Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Gamma-ray observations and massive stars

Roland Diehl
Max Planck Institut für extraterrestrische Physik
D-85740 Garching, Germany

Abstract. Gamma-rays from astrophysical sources testify energetic processes such as nucleosynthesis and cosmic ray collisions. Gamma-rays are observable from throughout the Galaxy, unattenuated by interstellar matter, provided their intensity exceeds the current instrumental sensitivity level ($\sim 10^{-5}$ph cm^{-2}s^{-1} at 1 MeV). Massive stars are at the origin of relevant sources: The all-sky image in the 1.809 MeV γ-ray line from radioactive ^{26}Al traces nucleosynthesis throughout the Galaxy. The structure of this emission along the plane of the Galaxy suggests massive stars as dominating sources of this radioactivity. Discrimination of the contribution from core collapse supernova against that from WR-wind ejected hydrostatic nucleosynthesis products may be obtained from ^{60}Fe γ-ray line observations, or from spatial-profile consequences of the metallicity dependence of ^{26}Al production in theories for both source sites. As a single source, the nearest WR star in the γ^2 Vel system is found to eject less ^{26}Al into interstellar space than current theories predict. However, a more adequate comparison must be based on a time-dependent ^{26}Al light-curve of the system. Furthermore, continuum γ-ray production in WR binaries through wind-wind interaction, and constraints on the low-energy cosmic ray origin in WR winds through characteristic nuclear deexcitation line studies are targets of research. Studies stimulated by COMPTEL's 3–7 MeV excess report from the Orion region indicate that the γ-ray line measurements could separate the origins from supernova ejecta and wind material. The COMPTEL Orion result is now attributed chiefly to an instrumental artifact, and has been withdrawn. Nevertheless, the search for MeV emission from massive star clusters, as well as from interacting binaries such as WR 140, promises a unique test of particle acceleration scenarios related to the source mechanism for cosmic ray production.

1. Introduction

The connection of γ-ray astronomy and astrophysics in massive stars is provided through physical processes within the massive star itself, and even more so through interactions of the winds from massive stars with their surroundings. The strong stellar winds which characterize massive stars are linked to fundamentals of all these processes.

The wind interaction with a binary companion can be sufficiently energetic to produce a γ-ray source, when the companion comes close enough around orbital perigee. More globally, colliding winds from groups of massive stars provide an acceleration setup for charged ions and electrons, probably producing what we know as cosmic rays (at least on the low-energy end in the regime up to tens of MeV/nucleon). Moreover, the strong stellar winds undergone by massive stars remove the outer layers and uncover the stellar core which contains the

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products of nuclear burning. From this stage on stellar winds are enriched in new synthesized elements; among those, radioactive trace isotopes such as ^{26}Al then decay in the interstellar medium, producing a γ-ray line at 1.809 MeV energy.

Massive stars thus give rise to a variety of observable γ-ray signatures, through their interior nucleosynthesis reactions, through their stellar winds, and through their shaping of the interstellar medium around groups of massive stars. Several astrophysical issues are addressed in the γ-ray study of massive stars:

- Stellar structure parameters such as mixing, rotation, the influence of a close companion, and initial metallicity translate into the intensity and composition of the wind; both the extraction efficiency of trace radioactivities from the core, and the composition of cosmic rays, will be sensitive to this, with correspondingly characteristic γ-ray signatures.
- Wind properties such as momentum, duration of wind phases, and spherical asymmetries will directly set the conditions for acceleration of particles to MeV energies in wind structures as modified by an approaching massive companion and its stellar wind. As an average over clusters of massive stars, those wind properties will leave a characteristic imprint on the circumstellar gas morphology and dynamics, thus defining the sites for the Fermi acceleration process of cosmic rays to high energies.
- The large-scale spatial distribution of massive stars with properties which make them γ-ray sources is expected to provide us with insights on metallicity effects and on star formation efficiencies, through galactocentric gradient correlations with the spatial distribution of diffuse γ-ray emission.

In this review, we first present the observational capabilities of γ-ray astronomy, then we discuss the continuum emission expected from WR wind interactions in binary systems, the nuclear excitation lines expected from low-energy cosmic ray interactions with the interstellar medium in massive-star cluster regions, and finally the γ-rays from radioactive decays of nucleosynthesis products from the stellar interior.

2. Gamma-ray observations

Gamma-rays are observable from sources throughout the Galaxy, unattenuated by interstellar matter; no corrections are required from reddening or incompletion, the sources are optically thin. Gamma-ray observations are technically challenging, however: The telescopes have to be operated above the Earth atmosphere, thus are exposed to cosmic radiation, which incurs activation of the telescope material itself; this turns the measurement apparatus into an intrinsic and overwhelming source of background. Sophisticated background recognition and suppression techniques are employed, still leaving signal-to-background ratios below the one-percent level. The intensity of celestial sources is required to exceed the relatively high current instrumental sensitivity level, typically $\sim 10^{-5}$ph cm^{-2}s^{-1} at MeV energies. Additionally, the penetrating nature of γ-rays requires detection techniques which cannot rely on focussing optics. The

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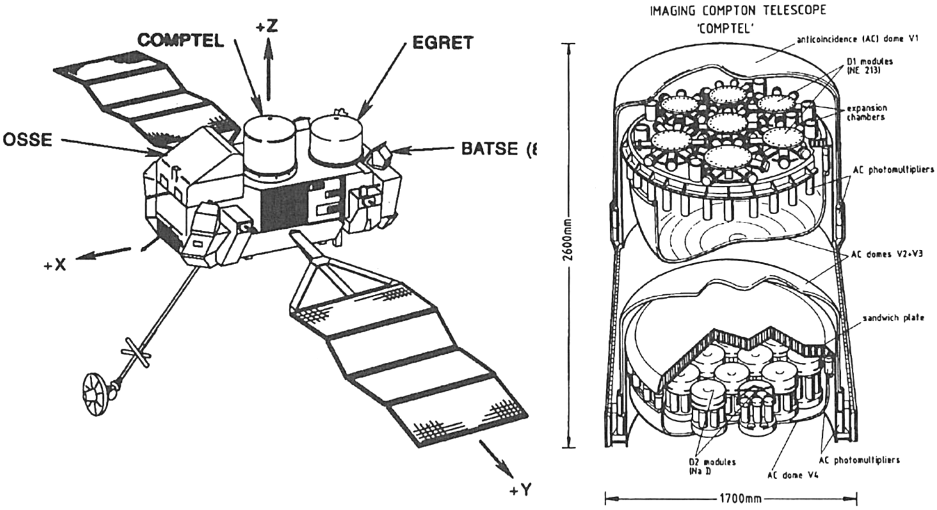

Figure 1. The NASA *Compton Gamma-Ray Observatory* (*left*) carries four γ-ray telescopes. Since its launch in 1991, it explores the full γ-ray sky for the first time, and is expected to continue for ~ 2 more years. The COMPTEL telescope (*right*) consists of two layers of scintillation detector modules. Imaging is achieved through ground processing of the event messages recorded per photon trigger.

required nuclear-physics type of detectors (Fig. 1, right) therefore can provide only angular resolutions on the order of a degree. Identification of specific γ-ray sources is therefore mostly based on unique timing or spectral signatures (pulsars, transients with phase correlation to other wavelength regimes).

In spite of these limitations, the straightforward connection of γ-ray measurements to their source processes stimulated experimental efforts ever since the pioneering measurements of the early 70ies (Kraushaar *et al.* 1972), especially since the *SAS-II* telescope's first view of the continuum γ-ray sky (Fichtel *et al.* 1975), and a balloon-telescope based report of line γ-rays from cosmic sources (Haymes *et al.* 1975).

The observational data-base for γ-rays has been greatly enriched from the NASA *Compton Gamma Ray Observatory* mission, launched in 1991 as a satellite platform with four γ-ray telescopes (Gehrels *et al.* 1993; Figure 1). All-sky surveys have been performed in several γ-ray energy bands, from the hard X-ray regime dominated by OSSE (Johnson *et al.* 1992) and BATSE (Fishman *et al.* 1992) instrument measurements, across the 1–30 MeV band of the imaging COMPTEL telescope (Schönfelder *et al.* 1993), to the high-energy γ-ray domain above 50 MeV up to 30 GeV as covered by the EGRET spark chamber telescope (Thompson *et al.* 1992). The high-energy telescopes COMPTEL and EGRET both have fields of view of about 1 sr, allowing simultaneous measurement of many γ-ray sources with typically few counts/sec to few counts/day each, so that full sky surveys in γ-rays have been possible.

The skymap of continuum γ-ray emission as measured by EGRET for energies above 100 MeV (Figure 2) reveals the entire plane of the Galaxy as a prominent

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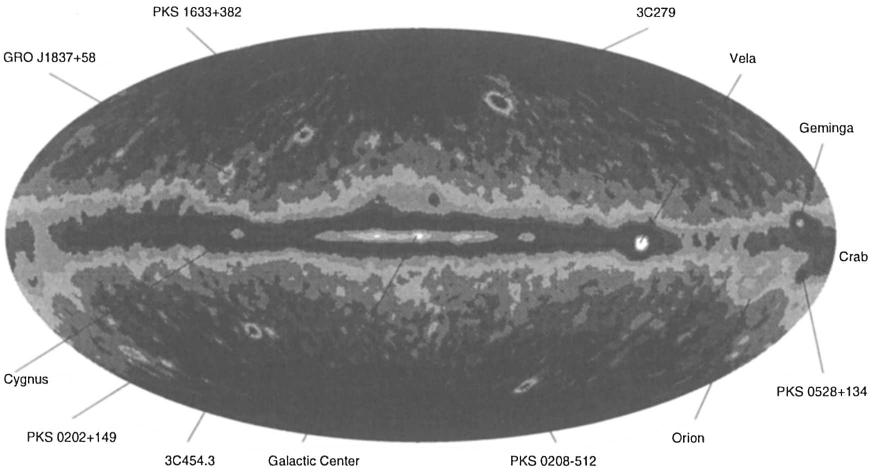

Figure 2. The γ-ray sky as seen at high-energy γ-rays. Here the cosmic-ray interaction with interstellar gas dominate the emission. Gamma-ray blazars are prominent sources outside the plane of the Galaxy.

source, additionally a group of tens of extragalactic sources have been detected, the γ-ray blazars (Hartman *et al.* 1997).

The emission along the plane of the Galaxy is understood as being dominated by processes of cosmic-rays interacting with the interstellar gas. In general, continuum γ-rays are produced in collisions of energetic charged particles (ions, electrons) through bremsstrahlung; the annihilation line radiation from pions produced in energetic collisions is smeared out through Doppler broadening of the past pions to add a broad bump centered at 70 MeV. The energetic cosmic radiation (which can directly be measured at Earth at energies above ~GeV) is the plausible source of particles. Assuming that cosmic rays fill the interstellar space throughout the Galaxy more or less homogeneously (although with some outward decrease of flux, see Strong & Mattox 1996), their collisions with interstellar gas serve as a useful first-order description of the Galactic continuum γ-ray emission (Bloemen *et al.* 1989; Hunter *et al.* 1997). In a more detailed look, there remains a significant population of γ-ray sources not explained by this process. For these "unidentified" EGRET sources (Mukherjee *et al.* 1997) massive stars are promising candidate counterparts. Models of massive-star wind interaction sources as well as stellar-wind and young supernova bubbles accelerating particles to γ-ray energies have been discussed. Alternative models relating those sources to the class of radio-quiet γ-ray pulsars remain a possibility.

In the MeV regime, the explanation of the measured emission in terms of Galactic continuum emission becomes more complicated due to the additional contribution from inverse-Compton collision of cosmic-ray electrons on galactic starlight, adding to the tail of the pion decay emission and the bremsstrahlung emission from cosmic-ray gas collisions. Additionally, the lower the energy of

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the primary particles, the more likely are spatial gradients and inhomogeneities, adding to the uncertainty on gas morphology (note that the γ-ray emissivity is proportional to the product of cosmic-ray flux- and gas density, which both may vary locally). Therefore an analysis of the MeV regime sky survey for sources other than cosmic-ray related emission could not be carried through with sufficient sensitivity; indications are that individual sources or source regions play a rather more significant role than at high γ-ray energies (Strong *et al.* 1999).

From the *Compton Observatory* sky survey, a large database exists, which may be exploited to constrain γ-ray emission from individual objects. More important at this stage of research is a confirmation of the principal source mechanism that would generate γ-rays within the wind region of a massive star. Observations of individual massive stars in γ-rays have rarely been carried out, the interacting-wind binary system WR 140 being the most notable exeption (see below).

3. Massive-star wind interactions

A standard setting for γ-ray production is provided in massive binary systems which consist of a Wolf-Rayet star and a companion that will approach the primary to within its wind zone. In this environment energetic charged particles may be produced, resulting in γ-ray continuum emission. Particle acceleration in electrostatic potentials is unlikely in astrophysical environments, because plasma currents eliminate any potential gradients (with the possible exception in strong fields of rapidly rotating neutron stars, the pulsar magnetospheres). Therefore particle acceleration in astrophysical environments occurs through the Fermi process (*e.g.*, Longair 1994): electrons with velocities from the high-energy tail of the Maxwellian thermal distribution enter zones of magnetic turbulence such as typical for shocks in colliding winds, and will scatter off magnetic field irregularities. Behind such a shock caused by plasma flows with velocity differences exceeding the speed of sound, turbulent plasma flows naturally result in turbulent magnetic fields; upstream from the shock region, fast electrons escaping from the shock zone excite Alfven waves in the (partially) ionized upstream medium, as their bulk flow resonates with small field irregularities and amplifies these. In the system of the energetic particle, both the upstream and downstream scattering centers appear to approach each other, resulting in an energy gain in each such collision. The achievable maximum particle energy is limited by the particle's escape probability from the shock region. The interaction of a WR wind with an O star wind is expected to create contact discontinuities which are likely to develop such Fermi acceleration sites (see also Gayley & Owocki, these Proceedings; Koenigsberger, these Proceedings). Gamma-ray continuum emission may result from these relativistic electrons through two main processes: Fast electrons will interact with lower-temperature ions and produce bremstrahlung photons, or the stellar UV photons will be boosted into the hard X and γ-ray domain through inverse Compton scattering on fast electrons (Chen & White 1991; Pollock 1987). A direct measure of the existence of relativistic electrons in colliding-wind scenarios is the synchrotron radiation which has been measured in the radio regime (White 1985). Therefore these candidate binary sources of

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γ-rays may be selected based on observed non-thermal radio emission. The list of candidate sources of this type comprises more than 20 objects (Wessolowski, these Proceedings). The study of suitable binaries during perigee and the search for signs of a γ-ray brightening during that phase is an important test of such models. Data for WR 140, the prototype of such a binary system, have been taken with *ASCA* and the instruments on the *Compton Observatory*, awaiting detailed analysis (see also Wessolowski, and Pollock *et al.* these Proceedings).

4. Low-energy cosmic rays

The 1994 report of nuclear de-excitation γ-rays observed by COMPTEL from the Orion region of nearby massive star formation at 10^{-4}ph cm^{-2}s^{-1} had surprised the scientific community (Bloemen *et al.* 1994). Although it had been expected that cosmic-ray collisions with ambient gas would produce γ-ray line emission most prominently in the 4.4 and 6.1 MeV lines from excited C and O, respectively, the predicted intensities of those lines should be below instrumental sensitivities ($<10^{-6}$ph cm^{-2}s^{-1}) for standard cosmic-ray energy densities around 1 eV/cm^3 and gas densities $\sim$1/cm^3 (Ramaty *et al.* 1979; Higdon 1987). The reported COMPTEL spectra indicated that the γ-rays would originate from excited cosmic-ray nuclei, the large width of the lines was attributed to Doppler broadening. This COMPTEL report had stimulated many studies on acceleration of low-energy cosmic rays in regions of massive-star formation. Problems for the standard model were expected in an excessive ionization rate from such enhanced cosmic-ray flux, but also from the absence of other signatures of this, such as electron bremstrahlung emission in the X-ray regime, and an absence of any excess high-energy γ-ray emission from the Orion region. The latter argument had been used to require that the enhancement was confined to low-energy cosmic rays, and that their specific acceleration mechanism would start from specific particle seed abundances that were enriched in C and O. Supernovae and winds from massive stars would be capable to provide such specific enhancements, with wind material from a WC star being the most favourable case (Ramaty *et al.* 1996). It was still difficult to understand, though, why this process was first seen from the Orion region, and not from the integrated emission from the inner Galaxy, where one would expect superposition of the emission from many such massive-star forming complexes; a transient nature of the emission was found plausible and satisfies observational constraints, with a supernova's kinetic energy injection causing a $< 10^5$ yr bright phase (see review by Bloemen & Bykov 1997).

Detailed studies and consistency checks from many exposures of the Orion region, accumulated over more than six years, now have resulted in withdrawal of the initial COMPTEL Orion result (Bloemen *et al.* 1999): A conspiracy of instrument activation and exposure inhomogeneities, with in addition the strong Crab γ-ray source nearby are held responsible for producing an artifact signal in the Orion region, superimposed and amplifying any true emission. Within the aluminium structure of the telescope, ^{27}Al(p,α) produces shortlived ^{24}Na ($\tau = 15$ hr), which emits 1.37 and 2.75 MeV γ-rays upon decay. The simultaneous detection of these γ-rays can mimic a celestial photon with an energy around 4 MeV due to the coincidence detection principle of COMPTEL (for details see

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Schönfelder *et al.* 1993). Normally those background events are distributed smoothly in data space, thus being eliminated by the imaging process. Under the special circumstances of Orion exposures, this appears to not have been the case. Other COMPTEL results are not affected, as this contamination only impacts on the energy regime 2.5-4.5 MeV (in particular, the inner-Galaxy results have been checked for absence of a ^{24}Na artifact see Bloemen *et al.* 1997).

After improving background suppression techniques over the years, and accumulating all available data over the years, the "Orion signal" appears confined to the suspect energy bands affected by ^{24}Na. Excluding those, the signal clearly vanishes, and an upper limit of $3 \times 10^{-5}\,\mathrm{ph\,cm^{-2}s^{-1}}(2\sigma)$ remains for the 3–7 MeV flux from the Orion region from COMPTEL data, consistent with the OSSE flux estimate of $1.5(\pm 1.0) \times 10^{-4}\,\mathrm{ph\,cm^{-2}s^{-1}}$ (Harris *et al.* 1997).

5. Nucleosynthesis products

Gamma-ray lines for cosmic nucleosynthesis studies originate from either relatively shortlived isotopes generated by individual events (^{56}Ni, ^{44}Ti, ^{22}Na, ^{7}Be), or from the cumulative build-up of trace radioactivity with longer decay times throughout the Galaxy, from events with sufficiently high frequency during a radioactive decay period (^{26}Al, ^{60}Fe). Typical instrumental sensitivities are $\geq 10^{-5}\,\mathrm{photons\,cm^{-2}s^{-1}}$, which translates into ranges of about one kpc to tens of kpc for a nova and supernova origin, respectively (except for ^{56}Ni in thermonuclear supernovae with a 10 Mpc range). This is to be compared to ranges of other astronomical observations, which are often affected by attenuation or obscuration beyond a few 100 pc in the Galaxy, and hence rely more on corrections of observational bias. From the above radioactivity list, specifically ^{26}Al and ^{44}Ti are clearly related to massive-star nucleosynthesis (see also the review by Diehl & Timmes 1998).

5.1. The ^{26}Al sky

With its one-million year decay time, ^{26}Al accumulates in the interstellar medium from many source events. We may interpret ^{26}Al measurements as reflecting nucleosynthesis activity of the Galaxy's recent history (characteristic times are $\tau_{\mathrm{Al26}} \simeq 10^{6}$ yr, $\tau_{\mathrm{Galaxy}} \simeq 10^{8}$ yr) (see review of Prantzos & Diehl 1996). Images from COMPTEL measurements (Fig. 3; Diehl *et al.* 1995; Oberlack 1997; Knödlseder 1997) revealed the spatial structure of the emission for the first time: The ridge of the Galactic plane dominates, demonstrating that nucleosynthesis is a widespread current Galactic phenomenon traced by ^{26}Al. But the emission is neither smooth along the Galactic plane nor following previous expectations: the inner Galaxy is a rather flat ridge without a prominent central peak, and further out there are several additional prominent regions of emission. Simulations of expected images from plausible source distributions, and comparisons of different imaging techniques (such as multi-resolution methods and noise suppression methods) show considerable uncertainty for details of the map, yet all confirm those prominent characteristics of the 1.809 MeV sky (Oberlack 1997; Knödlseder 1997; Knödlseder *et al.* 1999b). Although the apparent irregularity in the Maximum-Entropy image (Fig. 3) may be over-emphasized by artifacts incurred by fluctuations of the dominating background, the prominent emission

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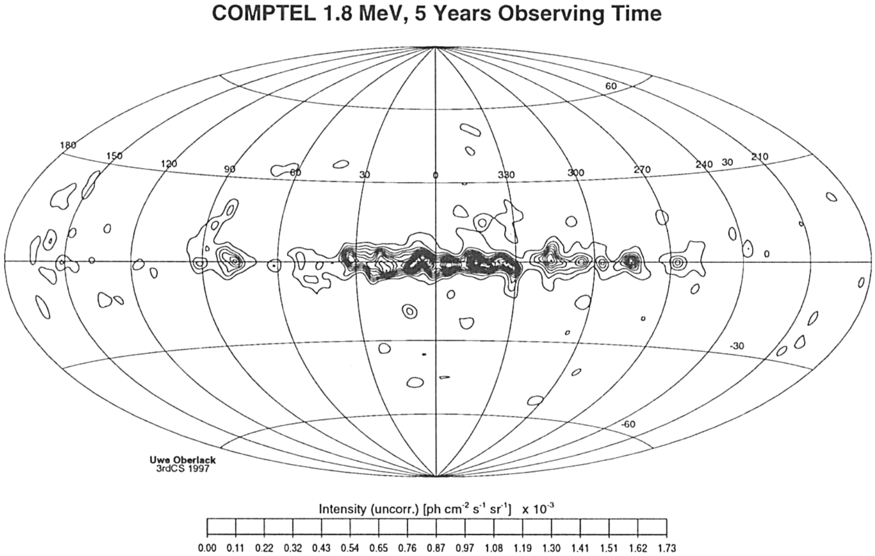
COMPTEL 1.8 MeV, 5 Years Observing Time

Figure 3. The COMPTEL 1.8 MeV image shows that Galactic-plane sources dominate the ^{26}Al production (Oberlack 1997).

features in the directions of Vela, Carina, Cygnus, and possibly the anticenter region hold key information on the ^{26}Al sources. Tracers of the candidate ^{26}Al sources (novae, WR stars, AGB stars, supernovae) have been compared to COMPTEL 1.8 MeV data in order to discriminate among them. Tracers resulting from the ionizing effects of massive stars, such as free-free emission, H_α emission, C II emission, but also warm dust emission at $\geq 100\,\mu$m do show a better correlation with COMPTEL 1.8 MeV data than tracers of total or molecular interstellar gas (H I, CO) (Knödlseder *et al.* 1999a). In particular, they explain those prominent emission features generally rather well (all tracers have imperfections and biases of some sort, localized discrepancies between 1.809 MeV emission and other source tracers are not surprising, see Diehl *et al.* 1996). For the Galactic free-free emission model derived from *COBE*-DMR 53 GHz data, consistency between the ionizing Lyman continuum luminosity and the ^{26}Al yields from massive stars can be demonstrated (Knödlseder 1999). A Lyc calibration for the entire Galaxy yields a Galactic amount of ^{26}Al of $\sim 2.4\,M_\odot$, quite consistent with the $\sim 2 \pm 0.5\,M_\odot$ determined from other analyses. In summary, it is generally agreed that massive stars most likely dominate ^{26}Al production in the Galaxy (from the alignment of prominent 1.8 MeV peaks with spiral arm tangents (Prantzos 1993; Chen *et al.* 1995), from the map irregularity along the plane, and most specifically from the above-described correlation with candidate tracers). Smooth models such as expected from classical novae or low-mass AGB stars appear rather inconsistent with the COMPTEL measurements, and thus their candidate sources do not play a dominant role for large-scale Galactic nucleosynthesis.

Beyond these imaging studies in its 1.809 MeV line, other observables may help discrimination between the ^{26}Al injection processes, WR winds versus core-

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collapse supernovae: correlation with other direct nucleosynthesis γ-rays, the detailed shape of the γ-ray line, and constraints from individual nearby sources.

^{60}Fe radioactivity may be a promising target for γ-ray line search: If core collapse supernovae are the dominant sources of ^{26}Al, then nucleosynthesis models for these objects predict substantial amounts of ^{60}Fe co-produced by the same objects, even within the same region inside the star: The supernova shock wave provides sufficient heating and compression for the necessary nuclear reactions only around the O-Ne shell of the pre-supernova star (Timmes *et al.* 1996). Normalizing on the ^{26}Al production, these ^{60}Fe sources would dominate ^{60}Fe production in the Galaxy, and a map of ^{60}Fe γ-rays should look like the 1.809 MeV map from ^{26}Al, exept being only 0.16 times as bright due to the decay time and yield differences. At present, γ-ray telescopes have not obtained sufficient sensitivity to clearly exclude this hypothesis, but upper limits (especially from the *GRIS* experiment (Naya *et al.* 1998)) are becoming a real constraint.

A line shape measurement of the interstellar ^{26}Al decay γ-ray line at 1.809 MeV by *GRIS* (Naya *et al.* 1996), a Germanium detector experiment, has reported clear evidence for broadening of the line, corresponding to Doppler-velocities up to $\sim 500\,\mathrm{km\,s^{-1}}$. This measurement appears difficult to understand, from plausibility checks for a physical mechanism (Chen *et al.* 1997). If ^{26}Al would be condensed on high-velocity dust within the sources, and sources could preferentially find diluted superbubbles in their vicinity, the line could appear somewhat broadened (Chen *et al.* 1997; Lingenfelter *et al.* 1998). A kinetic broadening of a few $100\,\mathrm{km\,s^{-1}}$ under such conditions would be consistent with COMPTEL's image, specifically its latitude profile width of $\sim 5°$. *INTEGRAL*'s 2-keV spectral resolution (Winkler *et al.* 1995) with simultaneous $\sim$3° imaging resolution can probably clarify whether line broadening is associated with such specific source environments.

The study of specific galactic regions which stand out in their nucleosynthesis activity as measured in ^{26}Al may test the massive-star origin for ^{26}Al more specifically. In the Cygnus region at $\sim$2 kpc distance, the census of massive stars should be rather complete, also observations of H I structure and X- and radio emission appears reliable and largely free from confusion with other regions. Therefore the consistency of a picture based on the evolution of coeval stellar associations may be checked in different observables (*e.g.*, Leitherer *et al.* 1999; Oberlack 1997; del Rio *et al.* 1996).

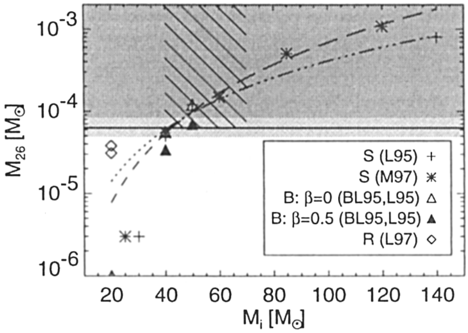

Figure 4. The updated WR model yields appear a factor of 2 or more higher than observations for the case of γ^2Vel (from Oberlack 1997).

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In the Vela region, two prominent candidate sources of ^{26}Al appear so close, that their individual detection may be possible. Contrary to early belief (Diehl *et al.* 1995b), the 11 000 year-old Vela supernova remnant is not responsible for the main ^{26}Al signal from this region (Diehl *et al.* 1999); this is however in agreement with the range of expectations from supernova nucleosynthesis. The other candidate source of ^{26}Al in this region is the γ^2 Vel binary system including WR 11. With its revised distance of now 260 pc (van der Hucht *et al.* 1997), current models for WR ^{26}Al yields (Meynet *et al.* 1997) would suggest a detectable signal (Fig. 4). Such models predict integrated yields, however, and a more adequate comparison must be based on a time-dependent ^{26}Al light curve of the system (Diehl & Meynet, in preparation). The expected yield depends critically on the initial mass of the WR star, which must be inferred from measurements of the binary mass function (see DeMarco & Schmutz, these Proceedings) through evolutionary models. Additional uncertainty arises from the unknown impact of the binary companion on the ejected ^{26}Al (Braun & Langer 1995). Yet, even if the study of γ^2 Vel should result in a minor ^{26}Al yield from this system, WR stars in general could be the dominating source of Galactic ^{26}Al (Knödlseder 1999), specifically if binaries including a WR star may boost ^{26}Al yields through mass transfer of metal rich seed material (Langer *et al.* 1998).

5.2. The ^{44}Ti sky

From the inner regions of supernovae, production of typically $\sim 3 \times 10^{-5}$ M$_\odot$ of ^{44}Ti is predicted for the Type II models, or twice that value for the Type Ib models (Woosley & Weaver 1995; Thielemann *et al.* 1996); Type Ia supernovae of the sub-Chandrasekhar model could also be important sources (Woosley & Timmes 1997). This opens-up the prospect of revealing historic supernovae through their γ-ray emission. The COMPTEL discovery of 1.157 MeV γ-rays from the $\sim$300 year-old Cas A supernova remnant (Iyudin *et al.* 1994) was the first confirmation of this hope. The Cas A ^{44}Ti detection appears consolidated (Iyudin *et al.* 1997), although the flux value remains uncertain, at $3\pm1 \times 10^{-5}$ ph cm^{-2}s^{-1}. For standard parameters (SN Cas A in 1680 at 3.4 kpc, and ^{44}Ti decay time recently settled at 89 years) this translates into $\sim 2 \times 10^{-4}$ M$_\odot$ of ^{44}Ti. Some additional uncertainty in ^{44}Ti mass estimates may add from inhibited β-decay of ^{44}Ti, if the nucleus remains fully ionized in the young SNR (Mochizuki *et al.* 1999). The apparent observational problem for Cas A of co-producing a large amount of ^{56}Ni with ^{44}Ti, hence expecting a bright optical supernova in AD1680, probably is resolved by dust occultation of Cas A, as indicated from its low X-ray scattering halo compared to the inferred extinction towards Cas A (see discussion by Hartmann *et al.* 1997).

About 10^{-4} M$_\odot$ of ^{44}Ti have been inferred from the late light curve of SN 1987A (Kozma & Fransson 1997). This seems surprisingly close to the value inferred from the Cas A γ-ray data. If this ^{44}Ti ejection should be typical, core collapse supernovae could be revealed even from embedded and hence occulted sites through their ^{44}Ti decay γ-ray lines. The COMPTEL search for additional ^{44}Ti sources in the Galaxy from 1991-today's data is still plagued with considerable uncertainty in estimating instrumental background. Still, one finds clearly less than the expected $\sim$4 events (from the Galactic supernova rate; see Dupraz

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et al. 1997). Yet, a second ^{44}Ti source in the Vela region may have been detected (Iyudin *et al.* 1999, 1998). A new X-ray supernova remnant discovered at similar position appears to be a plausible counterpart (Aschenbach 1999). From the inferred nearby and young supernova however no confirming signs from other astronomical observations have been found. Nevertheless, with only two sources of this type we may be constraining the Galactic supernova rate, if ^{44}Ti production at the Cas A level were typical for core collapse supernovae. More likely, the variation of ^{44}Ti yields is large due to subtle differences in the inner supernova morphology (Woosley & Timmes 1997; Diehl & Timmes 1998).

6. Summary

The study of massive-star astrophysics is closely linked with our understanding of the nature of a significant part of the observed γ-ray sources in our Galaxy. Particle acceleration scenarios which are plausibly associated with the source process for cosmic rays should produce continuum γ-rays in massive-star binaries with wind interactions, and also γ-ray line emission from nuclear de-excitations; both processes still await clear detections, most likely candidates being WR 140 and the Orion region, respectively. The NASA *Compton Gamma-Ray Observatory* has pioneered the exploration of the γ-ray sky during the past eight years. Nucleosynthesis trace radioactivities have been measured in ^{26}Al and ^{44}Ti. The ^{44}Ti results probe the inner core nucleosynthesis and dynamics of core collapse supernovae. ^{26}Al measurements as reflected by COMPTEL's all-sky image apparently reflect the nucleosynthesis output from massive stars throughout the Galaxy. The respective contributions from either WR phase winds or the final supernova event can possibly be disentangled through studies of spatial distributions of ^{26}Al and ^{60}Fe, but also through consistency studies using other knowledge about massive stars, such as their spatial distributions and stellar parameters affecting the ^{26}Al yield. The ESA *INTEGRAL* mission scheduled for launch in 2001 will present a quantum advance in observational capability, specifically through its large ($\geq$ one order of magnitude) sensitivity improvement in the hard-X/low γ-ray regime, and its superior spectral resolution ($\sim$keV) allowing the study of γ-ray line shapes.

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References

Bloemen, H., Wijnands, R., Bennett, K., Diehl, R. *et al.* 1994, A&A 281, L5

Bloemen, H., Bykov, A.M., Bozhokin, S.V. *et al.* 1994, ApJ 475, L25

Bloemen, H., Bykov, A. 1997, in: C.D. Dermer, M.S. Strickman & J.D. Kurfess (eds.), Proc. Fourth *Compton* Symp., AIP-CP 410, 249

https://doi.org/10.1017/S0074180900205317 Published online by Cambridge University Press

Bloemen, H., Bykov, A.M., Diehl, R., Hermsen, W. *et al.* 1997, in: C.D. Dermer, M.S. Strickman & J.D. Kurfess (eds.), Proc. Fourth *Compton* Symp., AIP-CP 410, 1074

Bloemen, H., Morris, D., Knödlseder, J. *et al.* 1999, ApJL submitted

Braun, H., Langer, N. 1995 , in: K.A. van der Hucht & P.M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, Proc. IAU Symp. No. 163 (Dordrecht: Kluwer), p. 305

Chen, W., Gehrels, N., Diehl, R., 1995, ApJ 440, L57

Chen, W., White, R.L., 1991, ApJ 366, 512

Chen, W., Diehl, R., Gehrels, N. *et al.* 1997, in: C. Winkler, T.J.-L. Courvoisier & Ph. Durouchoux (eds.), The Transparent Universe, Proc. 2nd *INTEGRAL* Workshop, ESA SP-382, p. 105

del Río, E., von Ballmoos, P., Bennett, K., Bloemen, H. *et al.* 1996, A&A 315, 237

Diehl, R., Dupraz, C., Bennett, K., Bloemen, H. *et al.* 1995, A&A 298, 445

Diehl, R., Bennett, K., Bloemen, H., Dupraz, C. *et al.* 1995a, A&A 298, L25

Diehl, R., Bennett K., Bloemen H. *et al.* 1995b, A&A 298, L25

Diehl, R., Bennett, K., Bloemen, H., Dupraz C. *et al.* 1996, A&AS, 120,4, 321

Diehl, R., Timmes F.X. 1998, PASP 110, 637

Diehl, R. *et al.* 1999, Proc. 3^{rd} *INTEGRAL* Science Workshop, in press

Dupraz, C., Bloemen, H., Bennett, K., Diehl, R. *et al.* 1997, A&A 324, 683

Fichtel, C.E., Hartman, R.C., Kniffen, D.A. *et al.* 1975, ApJ 198, 163

Fishman, G.J., Meegan, C.A., Wilson, R.B. *et al.* 1992, in: Shrader, C.R., Gehrels, N. & Dennis, B. (eds.), Proc. *Compton Observatory* Science Workshop, NASA-CP 3137, p. 26

Gehrels, N., Fichtel, C.E., Fishman, G.J. *et al.* 1993, Sci. Am. 269, 68

Harris, M.J., Murphy, R.J., Share, G.H. *et al.* 1998, A&A 329, 624

Hartman, R.C., Collmar, W., von Montigny, C., Dermer, C.D. 1997, in: C.D. Dermer, M.S. Strickman & J.D. Kurfess (eds.), Proc. Fourth *Compton* Symp., AIP-CP 410, 507

Hartmann, D.H. *et al.* 1997, Nucl. Phys. A 621, 83c

Haymes, R.C., Walraven, G.D., Meegan, C.A., Hall, R.D. *et al.* 1975, ApJ 201,593

Higdon, J.C. 1987, Proc. ICRC 20, 1, 160

Hunter, S.D., Bertsch, D.L., Catelli, J.R., Dame, T.M. *et al.* 1997, ApJ 481, 205

Iyudin, A.F., Diehl, R., Bloemen, H., Hermsen, W. *et al.* 1994, A&A 284, L1

Iyudin, A.F., Diehl, R., Lichti, G.G. *et al.* 1997, in: C. Winkler, T.J.-L. Courvoisier & Ph. Durouchoux (eds.), The Transparent Universe, Proc. 2nd *INTEGRAL* Workshop, ESA SP-382, p. 37

Iyudin, A.I., Schönfelder, V., Bennett, K. *et al.* 1998, Nature 369, 142

Iyudin, A.I. *et al.* 1999, Proc. 3^{rd} *INTEGRAL* Science Workshop, in press

Johnson, W.N., Kinzer, R.L., Kurfess, J.D., Strickman, M.S. *et al.* 1993, ApJS 86, 269

Knödlseder, J. 1997, The Origin of ^{26}Al in the Galaxy, PhD Thesis, UPS Toulouse

Knödlseder, J. 1999, ApJ 510, 915

Knödlseder, J., Bennett, K., Bloemen, H., Diehl, R., Hermsen, W., Oberlack, U., Ryan, J., Schönfelder, V., von Ballmoos, P. 1999a, A&A 344, 68

Knödlseder, J., Dixon, D., Bennett, K., Bloemen, H., Diehl, R., Hermsen, W., Oberlack, U., Ryan, J., Schönfelder, V., von Ballmoos, P. 1999b, A&A 345, 813

Kozma, C., Fransson, C. 1998, ApJ 497, 431

Kraushaar W.L., Clark, G.W., Garmire, G.P. *et al.* 1972, ApJ 177, 341

https://doi.org/10.1017/S0074180900205317 Published online by Cambridge University Press

Langer, N., Heger, A., Braun, H. 1998, in: T. Mezzacappa (ed.), Atomic and Nuclear Physics, Proc. 2nd Oak Ridge Symp. (Bristol: IOP Publ.), p. 377

Leitherer C. *et al.* 1999, ApJS in press

Lingenfelter, R.E., Ramaty, R., Kozlovsky, B. *et al.* 1998, ApJ 500, L153

Longair M.S. 1994, High Energy Astrophysics, Ch.21 (Cambridge: CUP)

Meynet, G., Arnould, M., Prantzos, N., Paulus, G., 1997, A&A 320, 460

Mochizuki, Y.S. *et al.* 1999, Proc. Nuclei in the Cosmos V, in press

Mukherjee, R., Grenier, I.A., Thompson, D.J. 1997, in: C.D. Dermer, M.S. Strickman & J.D. Kurfess (eds.), Proc. Fourth *Compton* Symp., AIP-CP 410, 394

Naya, J.E., Barthelmy, S.D., Bartlett, L.M. *et al.* 1996, Nature 384, 44

Naya, J.E., Barthelmy, S.D., Bartlett, L.M. *et al.* 1998, ApJ 499, L169

Oberlack, U. 1997, Über die Natur der galaktischen ^{26}Al-Quellen Untersuchung des 1,8-MeV-Himmels mit *COMPTEL*, PhD Thesis, TU München

Pollock, A.M.T. 1987, ApJ 320, 283

Prantzos, N. 1993, ApJ 405, L55

Prantzos, N., Diehl R. 1996, Phys. Rep. 267, 1

Ramaty, R., Kozlovsky, B., Lingenfelter, R.E, 1979, ApJ 316, 801

Ramaty, R., Kozlovsky, B., Lingenfelter, R.E, 1996, ApJ 456, 525

Schönfelder, V., Aarts, H., Bennett, K., de Boer, H. *et al.* 1993, ApJS 86, 657

Strong, A.W., Moskalenko, I., Reimer, O. 1999, ApJ in press

Thielemann, F.K., Nomoto, K., Hashimoto, M.,1996, ApJ 460, 408

Thompson, D.J., Bertsch, D.L., Fichtel, C.E. *et al.* 1993, ApJS 86, 629

Timmes, F.X., Woosley, S.E., Hartmann, D.H., Hoffman, R.D. 1996, ApJ 464,332

van der Hucht K.A., Schrijver, H., Stenholm, B. *et al.* 1997, New Astron. 2, 245

White, R.L. 1985, ApJ 289, 698

Winkler, C. 1995, Exp. Astron. 6, 71

Woosley, S.E., Weaver, T.A. 1995, ApJS 101, 181

Woosley, S.E., Timmes, F.X. 1997, in: C. Winkler, T.J.-L. Courvoisier & Ph. Durouchoux (eds.), The Transparent Universe, Proc. 2nd *INTEGRAL* Workshop, ESA SP-382, p. 21

Discussion

Stevens: How far away could you detect our galaxy if all the emission were in a point source, with *GRO* and with *INTEGRAL*?

Diehl: *GRO*-COMPTEL presently can clearly detect $0.1\,M_\odot$ of ^{26}Al at the center of our Galaxy. With *INTEGRAL*, the LMC should be detectable in ^{26}Al, but more distant galaxies will probably remain undetected.

Shara: How do you rule out novae as significant sources of ^{26}Al?

Diehl: We only can constrain the maximum contribution of novae in the Galaxy, assuming spatial distributions inferred from the large number of contributing sources (→ smooth) and nova observations in other galaxies. Depending on the spatial distributions used (also for the massive-star contribution), this limit is around or below $1\,M_\odot$, significantly below the predictions advertised by nova ^{26}Al models.

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