FOCUSING TELESCOPES IN NUCLEAR ASTROPHYSICS

Edited by:

PETER VON BALLMOOS

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Over the last decade, a small but growing community has been pursuing various techniques for the focusing of hard X-rays and gamma-rays. The workshop *Focusing Telescopes in Nuclear Astrophysics* provided a first opportunity for this young “gamma-wave” community to meet, exchange technological know-how, and discuss scientific objectives and synergies. The workshop took place in Bonifacio, Corsica, September 12–15, 2005. It brought together sixty participants with different horizons, and with competence in a wide range of disciplines—but with the common interest in finding alternative instrumental approaches for use in nuclear astrophysics.

Participants from the high energy astrophysics community emphasized the extraordinary scientific potential of nuclear astrophysics for the study of the most powerful sources and the most violent events in the Universe. Their contributions are collected in the first part of this volume and discuss science objectives on all levels: neutron stars, X-ray binaries, pulsars, novae, supernovae, AGN, blazars, cosmology... but also our sun! In order to achieve the ambitious scientific goals, experimental gamma-ray astronomy must find new ways to improve the performance of its instruments, with better sensitivity being unquestionably the foremost requirement.

In the second part of this volume, the evolving “gamma-wave” community examines the options for focusing optics for hard-X and soft gamma rays. A few years back, there was no way to focus gamma-rays; today we have many: grazing incident mirrors and multilayer coatings, Laue- and Fresnel-lenses; even an optic using the curvature of space-time is proposed. In more than twenty articles various aspects of the techniques are discussed, from the theoretical basis to the ambitious mission concepts for future space observatories. A particular emphasis is on the progress in R&D for the various techniques, on results from prototypes and on first results obtained from stratospheric balloon flights.

The goal of improving instrument sensitivities by up to two orders of magnitude which is the main incentive for developing focusing telescopes, also drives the development of new detector technologies. One of the focal points of the workshop was the consideration
of detectors matching the ambitious objectives of gamma ray optics and their capability of taking maximum advantage of the concentrated signal flux. In the third part of this volume, a number of innovative detector concepts for focusing telescopes are discussed. Besides offering high detection efficiencies, these focal plane instruments will provide imaging capabilities, perform high resolution spectroscopy and measure the polarization of the incident photons.

The deflection of photons in focusing X/$\gamma$-ray optics is only by small angles. As a consequence, telescope systems have long focal lengths and require a new class of flight systems and ground facilities. Part four of this volume is dedicated to the associated challenges. Facilities for testing hard X-ray focusing telescopes on the ground and techniques for testing using stratospheric balloons are presented. The space missions that seem best adapted for X/$\gamma$-ray optics involve “formation flying” of two spacecraft. Photons are collected by an optics spacecraft and are focused onto a separate detector spacecraft. Formation flying missions present a number of complex challenges for spacecraft engineering which are discussed in this volume.

Eleven years have past since the workshop on imaging in high energy astronomy in Capri (1994), which itself followed by the same interval a similar meeting in Southampton (1983). Eleven years is also roughly the time separating launches of successive major space missions in nuclear astrophysics – HEAO-3 (1979), GRO (1991) and then INTEGRAL (2002). One of the foremost objectives of the Gamma Wave 05 workshop was to consider the next generation of instrumentation required for nuclear astrophysics and consider implementation approaches within National and European Space Science programs. In sunny Bonifacio the Gamma-Wave community expressed their wish that the eleven year cycle continue with the launch of a major focusing X/$\gamma$-ray mission on a 2013 horizon.

On behalf of the local and scientific organizing committees, we acknowledge the generous contributions of ESA, CNES, ASTRIUM and ALCATEL, which allowed the organisation of the workshop and the publication of the present volume.

We thank Dolores Granat, Eric Deleage and Nicolas Barrière for their tireless effort behind the scenes to ensure the success of this workshop. Many thanks to Gerry Skinner, who has attempted to provide a scientific conscience for the present volume, and to Sylvia Iviglia from Springer for shepherding its completion.

Finally, we thank the participants of the Gamma-Wave 05 workshop for their dedication to this project, and look forward to the exciting promise of the next phase of nuclear astrophysics instrumentation.

Toulouse, July 2006
PvB
Prospects in space-based gamma-ray astronomy

J. Knödlseder

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Abstract Observations of the gamma-ray sky reveal the most powerful sources and the most violent events in the Universe. While at lower wavebands the observed emission is generally dominated by thermal processes, the gamma-ray sky provides us with a view on the non-thermal Universe. Here particles are accelerated to extreme relativistic energies by mechanisms which are still poorly understood, and nuclear reactions are synthesizing the basic constituents of our world. Cosmic accelerators and cosmic explosions are the major science themes that are addressed in the gamma-ray regime.

With the INTEGRAL observatory, ESA has provided a unique tool to the astronomical community revealing hundreds of sources, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. While INTEGRAL provides the global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investigations of gamma-ray sources. In soft X-rays a comparable step was taken going from the Einstein and the EXOSAT satellites to the Chandra and XMM/Newton observatories. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction and multilayer-coated mirror techniques have paved the way towards a gamma-ray mission, providing major improvements compared to past missions regarding sensitivity and angular resolution. Such a future Gamma-Ray Imager will allow to study particle acceleration processes and explosion physics in unprecedented detail, providing essential clues on the innermost nature of the most violent and most energetic processes in the Universe.

Keywords Gamma-ray astronomy astronomy · Cosmic accelerators · Cosmic explosions

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1. Why gamma-ray astronomy?

As introductory remark, it is worth emphasising some unique features of gamma-ray astronomy: the specific character of the emission processes, the diversity of the emission sites, and the penetrating nature of the emission.

First, the emission process that leads to gamma-rays is in general very specific, and as such, is rarely observable in other wavebands. At gamma-ray energies, cosmic acceleration processes are dominant, while in the other wavebands thermal processes are generally at the origin of the emission. For example, electrons accelerated to relativistic energies radiate gamma-ray photons of all energies through electromagnetic interactions with nuclei, photons, or intense magnetic fields. Accelerated protons generate secondary particles through nuclear interactions, which may decay by emission of high-energy gamma-ray photons. At gamma-ray energies, nuclear deexcitations lead to a manifold of line features, while in the other wavebands, it is the bound electrons that lead to atomic or molecular transition lines. For example, the radioactive decay of tracer isotopes allows the study of nucleosynthesis processes that occur in the deep inner layers of stars. The interaction of high-energy nuclei with the gas of the interstellar medium produces a wealth of excitation lines that probe the composition and energy spectrum of the interacting particles. Finally, annihilation between electrons and positrons result in a unique signature at 511 keV that allows the study of antimatter in the Universe.

Second, the sites of gamma-ray emission in the Universe are very diverse, and reach from the nearby Sun up to the distant Gamma-Ray Bursts and the cosmic gamma-ray background radiation. Cosmic acceleration takes place on all scales: locally in solar flares, within our Galaxy (e.g. in compact binaries, pulsars, supernova remnants), and also in distant objects (such as active galactic nuclei or gamma-ray bursts). Cosmic explosions are another site of prominent gamma-ray emission. They produce a wealth of radioactive isotopes, are potential sources of antimatter, and accelerate particles to relativistic energies. Novae, supernovae and hypernovae are thus prime targets of gamma-ray astronomy.

Third, gamma-rays are highly penetrating, allowing the study of otherwise obscured regions. Examples are regions of the galactic disk hidden by dense interstellar clouds, or the deeper, inner, zones of some celestial bodies, where the most fundamental emission processes are at work. New classes of sources become visible in the gamma-ray domain, that are invisible otherwise.

In summary, gamma-ray astronomy provides a unique view of our Universe. It unveils specific emission processes, a large diversity of emission sites, and probes deeply into the otherwise obscured high-energy engines of our Universe. The gamma-ray Universe is the Universe of particle acceleration and nuclear physics, of cosmic explosions and non-thermal phenomena. Exploring the gamma-ray sky means exploring this unique face of our world, the face of the evolving violent Universe.

2. Cosmic accelerators

2.1. The link between accretion and ejection

As a general rule, accretion in astrophysical systems is often accompanied by mass outflows, which in the high-energy domain take the form of (highly) relativistic jets. Accreting objects are therefore powerful particle accelerators, that can manifest on the galactic scale as...
microquasars, or on the cosmological scale, as active galactic nuclei, such as Seyfert galaxies and Blazars.

Although the phenomenon is relatively widespread, the jet formation process is still poorly understood. It is still unclear how the energy reservoir of an accreting system is transformed in an outflow of relativistic particles. Jets are not always persistent but often transient phenomena, and it is still not known what triggers the sporadic outbursts in accreting systems. Also, the collimation of the jets is poorly understood, and in general, the composition of the accelerated particle plasma is not known (electron-ion plasma, electron-positron pair plasma). Finally, the radiation processes that occur in jets are not well established.

Observations in the gamma-ray domain are able to provide a number of clues to these questions. Gamma-rays probe the innermost regions of the accreting systems that are not accessible in other wavebands, providing the closest view to the accelerating engine. Time variability and polarisation studies provide important insights into the physical processes and the geometry that govern the acceleration site. The accelerated plasma may reveal its nature through characteristic nuclear and/or annihilation line features which may help to settle the question about the nature of the accelerated plasma.

2.2. The origin of galactic soft γ-ray emission

Since decades, the nature of the galactic hard X-ray (>15 keV) emission has been one of the most challenging mysteries in the field. The INTEGRAL imager IBIS has now finally solved this puzzle. At least 90% of the emission has been resolved into point sources, settling the debate about the origin of the emission (Lebrun et al., 2004) (c.f. Figure 1).

At higher energies, say above ~300 keV, the situation is less clear. In this domain, only a small fraction of the galactic emission has so far been resolved into point sources, and the nature of the bulk of the galactic emission is so far unexplained. That a new kind of object or emission mechanism should be at work in this domain is already suggested by the change of the slope of the galactic emission spectrum. While below ~300 keV the spectrum can be explained by a superposition of Comptonisation spectra from individual point sources, the spectrum turns into a powerlaw above this energy, which is reminiscent of
particle acceleration processes. Identifying the source of this particle acceleration process, i.e. identifying the origin of the galactic soft gamma-ray emission, is one of the major goals of a future European gamma-ray mission.

One of the strategies to resolve this puzzle is to follow the successful road shown by INTEGRAL for the hard X-ray emission: trying to resolve the emission into individual point sources. Indeed, a number of galactic sources show powerlaw spectra in the gamma-ray band, such as supernova remnants, like the Crab nebula, or some of the black-hole binary systems, like Cyg X-1 (Mc Connell et al., 2000). Searching for the hard powerlaw emission tails in these objects is therefore a key objective for a future gamma-ray mission.

2.3. The origin of the soft $\gamma$-ray background

After the achievements of XMM-Newton and Chandra, the origin of the cosmic X-ray background (CXB) is now basically solved for energies close to a few keV. However, whilst the CXB is $\sim$85% and 80% resolved in the 0.5–2 keV and 2–10 keV bands, respectively, it is only $\sim$50% resolved above $\sim$8 keV (Worsley et al., 2005). The situation is even worse in the hard X-ray and soft gamma-ray bands. Although about 20% of the sources detected in the second IBIS catalogue are of extragalactic nature (Bassani et al., 2006) they only account for $\sim$1% of the background emission seen in the 20–100 keV band, i.e. where the bulk of the energy density is found.

Looking from another point of view, synthesis models, which are well established and tested against observational results, can be used to evaluate the integrated AGN contribution to the soft $\gamma$-ray background. Unfortunately, they lack some key information at high energies: the absorption distribution is currently biased against low column densities due to the lack of soft gamma-ray surveys, no AGN luminosity function is available above 10 keV nor has the input spectral shape of the different classes of AGN been firmly established at high energies. Furthermore, the integrated AGN contribution changes as a function of model input parameters. As an illustration, Figure 2 shows how different results can be obtained.

**Fig. 2** The 0.25–400 keV cosmic X-/\gamma−ray background spectrum fitted with synthesis models (Comastri, 2004). None of the models provides a satisfactory fit of the observations.

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by varying the power law energy cut-off. A large region of this parameter space is virtually unexplored because we currently lack information on large AGN samples. Observations by BeppoSAX (Risaliti, 2002; Perola et al., 2002) of a handful of radio quiet sources, loosely locate this drop-off in the range 30–300 keV; furthermore these measurements give evidence for a variable cut-off energy and suggest that it may increase with increasing photon index (Perola et al., 2002). In radio loud sources the situation is even more complicated with some objects showing a power law break and others no cut-off up to the MeV region. In a couple of low luminosity AGN no cut-off is present up to 300–500 keV. The overall picture suggests some link with the absence (low energy cut-off) or presence (high energy cut-off) of jets in the various AGN types sampled, but the data are still too scarce for a good understanding of the processes involved. One method to tackle this issue is to measure the soft gamma-ray Spectra Energy Distribution (SED, which includes a power law continuum plus high energy cut-off as well as hard tails if present) in a sizeable fraction of AGN in order to determine average shapes in individual classes and so the nature of the radiation processes at the heart of all AGN. This would provide at the same time information for soft $\gamma$-ray background synthesis models. On the other hand, sensitive deep field observations should be able to resolve the soft $\gamma$-ray background into individual sources, allowing for the ultimate identification of the origin of the emission.

2.4. Particle acceleration in extreme B-fields

The strong magnetic fields that occur at the surface of neutron stars in combination with their fast rotation make them to powerful electrodynamic particle accelerators, which may manifest as pulsars to the observer. Gamma-ray emitting pulsars can be divided into 3 classes: spin-down powered pulsars, such as normal or millisecond pulsars, accretion powered pulsars, occurring in low-mass or high-mass binary systems, and magnetically powered pulsars, known as magnetars.

Despite the longstanding efforts in understanding the physics of spin-down powered pulsars, the site of the gamma-ray production within the magnetosphere (outer gap or polar cap) and the physical process at action (synchrotron emission, curvature radiation, inverse Compton scattering) remain undetermined. Although most of the pulsars are expected to reach their maximum luminosity in the MeV domain, the relatively weak photon fluxes have only allowed the study of a handful of objects so far. Increasing the statistics will allow the study of the pulsar lightcurves over a much broader energy range than today, providing crucial clues on the acceleration physics of these objects.

Before the launch of INTEGRAL, the class of anomalous X-ray pulsars (AXPs), suggested to form a sub-class of the magnetar population, were believed to exhibit very soft X-ray spectra. This picture, however, changed dramatically with the detection of AXPs in the soft gamma-ray band by INTEGRAL (Kuiper et al., 2004). In fact, above $\sim 10$ keV a dramatic upturn is observed in the spectra which is expected to cumulate in the 100 keV – 1 MeV domain. The same is true for Soft Gamma-ray Repeaters (SGRs), as illustrated by the recent discovery of quiescent soft gamma-ray emission from SGR 1806-20 by INTEGRAL (Molkov et al., 2005) (c.f. Figure 3). The process that gives rise to the observed gamma-ray emission in still unknown. No high-energy cut-off has so far been observed in the spectra, yet upper limits in the MeV domain indicate that such a cut-off should be present. Determining this cut-off may provide important insights in the physical nature of the emission process, and in particular, about the role of QED effects, such as photon splitting, in the extreme magnetic field that
occur in such objects. Strong polarisation is expected for the high-energy emission from these exotic objects, and polarisation measurements may reveal crucial to disentangle the nature of the emission process and the geometry of the emitting region. Complementary measurements of cyclotron features in the spectra provide the most direct measure of the magnetic field strengths, complementing our knowledge of the physical parameters of the systems.

3. Cosmic explosions

3.1. Understanding type Ia supernovae

Although hundreds of Type Ia supernovae are observed each year, and although their optical lightcurves and spectra are studied in great detail, the intimate nature of these events is still unknown. Following common wisdom, Type Ia supernovae are believed to arise in binary systems where matter is accreted from a normal star onto a white dwarf. Once the white dwarf exceeds the Chandrasekhar mass limit a thermonuclear runaway occurs that leads to its incineration and disruption. However, attempts to model the accretion process have so far failed to allow for sufficient mass accretion that would push the white dwarf over its stability limit (Hillebrandt and Niemeyer, 2000). Even worse, there is no firm clue that Type Ia progenitors are indeed binary systems composed of a white dwarf and a normal star. Alternatively, the merging of two white dwarfs in a close binary system could also explain the observable...
features of Type Ia events (Livio and Riess, 2003). Finally, the explosion mechanism of the white dwarf is only poorly understood, principally due to the impossibility to reliably model the nuclear flame propagation in such objects (Hillebrandt and Niemeyer, 2000).

In view of all these uncertainties it seems more than surprising that Type Ia are widely considered as standard candles. In particular, it is this standard candle hypothesis that is the basis of one of the fundamental discoveries of the last decade: that the expansion of the Universe is currently accelerating (Riess et al., 1998). Although empirical corrections to the observed optical lightcurves seem to allow for some kind of standardisation, there is increasing evidence that Type Ia supernovae are not an homogeneous class of objects (Mannucci et al., 2005).

Gamma-ray observation of Type Ia supernovae provide a new and unique view of these events. Nucleosynthetic products of the thermonuclear runaway lead to a rich spectrum of gamma-ray line and continuum emission that contains a wealth of information on the progenitor system, the explosion mechanism, the system configuration, and its evolution (c.f. Figure 4). In particular, the radioactive decays of $^{56}\text{Ni}$ and $^{56}\text{Co}$, which power the optical lightcurve which is so crucial for the cosmological interpretation of distant Type Ia events, can be directly observed in the gamma-ray domain, allowing to pinpoint the underlying progenitor and explosion scenario. The comparison of the gamma-ray to the optical lightcurve will provide direct information about energy recycling in the supernova envelope that will allow a physical (and not only empirical) calibration of Type Ia events as standard candles.

In addition to line intensities and lightcurves, the shapes of the gamma-ray lines hold important information about the explosion dynamics and the matter stratification in the system. Measuring the line shapes (and their time evolution) will allow to distinguish between
the different explosion scenarios, ultimately revealing the mechanism that creates these most violent events in the Universe (Gomez-Gomar et al., 1998).

3.2. Understanding core-collapse explosions

Gamma-ray line and continuum observations address some of the most fundamental questions of core-collapse supernovae: how and where the large neutrino fluxes couple to the stellar ejecta; how asymmetric the explosions are, including whether jets form; and what and where are quantitative nucleosynthesis yields from both static and explosive burning processes?

The ejected mass of $^{44}\text{Ti}$, which is produced in the innermost ejecta and fallback matter that experiences the alpha-rich freezeout of nuclear statistical equilibrium, can be measured to a precision of several percent in SN 1987A. Along with other isotopic yields already known, this will provide an unprecedented constraint on models of that event. $^{44}\text{Ti}$ can also be measured and mapped, in angle and radial velocity, in several historical galactic supernova remnants. These measurements will help clarify the ejection dynamics, including how common jets initiated by the core collapse are.

Wide-field gamma-ray instruments have shown the global diffuse emission from long-lived isotopes $^{26}\text{Al}$ and $^{60}\text{Fe}$, illustrating clearly ongoing galactic nucleosynthesis. A necessary complement to these are high-sensitivity measurements of the yields of these isotopes from individual supernovae. A future European gamma-ray mission should determine these yields, and map the line emission across several nearby supernova remnants, shedding further light on the ejection dynamics. It is also likely that the nucleosynthesis of these isotopes in hydrostatic burning phases will be revealed by observations of individual nearby massive stars with high mass-loss rates.

For rare nearby supernovae, within a few Mpc, we will be given a glimpse of nucleosynthesis and dynamics from short-lived isotopes $^{56}\text{Ni}$ and $^{57}\text{Ni}$, as was the case for SN 1987A in the LMC. In that event we saw that a few percent of the core radioactivity was somehow transported to low-optical depth regions, perhaps surprising mostly receding from us, but there could be quite some variety, especially if jets or other extensive mixing mechanisms are ubiquitous.

3.3. Unveiling the origin of galactic positrons

The unprecedented imaging and spectroscopy capabilities of the spectrometer SPI aboard INTEGRAL have now provided for the first time an image of the distribution of 511 keV electron positron annihilation all over the sky (Knödlseder et al., 2005) (c.f. Figure 5). The outcome of this survey is astonishing: 511 keV line emission is only seen towards the bulge region of our Galaxy, while the rest of the sky remains surprisingly dark. Only a weak glim of 511 keV emission is perceptible from the disk of the Galaxy, much less than expected from stellar populations following the global mass distribution of the Galaxy. In other words, positron annihilation seems to be greatly enhanced in the bulge with respect to the disk of the Galaxy.

A detailed analysis of the 511 keV line shape measured by SPI has also provided interesting insights into the annihilation physics (Churazov et al., 2005). At least two components have been identified, indicating that positron annihilation takes place in a partially ionised medium. This clearly demonstrated that precise 511 keV line shape measurements provide important insights into the distribution of the various phases of the interstellar medium (ISM).

While INTEGRAL has set the global picture of galactic positron annihilation, high angular resolution mapping of the galactic bulge region is required to shed light on the still
mysterious source of positrons. So far, no individual source of positron emission could have been identified, primarily due to the expected low levels of 511 keV line fluxes. An instrument with sufficiently good sensitivity and angular resolution should be able to pinpoint the origin of the positrons, by providing detailed maps of the central bulge region of the Galaxy. With additional fine spectroscopic capabilities, comparable to that achieved by the germanium detectors onboard the SPI telescope, the spatial variations of the 511 keV line shape will allow to draw an unprecedented picture of the distribution of the various ISM phases in the inner regions of our Galaxy.

Thus, with the next generation gamma-ray telescope, galactic positrons will be exploited as a messenger from the mysterious antimatter source in the Milky-Way, as well as a tracer to probe the conditions of the ISM that are difficultly to measure by other means.

4. Mission requirements

The major mission requirement for the future European gamma-ray mission is sensitivity. Many interesting scientific questions are in a domain where photons are rare (say $10^{-7}$ ph cm$^{-2}$s$^{-1}$), and therefore large collecting areas are needed to perform measurements in a reasonable amount of time. It is clear that a significant sensitivity leap is required, say 50–100 times more sensitive than current instruments, if the above listed scientific questions should be addressed.

With such a sensitivity leap, the expected number of observable sources would be large, implying the need for good angular resolution to avoid source confusion in crowded regions, such as for example the galactic centre. Also, it is desirable to have an angular resolution comparable to that at other wavebands, to allow for source identification and hence multiwavelength studies.

As mentioned previously, gamma-ray emission may be substantially polarised due to the non-thermal nature of the underlying emission processes. Studying not only the intensity but also the polarisation of the emission would add a new powerful scientific dimension to the observations. Such measurements would allow to discriminate between the different plausible emission processes at work, and would allow to constrain the geometry of the emission sites.

Taking all these considerations into account, the following mission requirements derive (c.f. Table 1). The energy band should cover the soft gamma-ray band, with coverage down
Table 1  Mission requirements for the future European gamma-ray mission (sensitivities are for $10^6$ seconds at 3$\sigma$ detection significance)

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<th>Parameter</th>
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<tr>
<td>Energy band</td>
<td>50 keV – 2 MeV</td>
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<tr>
<td>Continuum sensitivity</td>
<td>$10^{-8}$ ph cm$^{-2}$s$^{-1}$keV$^{-1}$</td>
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<tr>
<td>Narrow line sensitivity</td>
<td>$5 \times 10^{-7}$ ph cm$^{-2}$s$^{-1}$</td>
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<tr>
<td>Energy resolution</td>
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<tr>
<td>Field of view</td>
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<td>Angular resolution</td>
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to the hard X-ray band (to overlap with future X-ray observatories), and coverage of the major gamma-ray lines of astrophysical interest. A real sensitivity leap should be achieved, typical by a factor of 50–100 with respect to existing gamma-ray instrumentation. For high-resolution gamma-ray line spectroscopy a good energy resolution is desirable to exploit the full potential of line profile studies. A reasonably sized field-of-view together with arcmin angular resolution should allow the imaging of field populations of gamma-ray sources in a single observation. Finally, good polarisation capabilities, at the percent level for strong sources, are required to exploit this additional observable.

Can these mission requirements be reached within the 2015–2025 time frame? We are convinced that the answer is yes. How can these mission requirements be reached? We think that the best solution is the implementation of a broad-band gamma-ray lens telescope based on the principle of Laue diffraction of gamma-rays in mosaic crystals (Von Ballmoos et al., 2004; Halloin et al., 2004; De Chiara et al., 2000). The Laue lens may eventually be complemented by a coded mask telescope or a multilayer-coated mirror telescope in order to achieve the hard X-ray coverage. The focal length of such a system would lie between a few tens and a few hundreds metres, requiring the technology of satellite formation flying. We note that such a gamma-ray lens telescope is currently under study at the French space agency CNES (project MAX (Von Ballmoos et al., 2004)) and at the ESA Science Payload & Advanced Concepts Office (project Gamma-Ray Lens), which both confirm the feasibility of such a scenario. We therefore believe that a gamma-ray lens telescope in formation flight configuration provides the most promising instrumental concept allowing advances in the field of space-based gamma-ray astronomy. The precise design of the gamma-ray lens telescope is currently under discussion (see http://gri.rm.iasf.cnr.it/).

The artists view in Figure 6 gives an idea how the future Gamma-Ray Imager mission may look like. In this example, the lens spacecraft is composed of concentric rings of crystals, where each ring is focusing a specific narrow energy band on the (same) focal spot on the...

**Fig. 6** Artists view of the Gamma-Ray Imager. A Laue lens, situated on the left spacecraft, is focusing gamma-rays onto a small detector, situated on the right spacecraft. Both spacecrafts are in formation flight with a typical focal length between a few tens and a few hundreds metres.
detector spacecraft. Higher energies show smaller diffraction angles and therefore are situated closer to the optical axis (inner rings). Conversely, lower energies show larger diffraction angles and therefore are situated on the outer rings. The lowest energies may require radial distances from the optical axis that exceed the available space in launcher fairings, therefore deployable lens petals may eventually be employed.

5. Conclusions

The gamma-ray band presents a unique astronomical window that allows the study of the most energetic and most violent phenomena in our Universe. With ESA's INTEGRAL observatory, an unprecedented global survey of the soft gamma-ray sky is currently performed, revealing hundreds of sources of different kinds, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. While INTEGRAL provides the longly awaited global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investigations of gamma-ray sources, comparable to the step that has been taken in X-rays by going from the EINSTEIN satellite to the more focused XMM-Newton observatory. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction techniques have paved the way towards a future European gamma-ray mission, that will outreach past missions by large factors in sensitivity and angular resolution. Such a future Gamma-Ray Imager will allow to study particle acceleration processes and explosion physics in unprecedented depth, providing essential clues on the intimate nature of the most violent and most energetic processes in the Universe.

References

Annihilation of positrons in the Galaxy

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Abstract Observations of electron-positron annihilation radiation from the Galactic Center region with the SPI instrument aboard INTEGRAL are summarized. The measured width of the 511 keV line and inferred fraction of positrons annihilating through positronium formation are consistent with the annihilation taking place in the warm ISM phase, although combinations of several ISM phases are also allowed by the data. The spatial distribution of 511 keV emission suggests that positron sources are concentrated toward the Galactic bulge and avoid the Galactic disk.

Keywords Galaxy: Center · Gamma rays: Observations · ISM: General

1. Introduction

The electron–positron annihilation line at 511 keV is the brightest line in the electromagnetic spectrum of the Galaxy at energies above 10 keV. It was discovered during balloon flights more than 30 years ago as emission at roughly $\sim476$ keV from the general direction of the Galactic Center (GC) [6], and later clearly identified as a narrow $e^- - e^+$ annihilation line at 511 keV in observations by high-resolution germanium detectors [8]. Although the Galactic annihilation radiation has since then been observed by many experiments, its origin remains unclear. Several mechanisms of positron production have been proposed, including:

– Radioactive $\beta^+$ decay of unstable isotopes, e.g. $^{26}$Al or $^{56}$Co, produced in supernovae or novae
– Decay of $\pi^+$ mesons produced by interaction of cosmic rays with the ISM
Generation of $e^- - e^+$ pairs by interaction of high-energy photons or in strong magnetic fields near black holes or radiopulsars

Annihilation of dark matter particles

Although not complete, this list demonstrates the very broad range of possible mechanisms, from widely accepted (nucleosynthesis in supernovae) to more exotic (dark matter annihilation). To find out the origin of the Galactic annihilation radiation it is crucial to (a) compare its spatial distribution with that of possible positron sources and (b) obtain constraints on the properties of the annihilation medium from the observed annihilation spectrum. The INTEGRAL observatory with its high-resolution spectrometer SPI is designed to pursue these goals.

2. Observations and data analysis

INTEGRAL is the ESA’s project with participation of Russia and the USA. The SPI instrument (Vedrenne et al., 2003) consists of 19 Ge crystals, providing energy resolution $\sim 2$ keV near 511 keV. A 3-cm thick tungsten coded mask located 1.7 m above the detector modulates the incoming flux. The field of view is $\sim 16^\circ$-radius. We analyzed observations from February–November 2003, with a total exposure of 3.9 Ms [2].

The absolute energy scale was for each observation calibrated to better than 10 eV near 511 keV using a set of background lines (\(^{71}\)Ge at 198.4 keV, \(^{69}\)Zn at 438.6 keV, \(^{68}\)Ge at 584.5 keV, and \(^{69}\)Ge at 882.5 keV). The energy resolution at 511 keV was found to be 2.1 keV (FWHM) by interpolating the observed widths of two bracketing lines, 438.6 keV and 584.5 keV.

Since the instrument background contribution to the 511 keV line exceeds the useful signal from the GC region by 50–100 times, it is necessary to predict the background to better than 1 percent accuracy. To construct a model of background spectrum we used observations of the sky $> 30^\circ$ away from the GC, with a total exposure of 3.7 Ms.

2.1. Galaxy map in the 511 keV line

Figure 1 shows the surface brightness map of the Galaxy in the 511 keV line. By construction, only large-scale structure exceeding the size of the instrument’s FOV has been retained on this map, while any small-scale structure is strongly suppressed. Nevertheless, the global pattern of annihilation radiation is evident: the central region of the Galaxy is a powerful source of 511 keV radiation, while there is no statistically significant annihilation signal outside this region.

One can obtain better constraints on the surface brightness distribution by specifying a model distribution with several free parameters, convolving it with the angular response of the instrument, and comparing the outcome with the measured distribution. In the simplest model, the surface brightness is described by a two-dimensional Gaussian around the GC. A more flexible model includes a constant component. The best agreement with the data is achieved for a Gaussian with FWHM $= 6^\circ$. The inferred flux is $\sim 7.6 \times 10^{-4}$ phot/s/cm$^2$ and $\sim 10^{-3}$ phot/s/cm$^2$ for the model with and without a constant component, respectively. This flux difference indicates that the true spatial distribution may be more complex than assumed in these simple models. Using more complicated models [7, 10] of 511 keV surface brightness distribution, in particular including components associated with the Galactic disk and bulge, leads to qualitatively the same results – the flux of the central component ($\sim 10^{-3}$ phot/s/cm$^2$) is much higher than that of the disk one, unless the disk thickness exceeds a few ten degrees.
2.2. Annihilation spectrum

Figure 2 shows the measured spectrum near 511 keV. It is well fit by a model consisting of a Gaussian line and a 3-photon (ortho-positronium) annihilation continuum. The flux ratio of these components yields the fraction of annihilations proceeding through positronium formation:

$$F_{PS} = \frac{2}{1.5 + 2.25(F_{2\gamma}/F_{3\gamma})},$$

where $F_{2\gamma}$ and $F_{3\gamma}$ are the flux in the line and in the 3-photon continuum, respectively. This expression accounts for the fact that ortho- and parapositronium are produced in 3:1 proportion and generate 3 and 2 photons, respectively. Table 1 summarized the results of our spectral analysis.

3. Constraints on the ISM parameters

The two measured quantities, the line width and the flux ratio of the line and 3-photon continuum, place constraints on the temperature and ionization degree of the annihilation.

Table 1  Best-fit parameters of the annihilation spectrum in the energy range 450–550 keV. The quoted uncertainties are 1σ for a single parameter of interest. Adapted from [2]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$, keV</td>
<td>510.954 [510.88–511.03]</td>
</tr>
<tr>
<td>FWHM, keV</td>
<td>2.37 [2.12–2.62]</td>
</tr>
<tr>
<td>$F_{2\gamma} 10^{-4}$ phot s$^{-1}$ cm$^{-2}$</td>
<td>7.16 ± 0.36</td>
</tr>
<tr>
<td>$F_{3\gamma} 10^{-4}$ phot s$^{-1}$ cm$^{-2}$</td>
<td>26.1 ± 5.7</td>
</tr>
<tr>
<td>$F_{3\gamma}/F_{2\gamma}$</td>
<td>3.65 ± 0.82</td>
</tr>
<tr>
<td>$F_{PS}$</td>
<td>0.94 ± 0.06</td>
</tr>
<tr>
<td>$\chi^2$ (d.o.f.)</td>
<td>192.7 (193)</td>
</tr>
</tbody>
</table>
medium. Using a Monte-Carlo code we simulated the formation of the annihilation spectrum in a pure hydrogen, dust-free plasma. The positrons are assumed to be born hot (with an energy higher than several hundred keV), then decelerate due to Coulomb losses in an ionized plasma or due to photoionization and atom excitation in a neutral gas, and eventually thermalize with the ambient medium. After the positron energy falls below several eV, charge exchange with neutral atoms, radiative recombination or direct annihilation with free or bound electrons occurs [1].

The predicted annihilation line has a non-Gaussian shape and contains a broad and a narrow components. In Figure 3 the effective line width and positronium fraction are shown as functions of temperature and ionization degree. These theoretical curves are compared with the constraints on the effective line width and positronium fraction provided by INTEGRAL observations. There are two families of theoretical curves.

One regime corresponds to a gas with temperature below $\sim 6,000$ K. In a cold and neutral medium about 94\% of positrons form positronium in flight. The remaining 6\% fall below the threshold for positronium formation (6.8 eV) and then annihilate with bound electrons, forming a narrow line ($\text{FWHM} = 1.7$ keV, [4]. The effective width of the line arising from in-flight annihilation through positronium formation is 5.3 keV, and that of the net line (sum of the broad and narrow components) is $\sim 4.6$ keV. If the ionization degree exceeds $\sim 10^{-3}$, Coulomb losses start to play an important role, decreasing the fraction of positrons forming positronium in flight. For positrons falling below 6.8 eV, three processes are important: radiative recombination with free electrons and annihilation with free and bound electrons. For an ionization degree $\sim 10^{-2}$ and temeperatures $\sim 1,000$ K, annihilation with bound electrons leads to a decrease of the net positronium fraction to 80–90 percent. If the ionization degree exceeds several per cent, only radiative recombination and annihilation with free electrons occurs.

![Galactic Center $e^+e^-$ line](image)

**Fig. 2** Spectrum of the GC annihilation radiation measured by INTEGRAL/SPI. The curves show the contributions of the 511 keV line and 3-photon continuum (not convolved with the energy response of the instrument)
are important, and both the positronium fraction and line width approach the values expected for a fully ionized plasma.

The second family of curves corresponds to temperatures above 7,000 K. In this regime, thermalized positrons can form positronium by charge exchange with hydrogen atoms. This process dominates over radiative recombination and direct annihilation if the plasma is not strongly ionized. The positronium fraction approaches unity. Only for a significantly ionized plasma (\(\sim 6–10\) percent) at \(T \geq 8,000\) K does annihilation with free electrons become important and the positronium fraction decreases with increasing ionization degree.

According to the standard model [9] there are several abundant ISM phases: hot (\(T >\) a few \(10^5\) K) ionized, warm (\(T \sim 8,000\) K), and cold (\(T < 100\) K) neutral. It is clear from Figure 3 that the hot phase cannot provide a dominant contribution to the observed annihilation spectrum, since the width of the line would be too large (e.g. \(\sim 11\) keV for \(T = 10^6\) K, Cranell et al., 1976) while the positronium fraction too low.

A similar conclusion can be drawn with respect to the cold, neutral ISM phase. In this case, the expected positronium fraction is consistent with the observed one but the expected line width (\(\sim 4.5\) keV) is too large. The line width can be reduced by raising the ionization degree above \(10^{-2}\), i.e. much higher than is typical of molecular and cold HI clouds, making such a solution unlikely.

Fig. 3 Positronium fraction vs. effective width of the 511 keV line for different temperatures and ionization degrees of the medium. There are two groups of theoretical curves: low-temperature \((T < 5,000\) K, dotted lines), and high-temperature \((T > 7,000\) K, solid lines). The temperature is fixed for each curve and the ionization degree varies from 0 to 1 along the curves. For the low-temperature curves and for the 8,000 K one, an ionization degree of 0.01 is indicated by empty squares, and 0.1 by dark squares. Each high-temperature curve has two regimes: thin (thick) lines correspond to the ionization degrees lower (higher) than expected for collision dominated plasma. The dashed line shows the prediction for a fully ionized plasma. The rectangle represents the range of parameter values allowed by INTEGRAL data. Adapted from [2].
On the other hand, in the warm ($T \sim 8,000–10,000$ K) ISM phase, the ionization degree can vary from less than 0.1 to more than 0.8. This phase alone can therefore explain the observed line width and positronium fraction. The required ionization degree is several per cent. This conclusion is in qualitative agreement with early observations of the Galactic annihilation radiation [1]. The spectrum predicted for the annihilation in a plasma with temperature 8,000 K and ionization degree 0.1 is shown in Figure 4. This spectrum is consistent with the INTEGRAL data.

Although the warm ISM model can reproduce the observations, this does not rule out more complicated solutions in which annihilation takes place in several ISM phases. For example, the observations can be explained by a combination of the cold and warm ISM phases in comparable proportions (see [2, 5]).

4. Discussion

INTEGRAL has enabled the most accurate to date measurement of the spectrum of positron annihilation radiation from the GC region.

The surface brightness of annihilation radiation is high in the central 5–10 degrees of the Galaxy and low outside this region. The total flux from the GC region is $\sim 10^{-3}$ phot/s/cm$^2$, with a significant uncertainty due to uncertainty in the spatial distribution of the radiation. Assuming a distance of 8.5 kpc to the annihilation site and taking into account that the fraction of annihilations occurring through positronium formation is close to unity, the observed flux implies a rate of $\sim 2 \times 10^{43}$ positron annihilations per second in the Galaxy.
corresponding luminosity is \( L_{e^+} \sim 1.6 \times 10^{37} \text{ erg/s} \). This imposes strong energetic constraints on the mechanisms of positron production. For an initial positron Lorentz-factor \( \gamma \) the minimum energy supply is \( \gamma L_{e^+} \). If positrons are generated by more energetic (or massive) particles, the minimum power required to produce the necessary number of positrons can be estimated as \( (E_0/m_e c^2)L_{e^+} \), where \( E_0 \) is the initial energy of the particles. For example, if positrons are generated by cosmic rays (through \( \pi^+ \) formation), the required energy supply is \( 3 \times 273 \times L_{e^+} \sim 10^{40} \text{ erg/s} \) (this takes into account that \( \pi^- \) and \( \pi^0 \) mesons are also produced). The decay of \( \pi^0 \) mesons should also lead to gamma radiation at energies 50–100 MeV with a luminosity \( \sim 3 \times 10^{39} \text{ erg/s} \).

The Galactic disk produces less annihilation flux than the GC region [7, 10], although the ratio of the two luminosities is a model-dependent quantity and in particular strongly depends on the thickness of the disk component.

The energy of the annihilation line coincides with the rest energy of electrons/positrons: \( E/m_e c^2 = 0.99991 \pm 0.00015 \), implying that the average radial velocity of the annihilation medium relative to the Earth is less than 44 km/s. The observed width of the annihilation line implies that the velocity dispersion in the annihilation medium is less than 800 km/s.

The combination of the observed line width (2.37 \( \pm \) 0.25 keV) and positronium fraction (0.94 \( \pm \) 0.06) can be explained by an annihilation in the warm ISM phase, with \( T \sim 8,000 \text{ K} \) and ionization degree \( \sim 0.1 \). Annihilation in neither the cold (\( T \leq 10^3 \text{ K} \)) nor hot (\( T \geq 10^5 \text{ K} \)) ISM phase is consistent with the observations. A combination of several ISM phases is also allowed by the data. The limit on the fraction of annihilations occurring in a very hot (\( T \geq 10^6 \text{ K} \)) ISM is \( \sim 8\% \). We note however that positrons injected into the hot ISM can live long enough to (a) leave the Galaxy or (b) propagate into a denser ISM phase to annihilate there. Therefore, the inferred low fraction of annihilations taking place in the hot ISM phase does not necessarily imply that positrons are not produced in that phase.

The above characteristics witness against a positron origin associated with Type 2 supernovae or massive stars, since these classes of object are concentrated toward the Galactic disk rather than the bulge. A positron origin due to interaction of cosmic rays with the ISM is also unlikely, in particular due to energetic considerations. The INTEGRAL data strongly favor bulgedominated populations of positron sources, such as Type Ia supernovae, lowmass X-ray binaries or dark matter. The continuing INTEGRAL observations will provide more stringent limits on the surface brightness distribution and spectral variations of the annihilation radiation along the Galactic plane and across it, allowing one to considerably narrow the range of physical processes responsible for positron production in the Galaxy.

References

Prospects and requirements for measurements of extragalactic $\gamma$-ray lines

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Abstract A brief summary is presented of requirements for the measurements of extragalactic $\gamma$-ray lines. The electron-positron annihilation line at 511 keV represents the best prospect, and although this line is greatly broadened in active galactic nuclei, a narrow line should be present in clusters of galaxies and radio lobes as a result of prior AGN activity. The strongest fluxes should be of the order of $10^{-4}$ photons cm$^{-2}$ s$^{-1}$ from the closest extended sources.

Keywords Extragalactic · Gamma-rays · AGN · Clusters of galaxies

1. Introduction

The status of $\gamma$-ray astronomy today is quite similar to the situation in X-ray astronomy in the early to mid-1970’s following the collimated rocket experiments and the early sky survey satellites UHURU, Ariel V and EXOSAT, i.e. the X-ray astronomy era before the advent of focussing X-ray optics. Before the launch of INTEGRAL, about 400 high-energy X-ray sources were known from the previous experiments such as COS-B and the Compton Gamma-Ray Observatory carrying COMPTEL and BATSE. These all-sky or Galactic plane $\gamma$-ray experiments have located the strongest $\gamma$-ray sources to a typical precision of about a degree. Source identifications have generally depended on correlated detections in the energy range of 10–100 keV (the INTEGRAL reference catalogue – see Figure 1, from Ebisawa et al. [7]), where the corresponding detection at lower energy with X-ray telescopes has resulted in optical identification. These $\gamma$-ray missions have not had the advantage of focussing and have therefore operated in the background-limited regime, with very little spectroscopy. With such missions, the sensitivity increases as the square root of the aperture, because the detector size is comparably large. The development of future missions of this kind is thus completely inappropriate – there cannot be order-of-magnitude improvements in sensitivity.
by pursuing such techniques and spectroscopic studies would stagnate. The development of gamma-ray astronomy can only proceed by following the lead of X-ray astronomy, and for the same reasons. In order for $\gamma$-ray astronomy to flourish, especially in extragalactic work, methods of focussing or concentrating $\gamma$-rays need to be developed, so that background is drastically reduced even if the experiments remain background-limited for most targets. This reduction in background will mean that gamma-ray astronomy will finally be opened up for spectroscopic studies. Considerable progress in this direction has already been made with non-focussing instruments, and these developments will be the starting point for the science requirements summarized below.

The primary targets for future $\gamma$-ray astronomy payloads are thus already generally known from the large area surveys, including the BAT instrument on the Swift satellite, or they are otherwise Targets of Opportunity within known classes of objects such as SuperNovae (SN) and Gamma Ray Bursters (GRB). With the sensitivities of previous experiments, the requirements below will show that exposure times would need to be very long (typically $10^6$–$10^7$ s) in order to conduct any significant astrophysics, e.g. to search for and measure nuclear lines rather than just object detection. Measurements of line strengths are needed for comparison with astrophysical models, so that the lines need to be detected at high significance (at least $5\sigma$) rather than just a marginal detection. Further, the sensitivities of future instruments need to be such that variability in the nuclear lines from transient objects (novae, supernovae and $\gamma$-ray bursts) can be observed – this implies that the required sensitivity to line flux needs to be reached within a typical exposure time of $10^5$ s, rather than $10^6$ or $10^7$ s. These are compelling arguments in favour of a pointed, focussing mission and an argument which eliminates future surveys of large sky areas with limited sensitivity.

Observations with the Integral satellite have now set the stage for future requirements on nuclear line spectroscopy in the high energy X-ray region and at gamma-ray energies. These observations are summarised in the Integral papers collected in a special issue of Astronomy & Astrophysics (INTEGRAL Special Issue [12]).

The source classes with potential $\gamma$-ray lines are as follows:

(i) supernovae, especially Type Ia, (ii) galactic novae and X-ray bursters, (iii) microquasars, (iv) Galactic X-ray binaries, (v) Galactic Center, (vi) Active Galactic Nuclei (AGN), (vii)
Clusters of Galaxies, (viii) Gamma-Ray Bursters, and (ix) GRB remnants. In this paper, the expected line fluxes will be reviewed for extragalactic objects, especially AGN and clusters of galaxies.

2. Extragalactic supernovae Ia

For a detailed review of the $\gamma$-ray lines predicted from Type Ia supernovae, see the paper by Leising (this volume). For the availability of at least one target at all times, the requirement is to reach SN Ia at distances of 50–100 Mpc (Cappellaro and Turatto [5]), because there are about 25 SN Ia’s within 100 Mpc per year, each brighter than $V_{\text{mag}} = 16$ so that they will be found with the planned large-area synoptic sky surveys. Recent estimates of the rates of SN Ia have been made by Scannapieco and Bildsten [21] and Mannucci et al. [17]. The predicted absolute line fluxes have been calculated by Hoeflich as a function of time following the explosion. For a SNIa the expected line flux in $^{56}\text{Ni}_{158}\text{keV}$ at 20 days past onset is

$$\phi(56\text{Ni}_{158}\text{keV}) = 10^{-2}/D^{2} \text{ ph cm}^{-2}\text{s}^{-1}$$

where distance $D$ is in Mpc. The required sensitivity to reach objects at 100 Mpc is thus better than $10^{-7}$ and approaching $10^{-8}$ ph cm$^{-2}$ s$^{-1}$ in this line, for integration periods not exceeding 1 day (so that the decay can be followed).

Similarly, at 70 days past onset

$$\phi(56\text{Co}_{847}\text{keV}) = 5 \times 10^{-3}/D^{2} \text{ ph cm}^{-2}\text{s}^{-1}$$

Relative to the peak visual magnitude $m_V$,

$$\log(\phi(56\text{Co}_{847}\text{keV}) \times 10^{4}) = 0.4[10.9 - m_V]$$

so that for $m_V \sim 16$, $\phi(56\text{Co}_{847}\text{keV}) \sim 10^{-6}$ ph cm$^{-2}$ s$^{-1}$.

A sensitivity of $10^{-7}$ ph cm$^{-2}$ s$^{-1}$ would mean that a SNIa at V mag. 18 would have detectable nuclear line flux. The astrophysics resulting from line detection alone is, of course, very limited. The optical decay curves of SN Ia already show unambiguously that radionuclides of Ni$^{56}$ and Co$^{56}$ are the source of energy. In order to distinguish between the various models for the supernova explosion (see [11]), line widths and ratios need to be measured as a function of time (in days).

As an additional cautionary note on the use of nuclear lines for the astrophysics of SNIa, it is possible in principle to use higher energy lines to distinguish between the detonation and deflagration models for the initial event. However, this is very difficult to achieve in practice – the emission spectra calculated in Hoeflich et al. show that large numbers (thousands) of counts are needed in the lines in order to make progress, and the requirements then become prohibitively difficult.

3. Annihilation line from nearby galaxies

Results obtained with INTEGRAL have shown the presence of extended 511 keV emission from a region around the Galactic Center [14]. There may be individual compact sources