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Diffuse γ-ray line emission and cosmic rays

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Abstract. Gamma-ray lines arise from radioactivities produced in nucleosynthesis sites, and from deexcitation of nuclei which have been activated through energetic particle collisions. Nucleosynthesis products relate to activities inside massive stars. Supernova remnants show radioactivity afterglows at time scales which bracket their likely phases of relevance as cosmic-ray acceleration sites; ^{26}Al radioactivity may trace regions of intense wind interactions from groups of massive stars, and also encode information about the possible injection of matter into CR acceleration environments through interstellar dust grains. Nuclear excitation occurs mainly from low-energy cosmic rays which do not travel far from their acceleration sites. Hence both these gamma-ray line emission processes are related to the likely sources of cosmic rays.

1 Introduction

Although we believe now that the production of cosmic rays is the result of Fermi acceleration in interstellar shocks and associated magnetic turbulence, many site and process details have not been understood nor settled. Astronomical windows at different wavelength regions, complementing each other's findings, are required to further our insight. Observations of the sky in γ-ray lines provide us with an independent window to the physical environment in these regions responsible for the generation and acceleration of cosmic ray nuclei and electrons. The interaction of supernova blast waves and stellar winds with interstellar matter, in particular in regions with a high space density of such sources, plays a key role for cosmic ray production in the Galaxy. Characteristic γ-ray lines are expected to arise from such regions, through the processes of nuclear de-excitation following energetic particle collisions, and through radioactivities ejected along with other new elements from nucleosynthesis in massive stars and supernovae. Propagation of γ-rays is unaffected by magnetic fields and solar modulation, the penetration power of several g cm^{-2} allows to observe γ-rays also from sources deeply embedded in clouds.

In this paper we review the γ-ray line results and lessons with respect to cosmic-ray production and -propagation, and discuss prospects of upcoming studies.

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2 Massive Stars and Gamma-Ray Lines

Observations of the Milky Way and in particular of external galaxies in ionization-related emission (e.g. H_α) illustrate the clustered appearance of massive-star locations along spiral arms (Elmegreen & Efremov, 1996). Observations of HI shells then correlate to previous sites of such massive star activity and show loops and shells of former walls of hot cavities, which have been blown by the winds of massive stars and by supernova explosions (Walter and Brinks, 1996). These observations suggest an evolutionary sequence from correlated formation of stars in associations through evolution of bubbles and superbubbles around these out to the dissapearance of these hot cavities in interstellar-medium turbulences. In this sequence, observational traces are left behind through the energy output of mainly the most massive stars: During the stellar evolution intense starlight heats circumstellar dust and ionizes the gas in the vicinity, creating HII regions and Hα emission alongside; in late stages kintetic energy from massive-star winds and supernovae injects turbulent and shell streaming energies into the interstellar medium; radioactive nuclei which are freshly produced inside the stars or supernovae, and ejected into the circumstellar region through intense winds or supernovae, may be transported substantial distances of order several 100 pc before their decay, and thus provide a diffuse source of characteristic decay gamma-rays. Additionally, the spatial coherence of massive stars leads to a variety of expanding shells, which set up interface regions in the interstellar medium characterized by shocked gas. Such regions are the candidate regions for the acceleration of cosmic rays.

Cosmic γ-ray lines are well-known since pioneering experiments during 1960–1990 (Diehl & Timmes, 1998), now providing a new astronomical window to cosmic high-energy interactions: The 511 keV line from annihilation of positrons, discovered 1969 from the inner Galaxy by a balloon experiment (Haymes *et al.*, 1969), has been suggested from results of the OSSE instrument (Johnson *et al.*, 1993) aboard the NASA Compton Observatory (**?**) to include components from the Galactic disk, bulge, and some unknown extended inner-Galaxy region (Purcell *et al.*, 1997; **?**). The 1.809 MeV line from radioactive ^{26}Al , discovered with the HEAO-C experiment (Mahoney *et al.*, 1982) as the first direct proof of cosmic nucleosynthesis, has been mapped along the plane of the galaxy by the COMPTEL telescope (Schönfelder *et al.*, 1993) aboard the Compton Observatory (**?**), and is suggested to show a linewidth characterized by Doppler velocities above 500 km s^{-1} (Naya *et al.*, 1996). Supernova radioactivity was measured from SN1987A directly with SMM and several balloon experiments in shortlived radioactivity lines (Matz *et al.*, 1988; Tueller *et al.*, 1990), and in the longerlived ^{44}Ti gamma-ray line from the young Cas A supernova remnant (Iyudin *et al.*, 1994). Gamma-ray spectra from excited nuclei have been measured and studied in detail from solar flares (Murphy *et al.*, 1997); an initial report of cosmic de-excitation lines from the Orion star forming region had turned out false (Bloemen *et al.*, 1999).

3 Gamma-Rays from Supernovae

The impressive display of supernovae and their light curves is understood from the power of radioactive energy from freshly produced radio-isotopes, in particular large amounts of ^{56}Ni (τ=8.8 d). SMM's detection of the SN1987A ^{56}Co decay γ-rays at 847 and 1238 keV at early times, as well as the line profiles (Matz *et al.*, 1988; Tueller *et al.*, 1990), demonstrated substantial mixing and turbulence of the supernova explosion itself. Important for cosmic ray production are turbulent structures set up in the later phases of the early supernova remnant, when the blast wave from the explosion hits circumstellar and interstellar gas and sets up a shock region with magnetic-field turbulences. Not much observational diagnostics exists at times before the shock has heated gas to X-ray emitting temperatures; thereafter many radiation phenomena are produced, from a variety of recombination radiation of shock-ionized gas through nonthermal radiation of accelerated electrons from the radio through UV and even gamma-ray regime (synchrotron radiation, Bremsstrahlung, and inverse-Compton radiation).

In core-collapse supernovae, ^{44}Ti is expected to be coproduced with ^{56}Ni , and some of this could also be ejected rather than collapse onto the compact remnant. With its 89-year decay time, ^{44}Ti radioactivity could still be observable at remnant ages when cosmic ray acceleration begins to become effective, i.e. when the shock region is set up and the magnetic fields are still high. The measurement of ^{44}Ti line shapes with high spectral resolution should then provide another, and unique for this early phase, diagnostic of kinematics in the early remnant of a supernova. Gamma-rays from ^{44}Ti had been seen for the first time with COMPTEL, from the 300-year-old Cas A supernova remnant in the 1.16 MeV decay line (Iyudin *et al.*, 1994). Measurements by other γ-ray instruments (OSSE, RXTE, Beppo-Sax) were not sensitive enough for a ^{44}Ti confirmation, mainly attempted in the 68 and 78 keV lines unaccessible to COMPTEL.

But other interesting measurements of supernova remnant high-energy emission have been made, relevant for the direct proof of the existence of freshly-accelerated cosmic rays: The shell supernova remnant SN1006 has been proposed as a prototype source of cosmic ray electrons, based on its X-ray spectrum when interpreted as synchrotron emission (Allen *et al.*, 1997)and on very-high γ-ray emission detected with ground-based experiments and interpreted as inverse-Compton emission (Tanimori *et al.*, 1998). Although this interpretation is far from consolidated, it is worthwhile to pursue its detailed implications: Measurements of non-thermal X-ray emission confirm and extend the synchrotron radiation measurements at radio wavelengths on the cosmic-ray electron component, and suggest that cosmic ray electrons have energies up to TeV. Measurements of TeV γ-rays could be ambiguous, inverse-Compton emission and Bremsstrahlung from TeV electrons could be superimposed onto a nucleonic components from pion decay. Therefore this interpretation depends on the choice of physical parameters of the non-linear shock acceleration model developed recently (Ellison *et al.*, 1999); yet the consistent modelling of all these emission processes from the accelerated particles in the shock region promises that better measurements will complete the detailed picture. Main uncertainty is the magnitude of the magnetic field: 6.5$\pm$2 μG have been derived for SN1006, while for Cas A the low very-high energy (TeV) measurement with HEGRA (Pühlhofer *et al.*, 1999)suggests a much larger magnetic field of $\sim$mG in the acceleration region, in order to increase the synchrotron process efficiency.

The MeV domain could prove particularly interesting: The contribution from thermal emission peaks in the X-ray regime and vanishes towards the MeV region, while nucleonic emission is still unimportant, so that continuum emission from Bremsstrahlung of the cosmic ray electrons remains as a unique process. Only from Cas A, measurements have been obtained here. While OSSE reports clearly-detected continuum emission below 1 MeV (The *et al.*, 1995, 1997), the COMPTEL measurement in the 1-3 MeV regime is marginal and complicated by the ^{44}Ti signal (Strong *et al.*, 2000).

4 Diffuse Radioactivities

Measurements of ^{26}Al radioactivity with the COMPTEL telescope(**?**) aboard the *Compton Gamma-Ray Observatory* have obtained a sky survey, which clearly delineates recent nucleosynthesis sites within the Galaxy (**?**Plüschke et al., 2001). Fig. 1). With its mean lifetime of 1 Myr the 1.809 MeV gamma-ray emissivity results from thousands of unre-

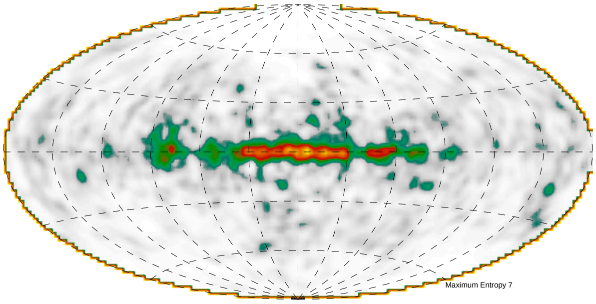

Fig. 1. COMPTEL 1.809 MeV all sky map based on a maximum entropy deconvolution of the complete mission data (Plüschke et al., 2001)

solved sources which contribute to the overall diffuse glow of the Galaxy in this γ-ray line. Massive stars have been recognized as dominating sources of ^{26}Al radioactivity (for a recent review see Prantzos & Diehl (1996)), from spatial correlations of different massive-star tracers with the 1.809 MeV image (Knödlseder *et al.*, 1999), from astrophysical plausibility arguments (Prantzos & Diehl, 1996; Knödlseder *et al.*, 1999), and from the study of localized regions with rather wellknown stellar history and supernova activity (**?**Plüschke *et al.*, 2000). Classical Novae of the O-Ne type and AGB stars also may contribute to the overall ^{26}Al content of the interstellar medium, but most likely only as a minor contribution.

From such analyses of the 1.809 MeV emission a total Galactic ^{26}Al mass of $\simeq$2 $M_\odot$ is estimated. In a steady-state situation, this corresponds to a global star formation rate of a few solar masses per year, equivalently to a galactic supernova rate of a few events per century, adopting a typical yield of 10^{-4} $M_\odot$ of ^{26}Al per supernova.

Two main possibilities of ^{26}Al ejection into the ISM are expected: (1) Stellar winds from massive stars diffuse inner nucleosynthesis products from core or shell nuclear burning, after they have been mixed into the envelope. (2) The core-collapse supernova ejects most of the stellar material, including pre-supernova nucleosynthesis products from the inner parts, and products of explosive nucleosynthesis from the passage of the supernova shock through the outer layers of the star.

The ^{26}Al consolidated image (Knödlseder *et al.*, 1999; Plüschke et al., 2001) (see Figure **??**) shows: The emission extends through the entire plane of the Galaxy, and traces the presumed locations of massive stars; ^{26}Al emission appears correlated with spiral arm patterns, and with locations of WR stars or young open stellar clusters. Such correlation can be indicative only, because the periods of ^{26}Al ejection from massive stars are offset by typically million years from the periods when massive-star formation can be detected at other wavelengths. In fact, the diffuse emission from free-free radiation, from warm dust grains, and from cosmic-ray produced high-energy γ-ray emission have been recognized as more similar to the ^{26}Al emission than (incompletion-biased) catalogues of WR stars, supernova remnants, stellar clusters, or even the map of molecular gas (CO) from which massive stars are born (Knödlseder *et al.*, 1999). Free-free emission is bremsstrahlung generated by free electrons in ion fields, hence it arises in the interstellar gas regions in the vicinity of ionization sources, HII regions and the diffuse interstellar gas (DIG) or warm ionized medium (WIM). Presumably the UV emission from massive stars is responsible for this ionization. This is demonstrated from global consistency of the ionization power of massive stars with the ^{26}Al ejection from the same stellar population (Knödlseder, 1999). Upon a closer look, for a standard initial-mass function it appears that WR stars in the inner Galaxy provide the bulk of the $\simeq$2–2.5 $M_\odot$ of ^{26}Al ; although a number of 10000 Galactic WR stars is not implausible, the metallicity trend of WR star ^{26}Al yields and the inferred low core-collapse rate of 1.8/100y may require adjustment of this first-order assessment of ^{26}Al sources. ^{60}Fe may be an important diagnostic here.

Clusters of young, massive stars play a prominent role in interstellar ^{26}Al emission. Stellar population synthesis models have been enhanced recently to model the evolution of radioactivity γ-ray luminosity, and to compare this to evolution of ionization power and of total kinetic energy released in the form of bubbles, which sweep up interstellar gas around massive-star locations (see Plüschke *et al.*, this conference, and Cerviño *et al.*, this conference). The interaction of such wind-blown or supernova-blast bubbles in regions of high space density of massive stars could play a key role in the acceleration of particles to cosmic-ray energies. Therefore, the diagnostics of the ^{26}Al γ-ray line shape may reflect the overall turbulence in massive star regions (see Kretschmer *et al.*, this conference: The ^{26}Al 1.809 MeV line appears broadened on a rather global scale, from the result of the high-resolution Ge detector experiment 'GRIS', obtained with the $\sim 100\mathrm{deg}$ field of view of this instrument (Naya *et al.*, 1996)). The measured broadening by 5 keV corresponds to rather high velocities above 500 km/s, which are not easily understood (Chen *et al.*, 1997). At least some of the decaying ^{26}Al nuclei have nonthermal velocities, either left over from their source, or obtained through acceleration in the ISM. Typical ejection velocities expected from ^{26}Al sources are around 1000 km/s only, and substantial slowing down should occur during the 10^6-year decay time even in dilute surroundings. But a significant fraction of the refractory aluminium may condense onto grains in the WR wind or even in the expanding supernova, so that the slowing-down time could be extended to a significant fraction of the ^{26}Al decay time. On the other hand, grain-deposited ^{26}Al could also be slowed down, e.g., over a typical supernova remnant evolution time of 10^5 y = 0.1 τ_{26Al}, but then encounter an acceleration region in this colliding-bubble environment around massive stars. Then, the broad ^{26}Al line may reflect the cosmic-ray component of heavy nuclei in the cosmic-ray source region, evaporized from the grain by a shock encounter, and boosted by Fermi acceleration to cosmic-ray velocity. Observationally, this should be reflected in two distinct components of ^{26}Al contributing to the line profile:

a narrow component from decay in the interstellar medium, and a broad, non-thermal component (displaying a significant high-velocity tail) from re-accelerated ^{26}Al (Sturner & Naya, 1999).

Adopting the picture of an inhomogeneous and rather clumpy distribution of massive stars throughout the Galaxy at a given time, one may ask how much of this could remain detectable in different observational windows. For standard cosmic rays, propagation time and relevant volume are such that direct detection of cosmic ray sources is feasible only at highest energies. Likewise, the radioactive-decay time scales for ^{26}Al and ^{60}Fe around 10^6 y will smear out cosmic-ray acceleration 'events' such as individual SNR, their typical lifetime being approximately 1/10 of this. Yet, the evolution time scale of an association of massive stars, even for burst-like formation, would be typically much longer, 10 τ_{26Al}, so that associations as a whole can be regarded as individual source regions. Therefore it is very interesting to note in the ^{26}Al γ-ray image that specific regions stand out, in the Cygnus (Plüschke *et al.*, 2000), Vela (Diehl *et al.*, 1999), Anticenter, and Sco-Cen regions. In these specific cases, the main candidate sources are well localized and foreground or background sources are less important, in contrast to the situation in the inner Galaxy, where the line of sight passes through several likely massive-star regions at different distances. In these cases, therefore, it appears possible to study how individual groups of massive stars evolve and interact to generate observable radioactivity with characteristic line profiles. It is a prominent goal for the upcoming ESA mission INTEGRAL (Winkler *et al.*, 1996) to provide those γ-ray line profiles at a spatial resolution of degrees, to enable such investigations related to cosmic ray source environments.

5 Nuclear De-excitation Lines

The reported COMPTEL detection of ^{12}C and ^{16}O deexcitation lines from the Orion region (Bloemen *et al.*, 1994), attributed to cosmic-ray nuclei, was received as a sensational proof of the existence of otherwise unobservable low-energy cosmic rays. Much useful theoretical studies had suggested physical problems and inconsistencies, e.g. excessive ionization of the ISM, absence of X-rays from electron bremsstrahlung, absence of lines other than from C and O (such as Ne, Mg). Speculations of nucleosynthetic-enriched cosmic ray composition or evaporated dust were seen as a way out. The result was withdrawn when contamination from instrumental radioactivity became a concern, with an upper limit for line emission at 3 10^{-5} ph cm^{-1}s^{-1}, which is consistent with expectations (Bloemen *et al.*, 1999). A promising hint in COMPTEL data from the inner Galaxy of spectral structure in the nuclear line region (Bloemen *et al.*, 1999) had not been pursued further. Nevertheless, these lines still are the best candidates to detect directly the existence, and to diagnose the composition of low-energy cosmic rays, and the nearby Orion region of massive stars will remain the most promising target for further searches. ESA's INTEGRAL mission (Winkler *et al.*, 1996) probably does not quite have the required sensitivity, new experiments such as the proposed MEGA explorer (Kanbach *et al.*, 2001) will be needed for further observational progress.

References

Allen *et al.*, 1997, *ApJ* **491**, 436.
Bloemen H. *et al.*, 1994, *A&A* **281**, L5.
Bloemen *et al.*, 1999, *ApJ* **521, 2**, L137.
Chen W. *et al.*, 1997, *ESA-SP* **382**, 105.
Diehl R. and Timmes F.X., 1998, *PASP* **110**, 637.
Diehl R. *et al.*, 1995 *A&A* **298**, 298.
Diehl R. *et al.*, 1999, *Astr.Lett.Commun.* **38**, 357.
Ellison D.C. *et al.*, 1999:, *Proc. ICRC 26* **OG 2.02.09**.
Elmegreen, B.G. and Efremov, Y.N., *ApJ* **466**:802+, 1996.
Garmany, C.D. et al., *ApJ* **263**:777+, 1982.
Gehrels N. and Kniffen D., 1999, *AIP* **410**, 3.
Haymes R.C. *et al.*, 1969, *ApJ* **157**, 1455.
Iyudin A.F. *et al.*, 1994, *A&A* **284**, L1.
Johnson N.W. *et al.*, 1993, *ApJS* **86**, 693.
Kanbach G. *et al.*, 2001, *www.gamma.mpe-garching.mpg.de/MEGA/mega.html*.
Knödlseder, 1999, *ApJ* **510**, 915.
Knödlseder *et al.*, 1999, *A&A* **344**, 68.
Mahoney J.W. *et al.*, 1982, *ApJ* **262**, 742.
Matz S. *et al.*, 1999, *Nature* **331**, 416.

Morris *et al.*, 1995, *N.Y.Acad.Sci.* **759**, 397.
Murphy *et al.*, 1997, *ApJ* **490**, 883.
Naya J.E. *et al.*, 1996, *Nature* **384**, 44.
Plüschke, S. et al., *Proc. of the 4^{th} INTEGRAL Workshop*, Alicante/Spain, ESA-SP series (in press), 2001.
Pühlhofer *et al.*, 1999, *Proc. 26th ICRC* **3**, 492.
Plüschke S. *et al.*, 2000, *AIP* **510**, 35.
Prantzos N. and Diehl R., 1996, *Phys.Rep.* **267**, 1.
Purcell W.R. *et al.*, 1997, ApJ **491**, 725
Ramaty R., Kozlovsky B.Z., and Lingenfelter R.E., 1979, *ApJ* **316**, 801.
Schönfelder V. *et al.*, 1993, *ApJS* **86**, 657.
Strong A.W. *et al.*, 2000, *AIP* **510**, 60.
Sturner S. & Naya J.E., 1999, *ApJ* **526**, 200.
Tanimori T. *et al.*, 1999, *ApJ* **497**, L25.
The L.-S. *et al.*, 1995, *ApJ* **444**, 244.
The L.-S. *et al.*, 1997, *AIP* **410**, 1147.
Tueller J. *et al.*, 1990, *ApJ* **351**, L41.
Walter F. and Brinks E. , 1996, *AJ* **118**, 273.
Winkler C. *et al.*, 1996, *A&AS* **120**, 637.