than in any other wavelength, Knödlseder et al. 2005) and the emission from a disk, albeit with a poorly constrained morphology. It is not yet clear whether the disk is asymmetric (as found in Weidenspointner et al. 2008a) or whether the bulge centroid is slightly off with respect to the Galactic center (Bouchet et al. 2010) [6].

According to the imaging analysis of *SPI* data (Weidenspointner et al. 2008a) the total Galactic e$^+$ annihilation rate is at least $\dot{N}_{e^+} \sim 2\ 10^{43}$ s^{-1}, with a luminosity bulge/disk ratio B/D=1.4. This model is further refined by considering a narrow ($FWHM = 3^o$) and a broad ($FWHM = 11^o$) bulge, the former contributing to $\sim$35% of the total bulge emission. However, the data analysis also allows for other morphologies, involving extended regions of low surface brightness but high total emissivity, e.g. a "halo" of total $\dot{N}_{e^+} \sim 3\ 10^{43}$ s^{-1} and a thin disk of $\dot{N}_{e^+} \sim 5\ 10^{42}$ s^{-1}, leading to a high B/D$\sim$6 (Weidenspointner et al. 2008b).

Information on the origin of those positrons is also obtained via the spectral analysis of the 511 keV emission (Guessoum et al. 2005, Jean et al. 2006, Churazov et al. 2010). The observed flux at $\sim$MeV energies from the inner Galaxy constrains the initial energy of the positrons to less

[6] See also talks by Bouchet, Roques and Skinner in this workshop.

than a few MeV (otherwise the emission from in-flight annihilation would exceed the observed flux, Beacom and Yuksel 2006). Moreover, the spectral analysis provides important information on the physical properties of the e^+ annihilation sites. The large positronium fraction f_{P_S} ∼94-97 % implies that positrons annihilate mostly at low energies, since direct annihilation cross-sections are important only at high energies. The overall spectral shape suggests that annihilation occurs mostly in warm (T∼8 000 K) media, at about equal amounts in neutral and ionized phases but it cannot be excluded that less than 23% of annihilation occurs in the cold neutral medium (T ∼ 80 K); annihilation in the neutral media may account for the presence of a broad 511 keV line component (FWHM ∼5 keV) and the annihilation in the warm ionized medium for the narrow one (FWHM ∼1 keV).

Among the various astrophysical sources of positrons proposed so far, the only one known with certainty to release e^+ in the ISM is β^+ radioactivity of ^{26}Al; the observed intensity of its characteristic 1.8 MeV emission in the Galaxy corresponds to ∼3-4 10^{42} e^+ s^{-1}. A similar amount is expected from the decay of ^{44}Ti, on the grounds of nucleosynthesis arguments. Both radionuclides are produced mostly in massive stars and their positrons should be released along the Galactic plane, as traced by the 1.8 MeV emission; they could thus account for the observed disk 511 keV emission.

Radioactivity of ^{56}Co from SNIa was traditionally considered to be the major e^+ producer in the Galaxy. Both the typical ^{56}Ni yield of a SNIa and the Galactic SNIa rate are rather well constrained, resulting in 5 10^{44} e^+ s^{-1} produced *inside* SNIa. If only f_{esc} ∼4% of them escape the supernova to annihilate in the ISM, the observed total e^+ annihilation rate can be readily explained. However, observations of two SNIa, interpreted in the framework of 1-D (stratified) models, suggest that the positron escape fraction is negligible *at late times*. On the other hand, both observations of early spectra and 3-D models of SNIa suggest that a sizeable fraction of ^{56}Ni is found at high velocity (close to the surface), making - perhaps - easier the escape of ^{56}Co positrons. In our opinion, SNIa remain a serious candidate, with a potential Galactic yield of 2 10^{43} e^+ s^{-1}. But the expected spatial distribution of SNIa in the Galaxy corresponds to a much smaller B/D ratio than that of the observed 511 keV profile (see Prantzos et al. 2010 for a thorough discussion of SNIa issues in the context of Galactic positrons).

Most of the other astrophysical candidates can be constrained to be only minor e^+ sources, on the basis of either weak e^+ yields (novae, Galactic cosmic rays), high e^+ energy (compact objects, like pulsars or magnetars), spatial morphology of sources (hypernovae, gamma ray bursts) or a combination of those features (e.g. cosmic rays). Only two astrophysical candidates remain as potentially important contributors: LMXRBs (Prantzos 2004a) or the microquasar variant of that class of sources (Guessoum et al. 2006) and the supermassive black hole at the Galactic center (e.g. Cheng et al. 2006, Totani 2006, Chernysov et al. 2009 and references therein). It should be stressed that there is no evidence that either of those sources produces positrons, and the e^+ yields evaluated by various authors are close to upper limits rather than typical values. Furthermore, because of the current low activity of the central MBH (much lower than that of LMXRBs) it has to be assumed that the source was much more active in the past, thus dropping the assumption of "steady state" between e^+ production and annihilation, which is likely in all other cases.

Dark matter (DM) has been proposed as an alternative e^+ source, at least for the bulge 511 keV emission; in principle, it could complement disk emission originating from radioactivity of ^{26}Al and

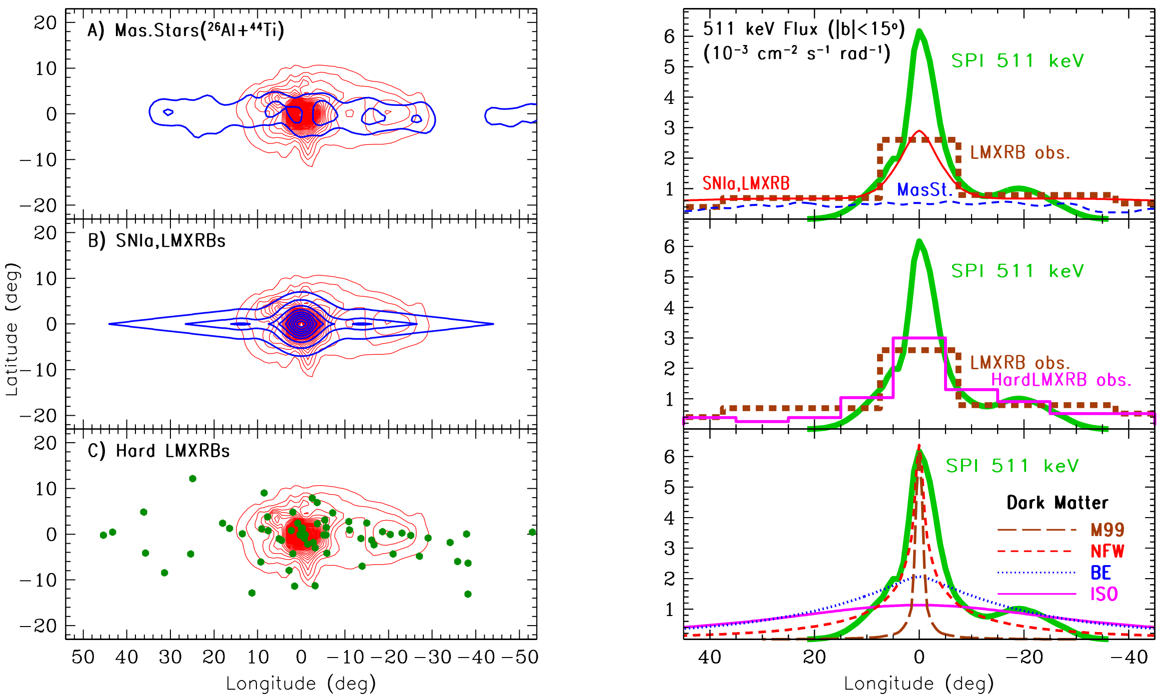

Figure 5: Left: Maps of the Galactic 511 keV emission (flux in cm^{-2} s^{-1} sterad^{-1}), as observed from SPI (in all panels, *thin isocontours* from Weidenspointneret al. 2008a) and from observationally based or theoretical estimates. A) Observed ^{26}Al (and, presumaby, ^{44}Ti) map (from Plüschke et al. 2001) ; B) Accreting binary systems (SNIa and, presumably, LMXRBs, see text); C) Observed Hard LMXRBs. The robustly expected e^+ annihilation from radioactivity in the disk (upper panel) is not yet fully seen by SPI. **Right:** Intensity of 511 keV emission as a function of Galactic longitude. All fluxes are integrated for latitudes $|b| < 15^o$. In all panels, the *thick solid curve* corresponds to SPI observations, i.e. the map of left figure. (*Note*: We emphasize that SPI maps and fluxes are provided here for illustration purposes only; quantitative comparison of model predictions to data should only be made through convolution with SPI response matrix.). The *thick dotted histogram* (*top* and *middle*) is the observed longitude distribution of LMXRBs (from Grimm et al. 2002); the latter resembles closely the theoretically estimated longitude distribution of SNIa (*thin solid curve* in the *upper panel*), which has been normalised to a total emissivity of 1.6 10^{43} e^+ s^{-1}, with Bulge/Disk=0.45 (maximum Bulge/Disk ratio for SNIa). Also, in the upper panel, the *lower dashed curve* corresponds to the expected contribution of the ^{26}Al and ^{44}Ti β^+-decay from massive stars. The *thin solid histogram* in the *middle panel* is the observed longitude distribution of Hard LMXRBs (from Bird et al. 2007) and it has the same normalization as the thick histogram. In the *bottom* panel, the SPI 511 keV profile is compared to profiles expected from dark matter annihilation). Both figures are from the review of Prantzos et al. (2010).

^{44}Ti or ^{56}Co. Observations of the MeV continuum from the inner Galaxy constrain the large phase space of DM properties. The mass of annihilating or decaying DM particles should be smaller than a few MeV, otherwise their in-flight annihilation would overproduce the MeV continuum. Scalar light DM particles with fermionic interactions appear as a possible candidate (e.g. Boehm et al. 2004); alternatively, the collisional de-excitation of heavy (100 GeV) DM particles could provide the required positrons, provided the energy separation between their excited levels is in the MeV range (e.g. Finkbeiner and Weiner 2007). On the other hand, the observed spatial profile of the 511 keV emission constrains the production mode of DM positrons, if it is assumed that they annihilate close to their production region: only "cuspy" profiles are allowed in the case of annihilating or de-exciting DM particles (for which $\rho_\gamma \propto \rho_{DM}^2$), while decaying DM particles (for which $\rho_\gamma \propto \rho_{DM}$) are excluded; the problem is that observations of external galaxies suggest rather flat, not cuspy, DM profiles.

Positrons produced in the hot, tenuous plasma filling the bulge (either from SNIa, LMXRBs or DM), have to travel long distances while slowing down and before annihilating (Jean et al. 2006, 2009). This is corroborated by the spectral analysis, which suggests that positrons annihilate in warm gas: such gas is filling mostly the inner bulge. Positron propagation over large distances appears then unavoidable, undermining the assumption that the e^+ production and annihilation profiles are correlated, at least in the bulge. A similar situation should hold for positrons produced away from the plane of the disk (i.e. from SNIa or LMXRBs), which is also dominated by hot, tenuous gas. The situation is less clear for positrons produced by massive star radioactivity, in the plane of the disk and inside spiral arms: although some of them may fill hot bubbles and cavities created by the SN explosions and ultimately escape from the disk, another fraction may annihilate in closeby dense molecular clouds. Propagation of MeV positrons in the ISM may then hold the key to understanding the 511 keV emission. It depends on the physical properties of the ISM (density, ionization) but also on the properties of turbulence and magnetic field configuration. Preliminary attempts to evaluate the extent of positron propagation and their implications for the Galactic 511 keV emission (Prantzos 2006, Higdon et al. 2009) are promising in that respect, but the situation is far from clear at present: the entanglement between the various uncertainties (concerning e^+ sources, e^+ propagation and annihilation sites) does not allow any strong conclusions to be drawn.

More than 30 years after its discovery, the origin of the first extra-solar γ-ray line remains unknown. Most probably, observations with next generation instruments will be required to unravel its mystery.

Acknowledgements During the INTEGRAL meeting I benefited from many discussions with R. Diehl, M. Leising and P. von Ballmoos. I am grateful to R. Diehl and J. Vink for constructive comments on the manuscript.

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