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AUTHOR'S PROOF

Gamma rays from cosmic radioactivities

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Abstract–Gamma rays from radioactive byproducts of cosmic nucleosynthesis are direct messengers from nuclear processes taking place in various cosmic sites, and can be measured with telescopes operated in space. Due to low detector sensitivity, up to now only a handful of sources have been detected in that electromagnetic window. Cobalt lines from SN1987A and ^{44}Ti lines from the Cassiopeia A (Cas A) supernova remnant offer unique constraints on the properties of the innermost regions of core collapse supernovae. Diffuse gamma-ray lines from the decay of radioactive ^{26}Al and the annihilation of positrons are bright enough for mapping the Milky Way in the MeV regime, and are both measured by recent spaceborne spectrometers with unprecedented precision. This constrains the sources of Al production and the state of interstellar gas in the vicinity of these sites: the total mass of ^{26}Al produced by stellar sources throughout the galaxy is estimated to be ~3 $M_\odot$ per Myr, and the interstellar medium near those sources appears to be characterized by velocities of ~100 km s^{-1}. Positron annihilation must occur in a modestly-ionized, warm phase of the interstellar medium, but at present the major positron production site(s) remain unknown. The spatial distribution of the annihilation gamma-ray emission strictly constrains positron production sites and positron propagation in the galaxy. ^{60}Fe radioactivity has been clearly detected recently; the flux ratio relative to ^{26}Al of about 15% is on the lower side of predictions from massive star and supernova nucleosynthesis models. Those views at nuclear and astrophysical processes in and around cosmic sources by space-based gamma-ray telescopes offer invaluable information on cosmic nucleosynthesis.

INTRODUCTION

Branches of astronomy are often defined by their observational band or technique, such as "optical" or "radio" or "high-energy" astronomy. Ernst Zinner has been one of the pioneers of a completely different and alternative "astronomy" rooted in terrestrial laboratories: high precision mass spectrometry of the isotopic composition of presolar grains (included in meteorites as direct and material probes of cosmic nucleosynthesis), which is now established as an astronomy discipline in its own right (Anders and Zinner 1993; Zinner et al. 1987; Clayton and Nittler 2004; Zinner 1998). Much of the information that links such isotopic measurements to cosmic nucleosynthesis processes is based on radioactive decays of unstable isotopes. Characteristic daughter-product isotopes generate a unique isotope abundance signature, which is distinct from common isotopic varieties in meteoritic material. The astrophysical challenge that connects Ernst Zinner's investigations of meteorites and presolar grains to our work, which is based on radioactivity gamma rays (Fig. 1), concerns the physics underlying the formation of fresh nuclei in the universe. The relevant processes occur inside stars undergoing either hydrostatic or explosive nuclear burning, but also in interstellar space via high-energy particle interactions (Wallerstein et al. 1997). Theories for cosmic nucleosynthesis continue to be developed following the pioneering works of Cameron and Burbidge, and Burbidge, Fowler, and Hoyle in 1957 (Cameron 1970; Burbidge et al. 1957; Arnett 1969; Truran and Cameron 1971; Clayton 1968). Observations of radioactive isotopes through gamma rays ensued from pioneering gamma-ray experiments following the Apollo program of the 1970s and balloon experiments (Johnson and Haymes 1973). Parallel to this experimental development, the emergence of isotopic analyses of stardust in the laboratory (after Ca-Al-rich inclusions of meteorites had been recognized as carriers of presolar signatures [Zinner et al. 1987]) has been consolidated by Ernst Zinner and his colleagues (Zinner 1998). A direct

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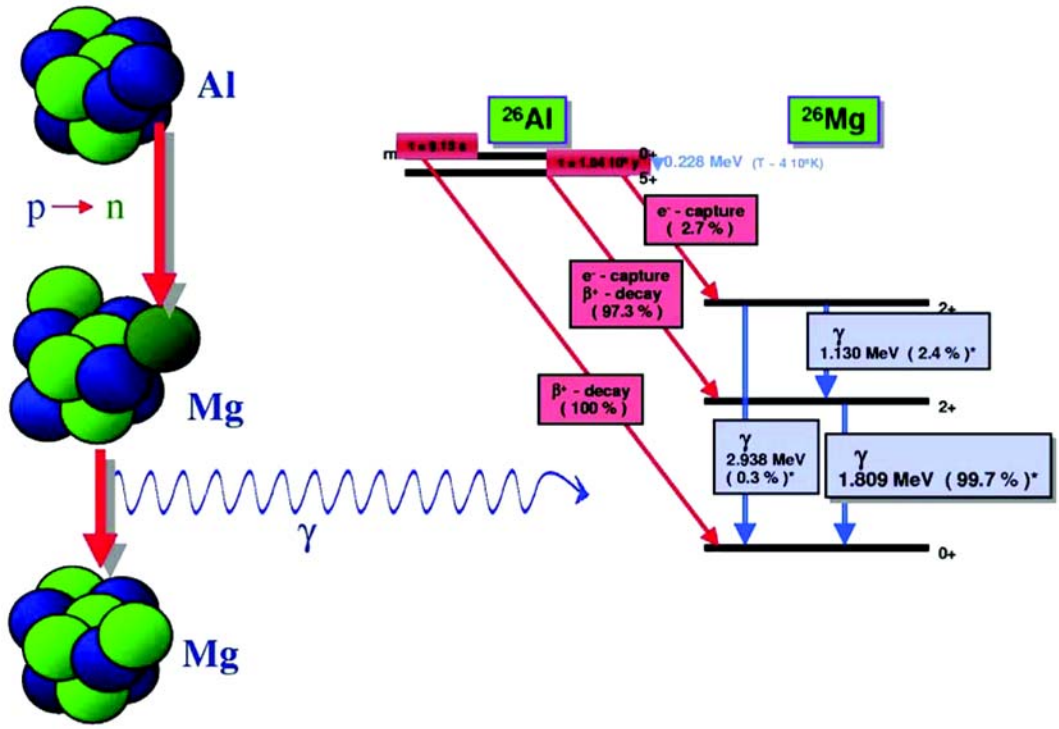

Fig. 1. Radioactive decay of unstable isotopes leads to gamma-ray emission, which can be measured from telescopes aboard satellites above the atmosphere of the Earth. Here the case of ^{26}Al is shown, decaying with a characteristic lifetime of 1.04 Myr into an excited state of ^{26}Mg, which de-excites into the Mg ground state by gamma-ray emission.

connection between theories of nucleosynthesis and observation of its products is possible with the detection of trace isotopes, which is feasible with current technology both in space and in terrestrial laboratories. In comparison, the vast amount of data on stellar spectroscopy (Cayrel and Cayerl de Strobel 1966; Cayrel de Strobel et al. 2001; Gratton et al. 2000; Edvardsson et al. 1993) offers complementary, but less direct, information: indeed, theories for element mixing and radiative transfer in stellar atmospheres must be employed to convert observed spectral features to information on nucleosynthesis. As part of the common theme of astronomy with radioactivities, here we present the experimental techniques and astrophysical achievements in astronomy with obtained with gamma-ray telescopes. We also point to a series of workshops on this topic, where over the past ten years we have enjoyed frequent discussions with Ernst Zinner and his colleagues on those common themes (Diehl and Hartmann 2000; Diehl et al. 2002; Diehl et al. 2004; Hartmann et al. 2006).

GAMMA-RAY TELESCOPES

Gamma rays typically penetrate matter of substantial density (on the order of a few grams cm^{-2})—this allows observers to probe far-away regions of the galaxy even if they are obscured by molecular clouds, or the interiors of supernova or nova explosions. The other side of this penetrating power is the difficulty to detect and measure cosmic gamma rays, and even more to derive the imaging information needed for many astronomical purposes. Gamma-ray telescopes (Fig. 2) consist of massive detector elements that are typically several centimeters thick (much larger than the millimeters-sized CCD cameras used for optical imaging). Moreover, many of those detectors have to be operated simultaneously to capture imaging information and to reduce instrumental backgrounds (for more details see Diehl et al. 2006a). Instrumental backgrounds are large in space environments due to the irradiation of telescopes and satellites from cosmic ray particles, which leads to nuclear excitations of atomic nuclei in those materials producing gamma rays locally, just as the remote cosmic sites of interest do. Massive shields of gamma-ray cameras through particle detectors are commonly used to provide a veto signal when cosmic-ray particles hit the instrument. In comparison with other wavelength regions, these experimental difficulties have slowed progress of astrophysical studies in the gamma-ray band. But the unique information from nuclear processes in cosmic sites makes these efforts worthwhile (Diehl et al. 2006a; Prantzos and Diehl 1996).

After pioneering work with detectors flown on stratospheric balloons, rockets and satellites in the 1960s and 1970s, NASA's Compton Gamma Ray Observatory mission of 1991–2000 performed the first sky survey of bright gamma-ray line emission, with a limiting sensitivity of about 10^{-5} ph cm^{-2} s^{-1} and spatial resolution of a few degrees (Gehrels et al. 1993). From these early observations, it was

Table 1. The isotopes that lead to astronomically relevant gamma-ray lines from their radioactive decay. Mean decay times are given for the slowest decay in the chain. Isotopes which have been detected in gamma-rays show their gamma-ray energies marked in green. The underlying nucleosynthesis processes are indicated, with H = hydrogen burning, NSE = nuclear statistical equilibrium, meaning nucleosynthesis in equilibrium among all strong nuclear reactions, α-NSE = α-rich freeze-out from NSE in core-collapse supernovae, Ne = explosive neon burning, υ = neutrino process which decomposes nuclei generating excess free nucleons.

Isotope	Mean decay time	Decay chain	γ-ray energy (keV)	Detected source	Source type	Nuclear process
^{7}Be	77 d	$^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li}^{*}$	478	None	Novae	H (explosive)
^{56}Ni	111 d	$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}^{*} \rightarrow {}^{56}\mathrm{Fe}^{*} + \mathrm{e}^{*}$	158, 812, 847, 1238	SN1987A, SN1991T	Supernovae	NSE
^{57}Ni	390 d	$^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}^{*}$	122	SN1987A	Supernovae	NSE
^{22}Na	3.8 yr	$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}^{*} + \mathrm{e}^{*}$	1275	None	Novae	H (explosive)
^{44}Ti	85 yr	$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc}^{*} \rightarrow {}^{44}\mathrm{Ca}^{*} + \mathrm{e}^{*}$	78, 68, 1157	SNR Cas A	Supernovae	α-NSE
^{26}Al	10.4 10^{6} yr	$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}^{*} + \mathrm{e}^{*}$	1809	Galactic plane regions	Stars, novae, supernovae	H, Ne (hydrost., explosive), υ
^{60}Fe	2.2 10^{6} yr	$^{56}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Co}^{*} \rightarrow {}^{60}\mathrm{Ni}^{*}$	59, 1173, 1332	Galaxy	Supernovae, stars	n capture
e^{+}	10^{5}–10^{7} yr	$\mathrm{e}^{+} + \mathrm{e}^{-} \rightarrow \mathrm{Ps} \rightarrow \gamma\gamma$	511, <511	Galactic bulge	Supernovae, novae	β^{+} decay

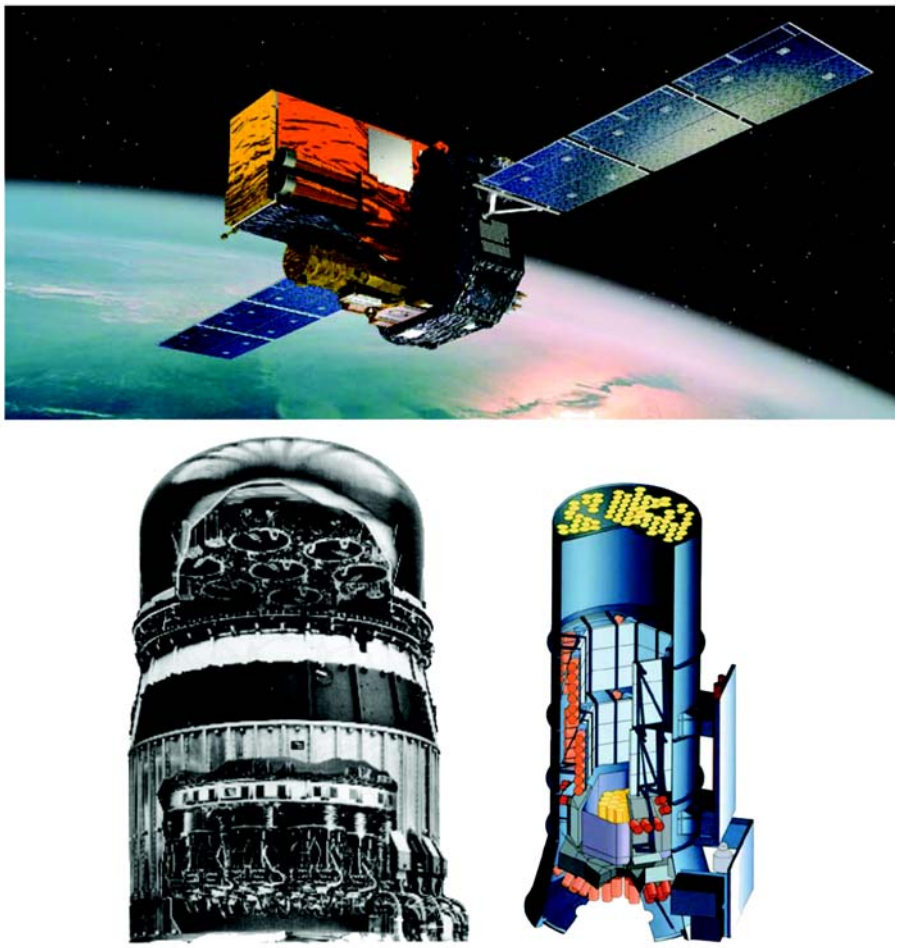

Fig. 2. Satellites such as ESA's INTEGRAL (top) carry gamma-ray telescopes above the atmosphere of the Earth. Gamma-ray telescopes consist of arrays of photon detectors, which image the sky either through a measurement of Compton scattering (left; the COMPTEL telescope consists of two planes of photon detectors operating in coincidence), or though a 'coded' telescope aperture (right; the SPI imaging spectrometer (Vedrenne et al. 2003; Roques et al. 2003) is built around a 19-element camera of Ge detectors; incident gamma-rays will cast a characteristic shadow onto this camera due to the coded mask, which allows to discriminate sources against instrumental background).

clearly established that the inner galaxy is a bright source of positron annihilation gamma rays at 511 keV (Purcell et al. 1997), the galaxy glows in ^{26}Al radioactivity (Diehl et al. 1995), and supernova radioactivity is observable in special circumstances, such as ^{44}Ti from the 340-year-old Cassiopeia A (Cas A) supernova remnant (Iyudin et al. 1994), and Ni decay gamma rays from SN1987A (Kurfess et al. 1992) and the bright type Ia supernova called SN1991T (Morris et al. 1997). However, several puzzles remained: nova radioactivity had not been seen directly (Iyudin et al. 1995), the observed supernova objects were less common than expected (Georgii et al. 2002), and the tantalizing reports of nuclear excitation lines from star-forming regions such as Orion (Bloemen et al. 1994), the 2.2 MeV gamma rays (McConnel et al. 1997) possibly from a nearby white dwarf, and a second ^{44}Ti supernova remnant in the Vela region (Iyudin et al. 1998) were too uncertain for realistic astrophysical interpretations (Bloemen et al. 1999; Shöenfelder et al. 2000). It should be noted that most of these gamma-ray line studies were made with modest spectral resolution and thus could not really resolve and autonomously identify the nuclear lines (see Table 1).

Recently established observatories with high-resolution solid-state detectors such as the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) (Lin et al. 2002) and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL)/SPI spectrometer (Winkler et al. 2003; Vedrenne et al. 2003; Roques and Schanne 2003) (Fig. 2) added a new quality to this field: spectroscopy of these nuclear lines allows to identify cosmic lines against reference lines from instrumental background and is capable to constrain the kinematics of cosmic isotopes in the gamma-ray emission region. The astrophysical importance of such velocity information for the study of particle acceleration in solar flares has been demonstrated and will not be further addressed here (Murphy and Share 2005; Gros et al. 2004; Hurford et al. 2006). Below we discuss how this information is exploited for cosmic sources, i.e., for supernova nucleosynthesis ejecta and for the turbulent interstellar medium in the vicinity of massive stars. The special processes involved in positron annihilation gamma-ray production (Guessoum et al. 2005) shape the corresponding gamma-ray line at 511 keV. This can be exploited to constrain ionization state and temperature of the interstellar gas in the region where positrons annihilate, which may be quite far from the locales where the positrons were generated in the first place.

Candidate sources of characteristic gamma-ray lines are supernovae and novae, but also the winds from massive stars (Diehl and Timmes 1998; Diehl et al. 2006a). In these objects, freshly produced nuclei from explosive layers near the surface of compact stars and from stellar interiors are ejected into interstellar space, where their decay can be observed directly in gamma rays. Once ejected, long-lived radioisotopes will decay in interstellar space; once merged with interstellar gas, they provide radioactive tracers which reflect the state of circumstellar and interstellar gas around the source. The kinematics of inner-ejecta material (rather than outer envelope and swept-up matter) can be studied in young supernova remnants, more or less complete ionization of matter will lead to modified decay histories for the total of ^{44}Ti produced in the explosion (mean decay time of 85 years [Ahmad et al. 2004] by electron capture only). Longer-lived isotopes such as ^{26}Al (τ ~1.04 Myr, Prantzos and Diehl 1996) will reflect interstellar-gas kinematics through Doppler shift or broadening of decay gamma-ray line(s); this interstellar medium around massive star sources is otherwise hard to study, as it is hot and tenuous in nature. Positrons from decays of isotopes on the proton-rich side of the valley of stability will typically be produced at MeV energies (Guessoum et al. 2005); their propagation before their annihilation is more complex, being controlled by density and magnetic field morphologies near the sources (Guessoum et al. 2005; Murphy and Share 2005); high-energy emission from annihilation-in-flight would be the “smoking gun” near the source, while the 511 keV line and lower-energy continuum arise from thermalized positrons with therefore unknown origin.

GAMMA-RAY LINES FROM SUPERNOVAE

Cobalt Gamma-Ray Lines from Radioactivity Powering Supernova Light Curves

Supernovae shine as bright as entire galaxies for weeks to months. The energy source providing this luminosity cannot be the explosion itself, as this would result in much more rapid fading; radioactive release of energy over those longer time scales is required and most likely can be attributed to the decay of freshly synthesized Ni and Co isotopes, with characteristic decay lifetimes of 8 and 111 days for ^{56}Ni and ^{56}Co, respectively. The amount of synthesized radioactive Ni provides one of the key parameters of supernova explosion models. Its determination is indirect, in general, involving models of energy conversion from radioactivity (gamma-rays and positrons) to optical light (Hoeflich 2006; Röpke et al. 2006). Gamma-ray lines from ^{56}Co and ^{57}Co decays have been detected from supernova SN1987A with the Gamma-Ray Spectrometer on the Solar Maximum Mission (Matz et al. 1988) and the Oriented Scintillation Spectrometer Experiment on the Compton Gamma Ray Observatory (Kurfess et al. 1992), respectively. These were the first and only direct confirmations that Ni decay and its products power supernova light curves. However, the accuracy of absolute flux determination was insufficient for direct calibration of the corresponding yields due to instrumental background and the embedding of those radioactivities in a massive and semi-opaque supernova envelope: SN1987A was the core-collapse termination of a massive star’s

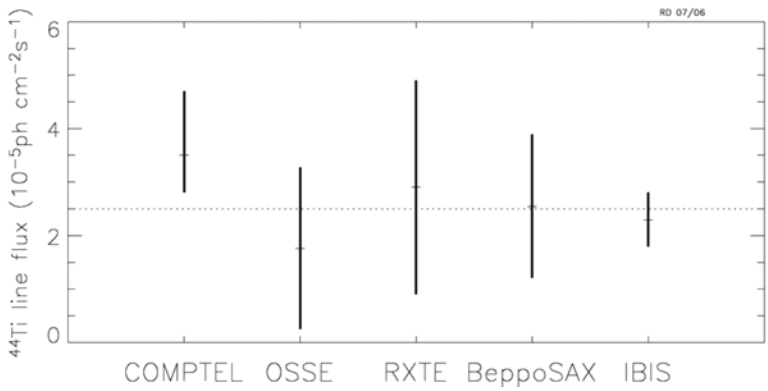

Fig. 3. Gamma-ray flux from Cas A from radioactive decay of ^{44}Ti has been measured by several X/gamma-ray instruments. In spite of instrumental uncertainties, results consistently suggest ~10^{-4} $M_\odot$ of ^{44}Ti production and make this supernova a unique study object for core-collapse models (see text).

evolution, and its explosion produced ~0.075 $M_\odot$ of ^{56}Ni and 0.003 $M_\odot$ of ^{57}Co under ~16 $M_\odot$ of ejecta. These amounts of radioactive material have been determined from the measurement of the fading supernova light assuming full deposit and conversion of the radioactive energy, and are consistent when compared with precision gamma ray flux results (Woosley et al. 1989).

A calibration of ^{56}Ni masses is particularly important for supernovae of type Ia because of their cosmological "standard candle" applications (Leibundgut 2000). These events are attributed to thermonuclear explosions of white dwarfs in binary systems (Hoeflich 2006), they produce about 0.5 $M_\odot$ of ^{56}Ni and have small overlying envelopes. Their remarkably homogeneous light curves ask for a thorough physical understanding of that kind of explosions so that the spectacular cosmological implications on the long-term expansion behavior of the universe derived from SNIa are put on more than empirical grounds (Röpke et al. 2006; Leibundgut 2000). Unfortunately, such events are rare in the nearby universe accessible to current-day gamma-ray telescopes. INTEGRAL can, in principle, detect SNIa up to 5 Mpc and, after four years of operation, is still waiting for such an opportunity (Isem et al. 2004). The results from the Compton observatory for two relatively nearby events were controversial: SN1991T at a distance of 13 Mpc was an exceptionally bright SNIa, but in order to explain COMPTEL's marginal gamma-ray line signal (Morris et al. 1997; Morris et al. 2002) 1.65 $M_\odot$ of ^{56}Ni is required; this is on the high side of indirect determinations and too uncertain for far-reaching interpretations. SN1998bu, at a distance of 11.6 Mpc, was somewhat closer; however, no gamma-ray lines were observed from the estimated 0.7–0.8 $M_\odot$ of ^{56}Ni, which put tight constraints on some models of SNIa (Georgii et al. 2002).

It is clear that gamma-ray telescopes will fulfill their promise of solving one of the key issues in astrophysical models of supernova explosions, namely their synthesis of ^{56}Ni, only with substantially more sensitive experiments that are able to reach SNIa from beyond the Virgo cluster and hence measure a substantial statistical sample of such events. Two experiments are being studied for this purpose: the European Gamma-Ray Imager (Knödlseder 2006) and the U.S. Advanced Compton Telescope (Boggs et al. 2006); they await announcements of mission opportunities by space agencies.

^{44}Ti from Cassiopeia A: Probing Asymmetries of Core Collapses?

The Cas A supernova remnant has an estimate age of 340 years and provides us with an excellent opportunity to study the recent explosion of a relatively nearby massive star. Ejecta kinematics has been studied in detail through recombination lines, and the emission morphology of the remnant imaged in X-rays through optical to infrared emission suggests substantial 3D effects and deviations from spherical symmetry (Hughes et al. 2000). A pioneering discovery of ^{44}Ti radioactivity gamma rays at 1.156 MeV was made with the Imaging Compton Telescope on NASA's Compton observatory (Iyudin et al. 1994). Several other instruments have confirmed ^{44}Ti decay in this young remnant (Fig. 3): from Beppo-Sax measurements, the 68 and 78 keV lines from ^{44}Sc deexcitation were found (Vink et al. 2001), and INTEGRAL/IBIS recently detected the same ^{44}Sc hard X-ray lines with improved significance (Renaud et al. 2006). The combined gamma-ray measurements indicate a flux of ~2.5 (±0.5) 10^{-5} ph cm^{-2} s^{-1} (Nittler et al. 1996). With the distance (~3.4 kpc [Reed et al. 1995]), a radioactive lifetime of ^{44}Ti (85.2 years [Ahmad et al. 2004]), and the ionization state for ^{44}Ti (Motizuki et al. 1999), the γ-ray flux translates into a ^{44}Ti yield of 0.8–2.5 10^{-4} $M_\odot$ of ^{44}Ti produced in this supernova. This places Cas A's ^{44}Ti yield somewhat on the high side when compared to the predictions of spherically symmetric models (Prantzos 2004a; Diehl et al. 2006a; Fig. 5).

Increased ^{44}Ti production in Cas A due to deviations from spherical symmetry in the explosion has been suggested

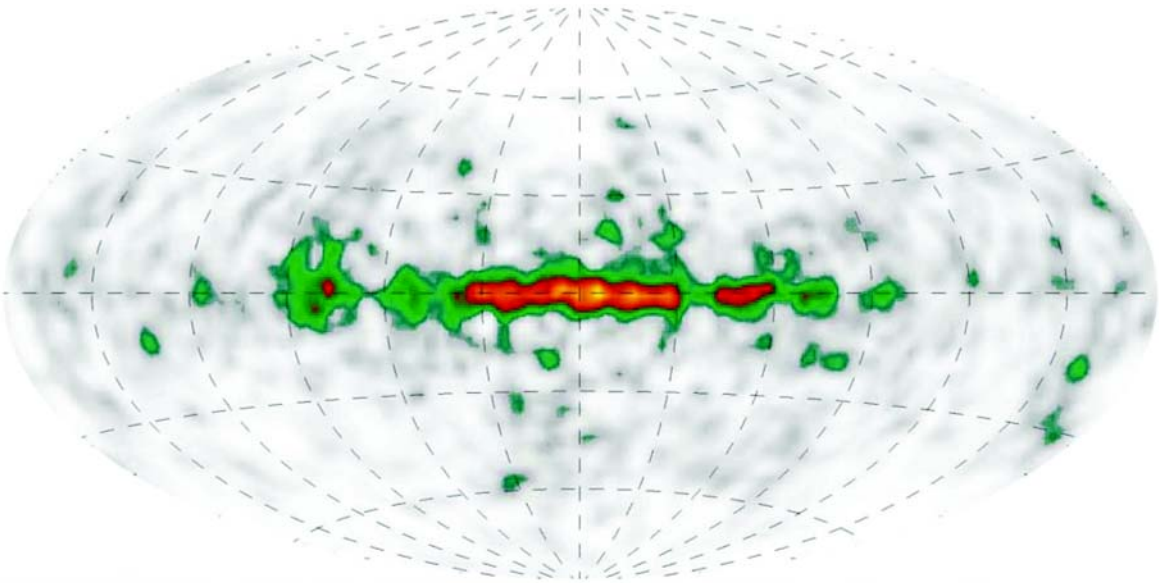

Fig. 4. The image obtained by the COMPTEL telescope through the 9-year Compton observatory mission in the 1808.65 keV line from ^{26}Al shows the nucleosynthesis traces from massive stars in the galaxy over the last several million years (^{26}Al decays with a radioactive lifetime of 1.04 Myr).

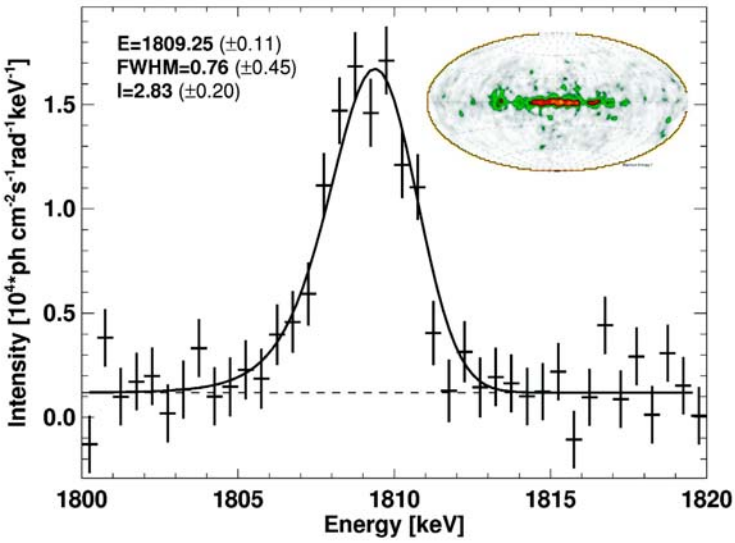

Fig. 5. The SPI measurement of the ^{26}Al line from the inner galaxy finds the line broadening from astrophysical effects (galactic rotation, ISM turbulence) to be rather small (Diehl et al. 2006b).

(e.g., Prantzos 2004a), combining the evidence from observations of Cas A jet (see e.g., Laming et al. 2006) and fast-moving knots (see e.g. Fesen et al. 2006) with supernova explosion models where polar regions show higher entropy caused by presupernova stellar rotation (Maeda and Nomoto 2003). This is reinforced by comparisons of ^{56}Ni and ^{44}Ti yields for SN1987A and by interpreting the solar abundances of ^{56}Fe and ^{44}Ca in terms of their radioactive parents of ^{56}Ni and ^{44}Ti, respectively (The et al. 2006; Prantzos 2004a). In all cases, the ^{44}Ti yields of 1D models for supernova production relative to ^{56}Ni appear lower than indicated by these measurements by a factor up to three. Note, however, that a recent re-determination of the rate of the key production reaction ^{40}Ca(α,γ)^{44}Ti (Nassar et al. 2006) suggests a factor of about 2 increase in model yields, which may weaken such reasoning.

No ^{44}Ti radioactivity has been seen clearly from any other core-collapse supernova, either in the Compton observatory survey or in INTEGRAL's mission up to now (The et al. 2006; Renaud et al. 2006). This is remarkable, as it implies that ^{44}Ti ejection is not common among core-collapse supernovae and that Cas A was an exceptional supernova

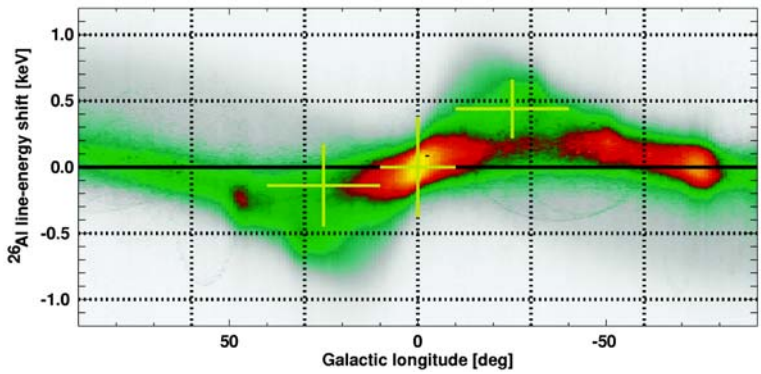

Fig. 6. New precision spectroscopy with the imaging spectrometer SPI on INTEGRAL allows to trace line characteristics over different regions along the plane of the galaxy. The first results on the centroid of the line (data points) are consistent with the expectations from Doppler shifts due to ^{26}Al rotating with the bulk gas throughout the inner galaxy (simulations shown in color/contours, e.g., Diehl et al. 2006c).

explosion rather than a typical one. It adds to the mounting evidence from hypernova and gamma-ray burst research, which suggests that variety of explosion types and 3D effects are typical for core-collapse events, and we may have sampled only a small part of the parameter range spanned by such terminations of the lives of massive stars (Woosley and Bloom 2006). Presolar grains, which are attributed to a core-collapse supernova origin, have been observed to show traces of ^{44}Ti inclusions, sometimes in identified subgrains (Nittler et al. 1996, Zinner 1998). This is yet another indication that supernovae from massive stars do eject ^{44}Ti, at least for some events.

Also the non-detection of the 1157 keV gamma-ray line with the SPI instrument on INTEGRAL fits into this picture: if ^{44}Ti ejection occurs mostly from the rapid (rather than slow-moving) inner part of ejecta, velocities could be as high as the 7000–8000 km s^{-1}, producing lines too broad to be detectable by SPI (Vink 2005).

^{26}Al IN THE GALAXY: DIAGNOSTICS OF RECENT GALACTIC NUCLEOSYNTHESIS

Diffuse gamma-ray emission at 1.8 MeV from the decay of ^{26}Al in the galaxy (Prantzos and Diehl 1996) has been mapped by COMPTEL from 9 years of observations with NASA's Compton observatory (1991–2000) (Plüschke et al. 2001) (Fig. 4). A disk-like distribution of the gamma-ray emission with irregularities and prominent intensity in the Cygnus region argues for predominant production of galactic ^{26}Al by massive stars (Prantzos 1993). In comparison, the contributions from AGB stars or novae (which are plausible sources of ^{26}Al found in presolar grains), should be small in the galaxy. The large numbers of such long-lived objects (each one with small contributions to the total) would result in a smooth glow along the plane of the galaxy, washing out, for example, the spiral-arm tangential viewing directions which can be seen in the ^{26}Al image (Prantzos and Diehl 1996).

^{26}Al gamma-rays reflect the integrated nucleosynthesis production from many individual sources in the galaxy. Due to the long decay time, most of the gamma rays are generated while ^{26}Al travels through interstellar space along with other nucleosynthesis ejecta while mixing with ambient interstellar gas. Around clusters of massive stars, we expect a hot and tenuous phase of interstellar gas, which is otherwise hard to observe; radioactivity and ^{26}Al gamma rays are able to convey information about the kinematics of this phase. A balloon-borne experiment reported the ^{26}Al gamma-ray line to be as broad as 6.4 keV, which would correspond to interstellar velocities above 500 km s^{-1} and would imply the existence of large interstellar cavities for such velocities to be maintained over the ^{26}Al decay time (Prantzos and Diehl 1996). Years of data from INTEGRAL/SPI have now resulted in a high-quality line shape measurement of the ^{26}Al line with a similar high-resolution Ge detector (Zinner et al. 1991) (Fig. 5). From this measurement, any astrophysical broadening is found to be on the order of ~1 keV, with a firm upper limit (2σ) of 2.8 keV (Diehl et al. 2006). Therefore, line broadening as expected from large-scale galactic rotation and from interstellar turbulence in massive-star regions is fully compatible with these recent measurements.

With fine spectroscopy and deep exposure of the inner regions of the galaxy, systematic centroid shifts of the ^{26}Al gamma-ray line were seen, consistent with what is in principle expected from the differential rotation of the galactic disk (Zinner et al. 1991) (Fig. 6). Line centroid offsets are a few tenths of keV only; hence they require the maintenance of fine energy resolution over these multi-year exposures through annealing and careful accounting of the time-variable spectral resolution due to cosmic ray damage. From this signature of galactic rotation, one may conclude that the observed source regions indeed are located in the inner regions of the galaxy, and that ^{26}Al production is a large-scale, galaxy-wide phenomenon that is not significantly distorted by localized sources. Therefore, the observed ^{26}Al gamma-ray flux represents ^{26}Al emission from all sources integrated over the entire galaxy, and geometrical source distribution models can be used to assign distances. With a model for the massive star population size distribution in the

galaxy, the observed ^{26}Al line flux then translates into a total galactic amount of 2.8 ± 0.9 $M_\odot$, where the uncertainty mainly arises from different spatial distribution models for the ^{26}Al sources (Diehl et al. 2006c). Because the ^{26}Al origin is predominantly attributed to massive stars, this ^{26}Al amount can be converted into a core-collapse supernova rate, assuming a steady-state situation and using the ^{26}Al production per stellar mass from nucleosynthesis models with the standard mass distribution function for massive stars (for details see Zinner et al. 1991). Therefore, a new and systematically different measurement of the rate of stellar births and deaths in our galaxy can be obtained from penetrating gamma rays from the otherwise occulted massive star population in the inner regions of our galaxy. This method relies on the stellar mass distribution for massive stars (which is rather well established in Kroupa 2002) and nucleosynthetic yields of ^{26}Al (which may be uncertain according to Zinner et al. 1991); unlike the other methods, no corrections for unobserved distant sources nor galaxy morphology arguments are important in this case, thus providing a useful independent view on the galactic SN rate. The INTEGRAL/SPI-derived value is 1.9 (±1.1) supernovae (100 yr)$^{-1}$, corresponding to a conversion of ~4 $M_\odot$ of interstellar gas into stars per year on average in our galaxy.

Another interesting quantity may be derived from this measuement: the ^{26}Al/^{27}Al isotopic ratio of the average interstellar medium, which is 8.4×10^{-6} (Zinner et al. 1991); here we assume an interstellar gas mass of 4.95×10^9 $M_\odot$ and an abundance by number of log N(^{27}Al) = 6.4 on the astronomical abundance scale with log N(H) = 12. Note that this ^{26}Al/^{27}Al ratio is about one order of magnitude lower than the solar nebula value of ~4.5×10^{-5} (Lee et al. 1998; Young et al. 2005). This seems plausible from continued production of Al since the birth of the solar system 4.6 Gyr ago and from several other hints for special enrichment of the solar nebula at birth from a nearby nucleosynthesis source (Wasserburg 1998; Clayton and Jin 1995; Goswami et al. 2001; Meyer and Clayton 2000), or from locally produced ^{26}Al enrichments made possible by jet outflows in the early stage of solar nebula accretion onto the central Sun (Gounelle et al. 2006).

^{60}Fe PRODUCTION BY SUPERNOVAE: ANOTHER LONG-LIVED TRACER

Stellar nucleosynthesis models have always predicted that the convective envelopes of massive stars are plausible production sites of long-lived ^{60}Fe isotopes (τ ~2.2 Myr), which would be ejected in the terminal core-collapse supernova explosion (Prantzos 1989; Limongi and Chieffi 2005; Woosley and Heger 2007; Limongi and Chieffi 2006). Because of the dominant origin of ^{26}Al in massive stars, the gamma-ray brightness ratio $R_{Fe\text{-}Al} = I_\gamma(^{60}Fe) / I_\gamma(^{26}Al)$ from the emission of diffuse radioactivities in steady state over the last several million years is a suitable test of the models. ^{60}Fe has been found to be part of meteorites formed in the early solar system (Shukolyukov and Lugmair 1993). The inferred ^{60}Fe/^{56}Fe ratio for these meteorites exceeded the interstellar medium estimates from nucleosynthesis models, which led to the suggestion of late supernova injection before formation of the solar system (Tachibana and Huss 2003). As another proof for cosmic ^{60}Fe production, accelerator mass spectroscopy of seafloor crust material from the southern Pacific Ocean revealed an ^{60}Fe excess in a crust depth corresponding to an age of 2–3 Myr (Knie et al. 2004). From this measurement, it was concluded that a supernova must have occurred very nearby at this time, depositing some of its debris directly in the Earth's atmosphere. Both of these measurements demonstrate that ^{60}Fe nucleosynthesis does occur; it is now interesting to search for current ^{60}Fe production in the galaxy through radioactive-decay gamma rays.

A hint for ^{60}Fe gamma-rays was recognized for the first time in 2003 with RHESSI (Smith 2003). The weak signal was found to correspond to 16 (±5)% of the ^{26}Al brightness (Smith 2005). This seemed to confirm earlier predictions of ~15% (Timmes et al. 1995) very well, but it was in disagreement with later studies of nucleosynthesis in massive stars which predicted much larger ratios (see discussion of studies since 1995 by Prantzos 2004b). In fact, substantial uncertainties both from stellar structure (establishment of suitable convective-burning regions, mass loss) and from nuclear cross sections (neutron capture on unstable ^{59}Fe is difficult to measure and its β decay lifetime is uncertain) still persist.

Confirmation of the RHESSI ^{60}Fe signal was reported from the INTEGRAL/SPI data collected during the first year of the mission (Harris et al. 2005), while a recent analysis with more data finds a significant ^{60}Fe signal (Wang et al. 2007) (at 5σ, Fig. 7). The SPI team finds the ^{60}Fe/^{26}Al gamma-ray brightness ratio $R_{Fe\text{-}Al}$ of 14%, with an uncertainty of a few percent (Knie et al. 2004). At first glance, this seems to be a nice confirmation of the original theoretical estimates. However, in view of the substantial revisions to nucleosynthesis models for massive stars and of nuclear reaction rates, this result should be carefully scrutinized. Massive-star nucleosynthesis models are the integrated (and evolving) result of what we know from all observations of massive stars' evolution and their nucleosynthesis in the presupernova stage, and from explosive nucleosynthesis reactions (e.g., Prantzos 1989; Gounelle et al. 2006).

ANNIHILATION OF POSITRONS AND OTHER TRACES OF RADIOACTIVITY

Nuclear processes in stars, supernovae, and novae are expected to release positrons from radioactive decays of isotopes on the proton-rich side of the valley of stability. Positrons do annihilate in our galaxy, as revealed through their characteristic annihilation gamma rays at 511 keV: this

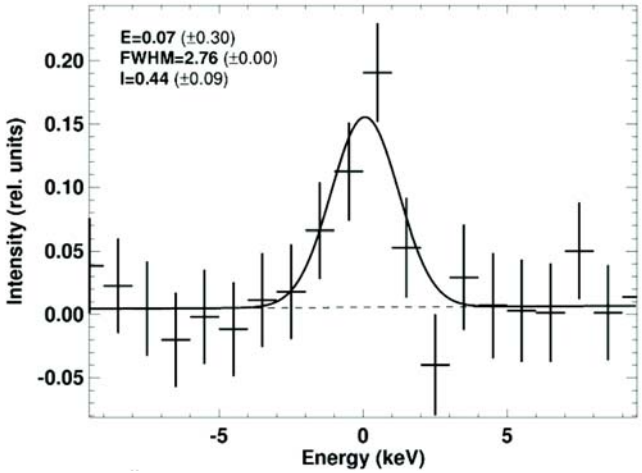

Fig. 7. INTEGRAL/SPI ^{60}Fe signal from the inner galaxy (Knie et al. 2004). Data from both lines have been superimposed, referencing to the laboratory line energies of 1173.23 keV and 1332.49 keV, respectively. The solid line represents a Gaussian fit with its width fixed from nearby instrumental background lines.

was the first gamma-ray line detected from cosmic sources in the galaxy (for a recent review, see Diehl et al. 2006a). In recent years, INTEGRAL/SPI made it possible to map this gamma-ray emission over large regions of the sky (Knödlseder et al. 2003, Knödlseder et al. 2005). But the map of annihilation emission resulted in a surprise that puzzles a broad community of astrophysicists (see detailed discussion and references in Smith 2005): rather than following the plausible spatial distribution of nucleosynthesis along the disk of the galaxy, annihilation emission is bright in an extended yet surprisingly spherically symmetric region, broadly coinciding with the galactic bulge. Although electron-positron pair production is expected from compact stars (strong magnetic fields of rapidly rotating neutron stars result in particle-accelerating electric potential gaps; accretion flow onto a compact star in a binary system results in plasma jets such as observed in microquasars), it was expected that nucleosynthesis sources would dominate. Annihilation emission appears to arise from the bulge region predominantly, outshining the weak galactic disk. The observed annihilation map (Smith 2003; Smith 2005) prompted several interesting ideas on cosmic-ray production and propagation (Prantzos 2006), other positron source types (Guessoum et al. 2006), and even dark matter physics (Hooper and Silk 2005; Ascascibar et al. 2006). At present, it is not clear whether nucleosynthesis is the major source of galactic positrons. It should be noted, however, that nucleosynthesis positrons are released at low energies (MeV) and do not produce high-energy gamma rays, contrary to positrons released in most of other (non-thermal) processes; nucleosynthesis then naturally satisfies constraints imposed from the observed galactic emissivity at a few tens of MeV (Beacom and Yüksel 2006).

Novae are the most common variety of explosive events in the galaxy. They are powered by nuclear reactions under runaway conditions on the surfaces of white dwarfs in binary systems (Gehrtz et al. 1998). Nuclear energy generation allows the overlying envelope to expand, extinguishing and partially uncovering the nuclear burning region. In these events, production of proton-rich isotopes is expected under the conditions of explosive hydrogen burning, and thus transient positron annihilation gamma-ray emission should be bright (Jose and Hernanz 1998). The key isotopes are too short-lived, however, and the gamma-ray flash occurs before the nova brightens enough in optical light to be discovered; sky surveys with large field-of-view gamma-ray telescopes are required. So far, none of these flashes has been discovered (Harris et al. 2000). Other longer-lived radioactive istopes could lead to observable gamma-ray line emission: ^{7}Be with a line at 478 keV and a decay lifetime of 78 days may still be substantially occulted, burried under the expanding envelope. But ^{22}Na should be sufficiently long-lived (lifetime 3.8 years), such that it would decay in the diluted nova wind and be observable from novae occuring out to distances of approximately one kiloparsec (Prantzos 2006). None of these have been clearly observed, but there are a few tantalizing reports (Iyudin et al. 1999); upper limits are consistent with expectations from current nova nucleosynthesis models (Iyudin et al. 1995; Jose et al. 2006).

SUMMARY AND PROSPECTS

The Compton Gamma-Ray Observatory mission opened the era of cosmic gamma-ray line astronomy in the 1990s, after experimental efforts through a variety of balloon and rocket campaigns had shown the promise of this field. The new high-resolution spectroscopy of cosmic gamma-rays with spaceborne Ge detectors has demonstrated new aspects of gamma-ray lines from nuclear and high-energy non-thermal processes: ^{44}Ti, ^{26}Al and ^{60}Fe radioactive decays have been measured from cosmic sources providing information on nuclear reactions inside massive stars. The width and centroid of ^{44}Ti lines constrain the kinematics of inner ejecta from core-collapse supernovae. Similarly, the line shape and centroid of the ^{26}Al line reflects nucleosynthesis yields and their dynamics in otherwise hardly accessible hot and tenuous gas regions near nucleosynthesis sources. With ^{60}Fe gamma-rays and their intensity ratio to those of ^{26}Al, the models for massive-star nucleosynthesis can be tested in a global sense. Although it is difficult to combine imaging and spectroscopy in an astronomical instrument for gamma-rays, the results from recent years demonstrate that such combination may open new frontiers, as in the case of the positron annihilation gamma-ray line with its puzzling morphology, dominated by an extended inner-galaxy source.

INTEGRAL will continue to operate well into the next decade and is expected to provide a gamma-ray line survey

of the galaxy down to the level of 10^{-5} ph cm^{-2} s^{-1}. This will reveal only the brightest sources of nuclear gamma-ray lines, but it will prepare the ground for deeper exploration of cosmic sources. We hope that it will be succeeded by future experiments with higher sensitivity, which are presently planned by the international space science community. We are confident that a deeper exploration of the nuclear universe will greatly improve our understanding of cosmic element production.

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