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Gamma-Rays from Nucleosynthesis Ejecta

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Abstract. Gamma-ray lines from radioactive decay of unstable isotopes produced in massive-star and supernova nucleosynthesis have been measured with INTEGRAL over the past ten years, complementing the earlier COMPTEL survey. ^{26}Al has become a tool to study specific source regions, such as massive-star groups and associations in nearby regions which can be discriminated from the galactic-plane background, and the inner Galaxy where Doppler shifted lines add to the astronomical information. Recent findings are that superbubbles show a remarkable asymmetry, on average, in the spiral arms of our galaxy. ^{60}Fe is co-produced by the sources of ^{26}Al, and the isotopic ratio from their nucleosynthesis encodes stellar-structure information. Annihilation gamma-rays from positrons in interstellar space show a puzzling bright and extended source region central to our Galaxy, but also may be partly related to nucleosynthesis. ^{56}Ni and ^{44}Ti isotope gamma-rays have been used to constrain supernova explosion mechanisms. Here we summarize latest results using the accumulated multi-year database of observations, and discuss their astrophysical interpretations. We also add a comparison of isotopic ratios between the ISM of the current Galaxy and the solar vicinity at solar-system formation time.

1. Introduction

Cosmic nucleosynthesis is expected to be ongoing in star-forming galaxies such as our Milky Way. Co-produced unstable nuclides, if ejected into interstellar space and sufficiently long-lived to not decay within the source already, can be observed through characteristic gamma-ray line emission with current gamma-ray telescopes. This makes nuclides ^{7}Be, ^{22}Na, ^{56}Ni, ^{44}Ti, ^{26}Al, and ^{60}Fe prime candidates for such gamma-ray line studies of ongoing nucleosynthesis in our galaxy, through massive stars, supernovae, and novae as candidate sources [1; 2].

After ^{26}Al observations with HEAO-C [3] had confirmed this connection, gamma-ray line surveys have been undertaken by NASA with the Compton Gamma-Ray Observatory (1991-2000) [4], and by ESA with the International Gamma-Ray Astrophysics Laboratory observatory INTEGRAL (since 2002 and currently ongoing) [5]. Instruments and missions up to now are characterized by sensitivities of a few 10^{-5} photons cm^{-2}s^{-1} that limit studies essentially to sources in our own galaxy[1]. Advances by up to two orders of magnitude in sensitivity would be feasible [6], but are unlikely to happen[2].

[1] except for ^{56}Ni from rare supernovae in nearby galaxies, and the ^{44}Ti measurements from SN1987A in the nearby LMC galaxy.

[2] because of high cost and competing astrophysics goals with broader community support than nuclear astrophysics has at present.

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Observations from these missions and their results and implications have been reviewed before [2; 7–9]. Here we therefore only summarize the status and results (Section 2), and add some details to stimulate a broader view, e.g. connecting gamma-ray data with presolar grain and early solar system data from meteorites. We finish this short contribution with comments on the open issues and prospects for this field of astronomy and astrophysics.

2. Selected Observational Results

2.1. Supernovae: ^{56}*Ni and* ^{44}*Ti*

Shortlived radioactivity in the ^{56}Ni and ^{44}Ti decay chains is expected to be bright enough to be detectable from supernova explosions even beyond our Galaxy. For ^{56}Ni telescopes such as INTEGRAL should reach out to a few Mpc distance for SNIa which eject up to $\sim$1 $M_\odot$ of 56Ni [10]. Even for core-collapse supernovae, nearby galaxies could be reached, in particular for hypernovae and pair instability supernovae. ^{44}Ti as the next nuclide in ranking gamma-ray brightness[3] can only be seen from Galactic young supernova remnants, and for the SN1987A supernova in the nearby LMC at 50 kpc distance.

INTEGRAL spent substantial observing time (4Ms), therefore, when a SNIa exploded on 23 Aug 2011 in M101 at about 6 Mpc distance [11]. It was clear that this was a challenging case for gamma-ray observers at the outer limb of the usable distance range, but an excellent one for astronomers in many other fields - the prospect of multi-wavelength measurements provides for another unique learning experience. The disappointment of not seeing ^{56}Ni decay gamma-rays [12] was not surprising after all, but we needed to take our chance of contributing to SNIa brightness calibrations through measurement of the gamma-rays directly from ^{56}Ni decay.

^{44}Ti had been detected from one young supernova remnant only, up to now: the 360-year old Cas A remnant at 3.4 kpc distance [13; 14]. For this object, the ^{44}Ti gamma-ray flux is rather well determined at 2.5 10^{-5} ph cm^{-2}s^{-1}. This corresponds to an amount of ^{44}Ti ejected by the explosion which is about a factor of three above expectations from models [15]. Spectroscopy with SPI, together with the IBIS flux measurement, sets a limit on the ejecta kinematics with INTEGRAL observations, requiring ^{44}Ti ejecta to coast at velocities above 500 km s^{-1} [16], compatible with expectations from supernova simulations [17; 18]. The imaging hard X-ray mission NuStar launched in 2012 [19] has recently reported first images of ^{44}Ti X-rays from Cas A (Harrison, priv.comm.). This will allow to test for the extent of explosion asymmetries in ^{44}Ti versus other observables; highly non-spherical explosions are suspected to be the reason of high ejected ^{44}Ti amounts in core-collapse supernovae [7; 15].

Surveys have been performed to search for more ^{44}Ti emitting young supernova remnants [20–22], and several candidates have been discussed, most intensely the Vela Junior/GROJ0852-4642 [23; 24] and G1.9+0.3 [25] remnants. But no other source has been assessed as detected so far in ^{44}Ti decay lines in our Galaxy apart from Cas A.

In 2011, IBIS data then showed a signature from SN1987A in the LMC [26] that plausibly is attributed to ^{44}Ti line emission, though IBIS cannot resolve the X-ray lines from ^{44}Sc decay (which follows ^{44}Ti decay). Although once more the ^{44}Ti amount inferred from the ^{44}Ti gamma-ray intensity lies well above model expectations, recent NuStar observations have confirmed this result (Harrison, priv.comm.).

2.2. Diffuse Radioactivity: ^{26}*Al,* ^{60}*Fe, and* e^+

The long-lived radio-isotopes of ^{26}Al and ^{60}Fe accumulate in interstellar medium around their sources, and result in a diffuse afterglow of nucleosynthesis with a My decay time. This is still shorter than the evolutionary time scale for star clusters (tens of My), but much longer

[3] This involves amounts produced in the event, multiplied by decay rate. Therefore short-lived nuclides up to the iron group are best candidates. See table/list in [2]

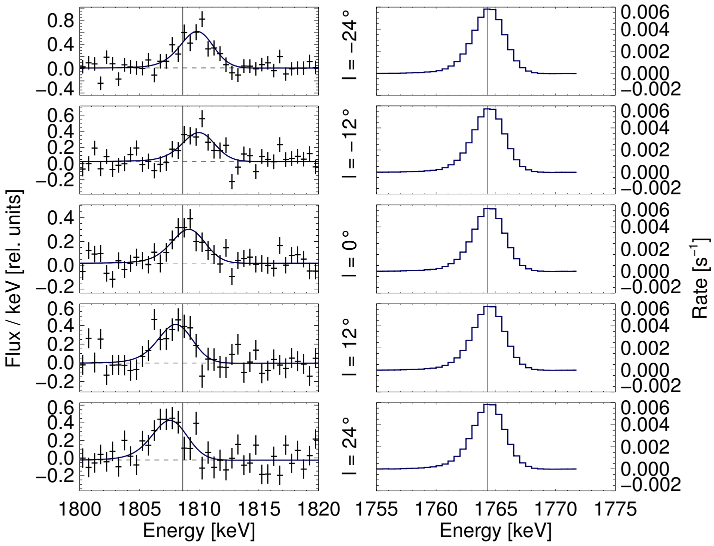

Figure 1. ^{26}Al line measurements with SPI along the plane or the Galaxy, for different lines of sight, show the systematic Doppler shift from large-scale rotation in the Galaxy (*left*). A nearby instrumental line at 1764 keV (*right*) does not show differences in line position, from the same data.

than the time scale of other observables related to nucleosynthesis events such as supernova remnants (tens of ky). The sky survey from COMPTEL had shown ^{26}Al emission correlating to known massive star activity in our Galaxy [27]. ^{60}Fe was an expected gamma-ray line emitter ejected from supernovae, but only detected in 2004/2005 with Ge spectrometers on RHESSI and INTEGRAL[28–30]. Its gamma-ray brightness is only about 1/7 of ^{26}Al, and therefore the measurement of its spatial distribution in the Galaxy and its gamma-ray line shape characteristics will be challenging even with many more years of INTEGRAL/SPI measurements.

Galactic ^{26}Al has been studied in more detail, and provides an independent observable for astrophysics questions relating to the Galaxy's massive-star population and the interstellar medium. From the total Galactic ^{26}Al amount, one can infer the Galactic core-collapse supernova rate (or the rate of star formation) through a measurement of penetrating gamma-rays. The result is consistent with expectations within uncertainties of the various star formation / supernova rate observables: A supernova rate of 1.x $\pm$0.x per 100 years corresponds to a star formation rate of x $M_\odot$ y^{-1} in the Galaxy as a whole. While that confirms our Galaxy forming stars at a rate that requires gas replenishing from outside the Galaxy (e.g. through infalling clouds from intergalactic space or from collisions with nearby galaxies), the question of where stars are being formed exactly, and why, is a key issue for evolution of galaxies. Studying the multi-messenger picture of massive-star feedback in specific regions hosting well-observed groups of massive stars is therefore a rich field for such studies, e.g. the Cygnus, Carina, Scorpius-Centaurus, and Orion regions.

With the exquisite spectral resolution of INTEGRAL's spectrometer SPI, a new measurement (Fig. 1) of the ^{26}Al line properties as it is Doppler shifted by large-scale Galactic rotation may shed additional and new light on this issue. Observations show Doppler shifts in the ^{26}Al line which exceeds values seen in other Galactic objects such molecular clouds. This surprising finding suggests that there may be a global asymmetry in outflows from massive-star groups, i.e. the ejecta show a tendancy of less-inhibited free streaming away from ^{26}Al sources in the direction of global galactic rotation. Studies are underway to investigate if massive-star groups may not be populated symmetrically on leading and training sides of spiral arms, and if that could lead to the observed effect. Superbubbles play a role here, as ejecta flows are directed by the density structures that have ben pre-shaped around the sources. It will be interesting to see how ^{26}Al sources relate to the drivers of the structure and dynamics of the interstellar medium in general, and the different phases of the interstellar medium.

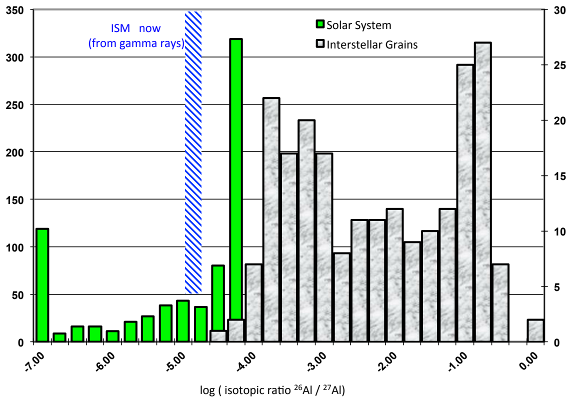

Figure 2. The ^{26}Al/^{27}Al isotopic ratio from meteoritic measurements of different types of presolar-grain inclusions (grey/shaded; A. Davis, priv.comm.), and CAI inclusions (green narrow columns, from [31])and from the gamma-ray result for the current interstellar medium average in the Galaxy (hatched).

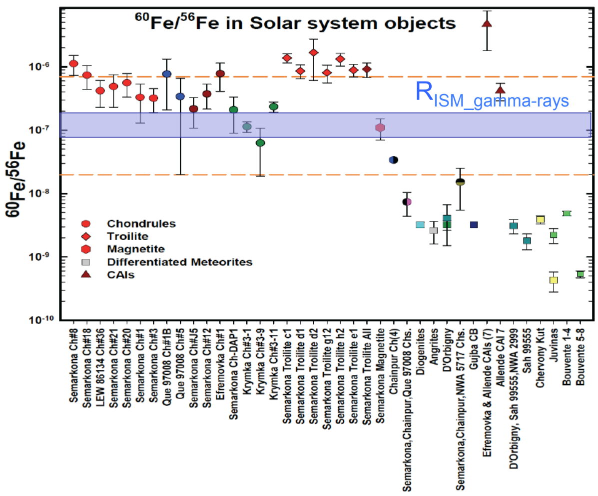

Figure 3. ^{60}Fe/^{56}Fe Isotopic ratios from different measurements relating to the early solar system [32], compared to the gamma-ray result for the current interstellar medium average in the Galaxy (shaded). (Figure adapted from [32])

Many nucleosynthesis sources involve H burning and the production of proton rich nuclei in general; examples are ^{26}Al from massive stars, but also ^{13}N and ^{18}F from novae, and even p-n symmetric nuclides ^{56}Ni and ^{44}Ti fall on the p-rich side of the valley of nuclide stability, as neutron number excesses compensate for increasing Coulomb repellence in heavier nuclei. Incurred β^+-decays release positrons, which eventually annihilate with ambient electrons to produce characteristic gamma-rays as the particle-antiparticle mass is radiated away. Characteristic e^+ annihilation gamma-rays at 511 keV have been measured since decades, and finally been mapped across the sky with INTEGRAL/SPI. This map presents a major puzzle, however: The expected e^+ sources are distributed throughout the Galaxy and in particular its plane, where massive stars are being formed and eject nucleosynthesis products plus leave behind compact stars that again can turn into e^+ sources (see for a detailed review and discussion). Again the structure and morphology of interstellar medium may hold the answer to this puzzle: positrons are typically produced with relativistic energies, and need to slow down before annihilating with interstellar electrons. Propagation of e^+ in the different phases of ISM and the impacts of interstellar magnetic fields are currently being studied. Interplanetary positron measurements have recently added excitement and may also teach us about propagation aspects. Once this is understood, nucleosynthesis e^+ and their role in observed annihilation will become clear, and next steps could then be exciting to possibly reveal new sources of e^+.

Ongoing nucleosynthesis activity ever increases the heavy-element content of interstellar gas. Our solar system samples ambient interstellar gas from 4.568 Gy ago, and solar-system matter composition is measured in great detail through solar radiation absorption-line spectroscopy and also through mass spectrometry of meteoritic inclusions [33; 34]. Solar abundances constitute our best-known reference for the study of cosmic abundances, and chemical evolution prescriptions are required to properly connect our models of cosmic nucleosynthesis sources to the various abundance measurements. We therefore compare the ^{26}Al and ^{60}Fe gamma-ray measurements of the current interstellar gas in our Galaxy to the record of those same isotopic ratios with respect to the stable reference isotope in the early solar system (ESS) (Fig's 2 and 3). The total Galactic ^{26}Al mass of 2.25 $M_\odot$ translates into an isotope ratio of 1.0 10^{-5}, assuming that the ^{26}Al mass reflects star forming activity and is in steady state. Here, we use a total Galactic gas mass of 4.95 $10^9 M_\odot$ [35] and solar abundances from [33]. The gamma-ray flux ratio for ^{60}Fe versus ^{26}Al of 15% yields a steady-state mass of ^{60}Fe of 1.53 $M_\odot$ for the Galaxy, or an isotopic ratio ^{60}Fe/^{56}Fe of 1.5 10^{-7}. The fractions of the unstable isotopes apparently decrease with time, consistent with proceeding enrichment of heavy nuclei in general and the decay of the unstable nuclei. We may ask if the early solar system isotopic ratios are consistent with large-scale averaged ISM composition as inferred from the current-ISM gamma-ray data and solar stable-isotope abundances, or if special enrichments may be suggested by these meteoritic data. There is a rich literature on special nearby events injecting short-lived radioactivities into the forming solar system. In recent years, increased precision of isotopic abundance measurements have reduced the significance of required enrichments for several of those radioisotopes, however. Within present uncertainties, it appears that ^{26}Al enrichments still persist, while this is less clear for ^{60}Fe. Simulations of abundance evolutions in a star-forming gas disk [36] also support these conclusions.

3. Open Issues and Prospects

Gamma-ray survey missions have shown the brightest sources, and confirm the approach of testing cosmic nucleosynthesis by measuring radioactive decays of trace isotopes co-produced herein. ^{56}Ni is an exception, as its decay is the dominating power source for supernova light Major open issues still are the variety of models discussed for all types of supernova explosions, the poor constraints for massive-star interior structure in late phases of the pre supernova evolution, and the inadequacy of nuclear explosion models on compact stars in general. Continued and deeper observations in gamma-rays are our best chance to learn about these nucleosynthesis sources as they happen in the present nearby universe, so that improved models can be developed and tested on the variety of nuclide abundance measurements with the help of chemical-evolution prescriptions and source population models.

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References

[1] Lingenfelter R E and Ramaty R 1978 *Physics Today* **31** 40–47

[2] Diehl R, Hartmann D H and Prantzos N 2011 *Astronomy with Radioactivities* (*Lecture Notes in Physics, Berlin Springer Verlag* vol 812) (Springer: Berlin, Heidelberg)

[3] Mahoney W A, Ling J C, Wheaton W A and Jacobson A S 1984 *ApJ* **286** 578–585

[4] Gehrels N, Fichtel C E, Fishman G J, Kurfess J D and Schonfelder V 1993 *Scientific American* **269** 68–+

[5] Winkler C, Courvoisier T J L, Di Cocco G, Gehrels N, Giménez A, Grebenev S, Hermsen W, Mas-Hesse J M, Lebrun F, Lund N, Palumbo G G C, Paul J, Roques J P, Schnopper H, Schönfelder V, Sunyaev R, Teegarden B, Ubertini P, Vedrenne G and Dean A J 2003 *A&A* **411** L1–L6

[6] Greiner J, Mannheim K, Aharonian F, Ajello M, Balasz L G, Barbiellini G, Bellazzini R, Bishop S, Bisnovatij-Kogan G S, Boggs S, Bykov A, DiCocco G, Diehl R, Elsässer D, Foley S, Fransson C, Gehrels N, Hanlon L, Hartmann D, Hermsen W, Hillebrandt W, Hudec R, Iyudin A, Jose J, Kadler M, Kanbach G, Klamra W, Kiener J, Klose S, Kreykenbohm I, Kuiper L M, Kylafis N, Labanti C, Langanke K, Langer N, Larsson S, Leibundgut B, Laux U, Longo F, Maeda K, Marcinkowski R, Marisaldi M, McBreen B, McBreen S, Meszaros A, Nomoto K, Pearce M, Peer A, Pian E, Prantzos N, Raffelt G, Reimer O, Rhode W, Ryde F, Schmidt C, Silk J, Shustov B M, Strong A, Tanvir N, Thielemann F K, Tibolla O, Tierney D, Trümper J, Varshalovich D A, Wilms J, Wrochna G, Zdziarski A and Zoglauer A 2012 *Experimental Astronomy* **34** 551–582 (*Preprint* 1105.1265)

[7] Prantzos N 1996 *A&AS* **120** C303+

[8] Diehl R, Prantzos N and von Ballmoos P 2006 *Nuclear Physics A* **777** 70–97 (*Preprint* arXiv:astro-ph/0502324)

[9] Diehl R 2013 *Reports on Progress in Physics* **76** 026301 (*Preprint* 1302.3441)

[10] Isern J, Bravo E and Hirschmann A 2008 *New Astronomy Review* **52** 377–380

[11] Nugent P E, Sullivan M, Cenko S B, Thomas R C, Kasen D, Howell D A, Bersier D, Bloom J S, Kulkarni S R, Kandrashoff M T, Filippenko A V, Silverman J M, Marcy G W, Howard A W, Isaacson H T, Maguire K, Suzuki N, Tarlton J E, Pan Y C, Bildsten L, Fulton B J, Parrent J T, Sand D, Podsiadlowski P, Bianco F B, Dilday B, Graham M L, Lyman J, James P, Kasliwal M M, Law N M, Quimby R M, Hook I M, Walker E S, Mazzali P, Pian E, Ofek E O, Gal-Yam A and Poznanski D 2011 *Nature* **480** 344–347 (*Preprint* 1110.6201)

[12] Isern J, Jean P, Bravo E, Diehl R, Knödlseder J, Domingo A, Hirschmann A, Hoeflich P, Lebrun F, Renaud M, Soldi S, Elias-Rosa N, Hernanz M, Kulebi B, Zhang X, Badenes C, Domínguez I, Garcia-Senz D, Jordi C, Lichti G, Vedrenne G and Von Ballmoos P 2013 *A&A* **552** A97 (*Preprint* 1302.3381)

[13] Iyudin A F, Diehl R, Bloemen H, Hermsen W, Lichti G G, Morris D, Ryan J, Schoenfelder V, Steinle H, Varendorff M, de Vries C and Winkler C 1994 *A&A* **284** L1–L4

[14] Renaud M, Vink J, Decourchelle A, Lebrun F, den Hartog P R, Terrier R, Couvreur C, Knödlseder J, Martin P, Prantzos N, Bykov A M and Bloemen H 2006 *ApJ* **647** L41–L44 (*Preprint* arXiv:astro-ph/0606736)

[15] The L S, Clayton D D, Diehl R, Hartmann D H, Iyudin A F, Leising M D, Meyer B S, Motizuki Y and Schönfelder V 2006 *A&A* **450** 1037–1050 (*Preprint* arXiv:astro-ph/0601039)

[16] Martin P, Knödlseder J, Vink J, Decourchelle A and Renaud M 2009 *A&A* **502** 131–137

[17] Kifonidis K, Plewa T, Janka H and Müller E 2003 *A&A* **408** 621–649 (*Preprint* arXiv:astro-ph/0302239)

[18] Wongwathanarat A, Janka H T and Müller E 2013 *A&A* **552** A126 (*Preprint* 1210.8148)

[19] Harrison F A, Craig W W, Christensen F E, Hailey C J, Zhang W W, Boggs S E, Stern D, Cook W R, Forster K, Giommi P, Grefenstette B W, Kim Y, Kitaguchi T, Koglin J E, Madsen K K, Mao P H, Miyasaka H, Mori K, Perri M, Pivovaroff M J, Puccetti S, Rana V R, Westergaard N J, Willis J, Zoglauer A, An H, Bachetti M, Barrière N M, Bellm E C, Bhalerao V, Brejnholt N F, Fuerst F, Liebe C C, Markwardt C B, Nynka M, Vogel J K, Walton D J, Wik D R, Alexander D M, Cominsky L R, Hornschemeier A E, Hornstrup

A, Kaspi V M, Madejski G M, Matt G, Molendi S, Smith D M, Tomsick J A, Ajello M, Ballantyne D R, Baloković M, Barret D, Bauer F E, Blandford R D, Niel Brandt W, Brenneman L W, Chiang J, Chakrabarty D, Chenevez J, Comastri A, Dufour F, Elvis M, Fabian A C, Farrah D, Fryer C L, Gotthelf E V, Grindlay J E, Helfand D J, Krivonos R, Meier D L, Miller J M, Natalucci L, Ogle P, Ofek E O, Ptak A, Reynolds S P, Rigby J R, Tagliaferri G, Thorsett S E, Treister E and Urry C M 2013 *ApJ* **770** 103 (*Preprint* 1301.7307)

[20] Dupraz C, Bloemen H, Bennett K, Diehl R, Hermsen W, Iyudin A F, Ryan J and Schoenfelder V 1997 *A&A* **324** 683–689

[21] Iyudin A F, Schönfelder V, Bennett K, Bloemen H, Diehl R, Hermsen W, Knödlseder J, Lichti G G, Oberlack U, Ryan J, Strong A W and Winkler C 1999 *Astrophysical Letters Communications* **38** 383–+

[22] Renaud M, Vink J, Decourchelle A, Lebrun F, Terrier R and Ballet J 2006 *New Astronomy Review* **50** 540–543 (*Preprint* arXiv:astro-ph/0602304)

[23] Aschenbach B 1998 *Nature* **396** 141–142

[24] Schönfelder V, Bloemen H, Collmar W, Diehl R, Hermsen W, Knödlseder J, Lichti G G, Plüschke S, Ryan J, Strong A and Winkler C 2000 *American Institute of Physics Conference Series* (*American Institute of Physics Conference Series* vol 510) ed McConnell M L and Ryan J M pp 54–+

[25] Borkowski K J, Reynolds S P, Hwang U, Green D A, Petre R, Krishnamurthy K and Willett R 2013 *ApJ* **771** L9 (*Preprint* 1305.7399)

[26] Grebenev S A, Lutovinov A A, Tsygankov S and Winkler C 2012 *Nature* **(tbd)** (accepted for publication)

[27] Diehl R, Dupraz C, Bennett K, Bloemen H, Hermsen W, Knoedlseder J, Lichti G, Morris D, Ryan J, Schoenfelder V, Steinle H, Strong A, Swanenburg B, Varendorff M and Winkler C 1995 *A&A* **298** 445–+

[28] Smith D M 2004 *5th INTEGRAL Workshop on the INTEGRAL Universe* (*ESA Special Publication* vol 552) ed Schoenfelder V, Lichti G and Winkler C pp 45–+

[29] Harris M J, Knödlseder J, Jean P, Cisana E, Diehl R, Lichti G G, Roques J P, Schanne S and Weidenspointner G 2005 *A&A* **433** L49–L52 (*Preprint* arXiv:astro-ph/0502219)

[30] Wang W, Harris M J, Diehl R, Halloin H, Cordier B, Strong A W, Kretschmer K, Knödlseder J, Jean P, Lichti G G, Roques J P, Schanne S, von Kienlin A, Weidenspointner G and Wunderer C 2007 *A&A* **469** 1005–1012 (*Preprint* 0704.3895)

[31] MacPherson G J, Davis A M and Zinner E K 1995 *Meteoritics* **30** 365–+

[32] Mishra R, Chaussidon M and Marhas K 2012 *Nuclei in the Cosmos (NIC XII)*

[33] Asplund M, Grevesse N, Sauval A J and Scott P 2009 *ARA&A* **47** 481–522 (*Preprint* 0909.0948)

[34] Lodders K 2003 *ApJ* **591** 1220–1247

[35] Robin A C, Reylé C, Derrière S and Picaud S 2003 *A&A* **409** 523–540 (*Preprint* arXiv:astro-ph/0401052)

[36] Vasileiadis A, Nordlund Å and Bizzarro M 2013 *ApJ* **769** L8 (*Preprint* 1302.0843)