SCIENCE PROSPECTS FOR SPI

Jürgen Knödlseder and Gilbert Vedrenne
Centre d’Etude Spatiale des Rayonnements, B.P. 4346, 31028 Toulouse Cedex 4, FRANCE

ABSTRACT

After the recent beautiful results on gamma-ray lines obtained with Compton GRO (OSSE and COMPTEL), the INTEGRAL mission with the imaging-spectrometer SPI will set the next milestone, combining improved sensitivity and angular resolution with a considerable increase in spectral resolution. SPI is expected to provide significant new information on galactic nucleosynthesis processes and star formation activity, as traced by the distributions of annihilation radiation and radioactive isotopes such as $^{26}\text{Al}$ and $^{60}\text{Fe}$. The unprecedented spectral resolution will allow the study of dynamic processes in stellar mass ejections and will provide access to kinematic distance estimates for gamma-ray line sources.

The study of supernovae and their remnants will be prime objectives for SPI observations. Nearby type Ia SN, within 15 Mpc or so, are in reach of the instrument and a few such events are expected during the lifetime of INTEGRAL. Young galactic supernova remnants, possibly hidden by interstellar dust, may be unveiled by their characteristic gamma-ray line signature from the radioactive decay of $^{44}\text{Ti}$, as has been demonstrated by COMPTEL for Cas A and possibly RX J0852.0-4622. Even SN1987A, which has already faded in the short lived radioisotopes $^{56}\text{Co}$ and $^{57}\text{Co}$, could again become a target of interest for gamma-ray line astronomy, since the longer lived isotope $^{44}\text{Ti}$ may be in reach of SPI.

Classical novae are also among the SPI targets, which may observe the gamma-ray lines from radioactive $^7\text{Be}$ and $^{22}\text{Na}$. Such observations can constrain the physics of the nova explosions and will allow to evaluate their role as nucleosynthesis sites. The interaction of cosmic rays with the dense matter in molecular clouds may be another source of gamma-ray lines that is potentially accessible to SPI. Finally after the SIGMA results on Nova Muscae and 1E1740.7-2942, and a possible 2.223 MeV line detection by COMPTEL, the search for lines from X novae is another way to participate in the understanding of the physical conditions in these close binary systems.

Key words: gamma-ray line spectroscopy; nucleosynthesis; radioactivities; nuclear interactions.

1. DESIGN CONSIDERATIONS FOR SPI

The successful Compton Gamma-Ray Observatory (CGRO) provided a brilliant demonstration of the great scientific potential promised by the field of gamma-ray line astronomy. The COMPTEL telescope established the first all-sky map in the light of the $^{26}\text{Al}$ decay line at 1.809 MeV, revealing diffuse structured emission from the entire galactic plane arising from massive star nucleosynthesis (e.g. Plischke et al., these proceedings). The detection of the 1.157 MeV line towards Cas A (Iyudin et al., 1994) was the first observation of radioactive $^{44}\text{Ti}$ decay related to a young supernova remnant, and the following possible detection of 1.157 MeV line emission towards Vela (Iyudin et al., 1998) triggered for the first time the discovery of a new young supernova remnant (RX J0852.0-4622). OSSE provided the first maps in the 511 keV line and positronium continuum emissions, identifying at least two galactic emission components (extended bulge and disk) with indications for a possible third component situated above the galactic plane (see Milne et al., these proceedings). Although OSSE observed SN 1987A more than 4 years after explosion, it still was capable to detect the $^{57}\text{Co}$ decay line at 122 keV, leading together with the $^{56}\text{Co}$ observations by SMM to the first determination of an isotopic abundance ratio through gamma-ray line measurements.

All these discoveries confirmed that gamma-ray line observations are a powerful probe of nuclear astrophysics, and the experience gained from the observations sets the design guideline for the spectrometer SPI on INTEGRAL. First, the most prominent gamma-ray lines (1.809 MeV and 511 keV) turned out to be extended over angular scales of $\sim 10$ degrees, hence an instrument was needed that provides good sensitivity to extended emission features. Second, gamma-ray line fluxes showed to be quite low – a few $10^{-5}$ ph cm$^{-2}$s$^{-1}$ at maximum – requiring an instrument that is sensitive to fluxes well below that level. And third, emission regions are often quite confused, asking for sufficient angular resolution to spatially resolve the emission, allowing for an adequate identification of candidate sources. Additionally, the CGRO instruments did not provide sufficient spectral resolution to resolve gamma-ray...
line profiles and to determine line centroids, hence an instrument was needed that can also access this extremely valuable complementary information.

Having these considerations in mind, the following design was chosen for SPI:

- a coded mask to modulate the gamma-ray emission, allowing for good angular resolution (2°) and source localisation throughout the field-of-view,
- a wide fully coded field-of-view of 16 degrees (34° partially coded), allowing for imaging of extended emission regions,
- the use of cooled Germanium detectors for good gamma-ray line sensitivity by effectively reducing the number of background counts thanks to an excellent energy resolution (2 keV at 1 MeV), which also allows studies of line shifts and line profiles.

It has to be emphasised that the sensitivity to detect gamma-ray lines is determined by the instrumental background underlying the line. Based on Monte-Carlo simulations of the instrumental background, the narrow-line sensitivity of SPI has been estimated to better than $8 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$ above 200 keV ([Jean et al., 1996]). Since a broadened line includes more background counts than a narrow line, the sensitivity of SPI is effectively reduced for lines that are broader than the detector spectral resolution. As a rule of thumb one can estimate the sensitivity to broad lines (expressed as the minimum detectable flux $\Phi_{\text{broad}}$) using

$$\Phi_{\text{broad}} = \Phi_{\text{narrow}} \sqrt{\Delta E_{\text{broad}} / \Delta E_{\text{GeD}}}.$$  

where $\Phi_{\text{narrow}}$ is SPI’s narrow line sensitivity, $\Delta E_{\text{broad}}$ is the line width, and $\Delta E_{\text{GeD}}$ is the instrumental line width (this formula is of course only valid for $\Delta E_{\text{broad}} \leq \Delta E_{\text{GeD}}$). For a more detailed description of the expected SPI performances, the reader is referred to [Mandrou et al. (1997)].

### 2. RADIOACTIVITIES

#### 2.1. The gamma-ray line menu

From the roughly 2500 isotopes that are known today, only about 1/10 are stable while all others decay radioactively or undergo spontaneous fission. Many of the decays are accompanied by gamma-ray line emission due to nuclear de-excitations of the daughter nuclei, but only few isotopes are indeed accessible to gamma-ray astronomy. In fact, there are three basic conditions that have to be fulfilled for the detectibility of a radioisotope. First, a hot and dense medium with sufficiently low entropy is required to allow for the synthesis of fresh radioisotopes. Such a medium can be found in stellar interiors, at the base of the accreted envelope of white dwarfs in close binary systems, or even in accretion disks around compact objects. The nuclear reaction networks in operation are characteristic for the composition, density, and temperature at the burning site, hence the observation of isotopic abundance patterns provide direct insight into the nucleosynthesis conditions. Second, the fresh radioisotopes have to be removed quickly from the formation site to prevent destruction by nuclear reactions or natural decay. This generally implies convection followed by mass ejection, either in form of stellar winds or explosions, and requires lifetimes of at least several days, better several months. Additionally, nucleosynthesis bases sites are generally optically thick to gamma-rays, hence escape of the radioisotopes to optically thin regions is mandatory for gamma-ray line observations. Consequently, radioisotopes can probe stellar convection and ejection processes, providing important information about the involved stellar physics. Third, the lifetime has to be short enough and the abundance of the isotope has to be high enough to assure a sufficient radioactive decay activity that is in reach of modern gamma-ray telescopes.

These constraints result in a list of candidate isotopes that may actually be accessible to gamma-ray line astronomy (cf. Table [1]). The observation of radioactivity lines implies various time-scales. For lifetimes that are short compared to the event frequency ($^{57}\text{Ni} - ^{57}\text{Co}$), individual transient gamma-ray line sources are expected, mainly in form of supernovae or novae. The observation of gamma-ray line lightcurves provides then an important complementary information for studying the physics of these explosive events (e.g. Leising & Share, 1990). For lifetimes of the order of the event frequency ($^{22}\text{Na} - ^{44}\text{Ti}$) several rather steady (over the lifetime of a typical gamma-ray mission) gamma-ray line sources are expected in form of supernova remnants or recent nova events. For lifetimes that are long compared to the event frequency ($^{26}\text{Al} - ^{60}\text{Fe}$) the superposition of numerous individual sources will lead to a diffuse glow of gamma-ray line emission along the galactic plane. Additionally, the longlived radioisotopes may travel considerable distances away from the production sites before they decay ($\sim 10 - 100$ pc), leading to intrinsically extended sources.

Some of the most prominent radioactive isotopes ($^{56}\text{Co}$, $^{22}\text{Na}$, $^{44}\text{Ti}$, and $^{26}\text{Al}$) are also positron emitters, and the annihilation of the positrons with electrons in the interstellar medium (ISM) may lead to 511 keV line emission, accompanied by a positronium continuum emission below 511 keV due to 3 photon decays. The typical lifetime for positrons in the ISM is of the order of $10^5$ yr ([Guessoum et al. 1991]), hence the annihilation radiation provides a long-lasting reverberation of the short-lived radioisotopes. In particular, since the positron lifetime considerably exceeds the period of supernova or nova events, numerous sources should contribute to the
Table 1. The menu of gamma-ray lines from radioactivities that may be accessible to gamma-ray astronomy (ordered by ascending lifetime). Theoretical nucleosynthesis yield estimates are quoted for different source types; the yields for AGB stars are split into low-mass AGBs (<5$M_\odot$, left column) and high-mass AGBs (>5$M_\odot$, right column). Positron emitters are marked by †.

| Isotope | Lifetime $\tau$ | Lines (keV) | Typical yields ($M_\odot$) |
|---------|----------------|-------------|---------------------------|
|         |                | AGB | WR | SN Ia | SN Ib/c | SN II | Nova |
| $^{57}$Ni | 2.14 d | 1378 | 0.02 | 5 $10^{-3}$ | 5 $10^{-3}$ |
| $^{56}$Ni | 8.5 d | 158, 812 | 0.5 | 0.1 | 0.1 |
| $^{58}$Fe | 64.2 d | 1099, 1292 | 5 $10^{-5}$ | 5 $10^{-5}$ |
| $^{7}$Be | 77 d | 478 | 10$^{-7}$ | 5 $10^{-7}$ | 5 $10^{-11}$ |
| $^{56}$Co† | 112 d | 847, 1238 | 0.5 | 0.1 | 0.1 |
| $^{57}$Co | 392 d | 122 | 0.02 | 5 $10^{-3}$ | 5 $10^{-3}$ |
| $^{22}$Na† | 3.76 yr | 1275 | 10$^{-8}$ | 10$^{-6}$ | 10$^{-6}$ | 5 $10^{-9}$ |
| $^{60}$Co | 7.61 yr | 1173, 1332 | 10$^{-5}$ | 10$^{-5}$ |
| $^{44}$Ti† | 87 yr | 1157 | 10$^{-5}$ | 5 $10^{-5}$ |
| $^{26}$Al† | 10$^6$ yr | 1809 | 10$^{-7}$ | 4 $10^{-6}$ | 10$^{-4}$ | 5 $10^{-5}$ | 5 $10^{-5}$ | 10$^{-8}$ |
| $^{60}$Fe | 2.2 $10^8$ yr | 1173, 1332 | 10$^{-10}$ | 5 $10^{-3}$ | 5 $10^{-5}$ | 5 $10^{-5}$ |

The intensity of the emission, however, turned out to be in excess of the nucleosynthesis calculations at that time, pushing theoreticians to look for other $^{26}$Al sources. As a consequence, many candidate $^{26}$Al sources, such as novae, red giants, Wolf-Rayet stars, or energetic cosmic-ray particle interactions have been proposed to fill the gap (see Prantzos & Diehl (1996) for a review). Others suggested more extreme scenarios to resolve the puzzle, such as the explosion of a high-metallicity supermassive star near the galactic centre (Hillebrandt et al., 1987), or a nearby recent supernova explosion (Mori & Hartquist, 1991). Thus, $^{26}$Al production seems related to the massive star population. Correlation studies using tracer maps for various source candidates populations strongly support this suggestion (Knödlseder et al., 1999b). Some extreme scenarios are now clearly excluded by the first all-sky map of the 1.809 MeV gamma-ray line which shows the galactic disk as the most prominent emission feature (Oberlack et al., 1996). Hence, $^{26}$Al production is clearly a galax-wide phenomenon and is not dominated by a single and possibly nearby object. Additionally, the observed intensity profile along the galactic plane shows asymmetries and localized emission enhancements, which should be characteristic for a massive star population that follows the galactic spiral structure (Prantzos, 1991). Thus, $^{26}$Al production seems related to the massive star population. Correlation studies using tracer maps for various source candidate populations strongly support this suggestion. Knödlseder et al. (1999b) demonstrated that the 1.809 MeV gamma-ray line emission follows closely the distribution of galactic free-free emission which is powered by the ionising radiation of stars with initial mass > 20 $M_\odot$. This suggests that explosive $^{26}$Al production in supernovae may be less important than previously thought (e.g. Timmes et al., 1995), and hydrostatic nucleosynthesis in massive mass-losing stars may possibly be the primary production channel for galactic $^{26}$Al. Although still a hypothesis, this suggestion is substantiated by the correlation of one of the most prominent 1.809 MeV emission features in the all-sky map with an agglomeration of young massive star associations in the Cygnus region which are lacking recent supernova activity (Knödlseder et al., these proceedings).

Having established the correlation between 1.809
Figure 1. SPI prospects for 1.809 MeV. The left panel shows the radial $^{26}$Al density profile as derived from COMPTEL data (Knödlseder, 1997). With improved sensitivity, SPI will refine this distribution, allowing for a detailed study of the galactic star formation activity. The right panel shows a COMPTEL image of the 1.809 MeV emission in the Vela region with potential $^{26}$Al sources superimposed (Oberlack, 1997). The better angular resolution and sensitivity of SPI will allow to identify counterparts of 1.809 MeV emission, constraining nucleosynthetic yields for individual objects or specific groups such as OB associations and young open clusters (the filled circles illustrate the SPI and COMPTEL angular resolutions).

MeV emission and massive star populations, $^{26}$Al becomes an excellent tracer of recent galactic star formation. By refining the knowledge about the 1.809 MeV emission distribution, SPI will provide a unique view on the star formation activity in our Galaxy, supplementing information obtained at other wavelengths. To illustrate this potential, the radial $^{26}$Al mass density distribution as derived from COMPTEL 1.809 MeV observations is shown in Fig. 1 (Knödlseder, 1997). Apparently, the bulk of galactic star formation occurs at distances of less than 6 kpc from the galactic centre. Star formation is also present within the central 3 kpc of the Galaxy, although at a poorly determined rate. There are indications for enhanced star formation between 3 – 6 kpc, coinciding with the molecular ring structure as seen in CO data (Dame et al., 1987). Enhanced star formation is also seen in the solar neighbourhood (8 – 9 kpc) which probably corresponds to the local spiral arm structure.

The radial $^{26}$Al profile is probably not directly proportional to the radial star formation profile since $^{26}$Al nucleosynthesis may depend on metallicity (e.g. Meynet, 1994). It will be important to determine this metallicity dependence in order to extract the true star formation profile from gamma-ray line data. Valuable information about the metallicity dependence will come from a precise determination of the 1.809 MeV longitude profile by SPI, and the comparison of this profile to other tracers of star formation activity, such as galactic free-free emission. Additionally, observations of gamma-ray lines from $^{60}$Fe, an isotope that is mainly believed to be produced during supernova explosions (see Section 2.3), may help to distinguish between hydrostatically and explosively produced $^{26}$Al, and therefore may allow disentangling the metallicity dependencies for the different candidate sources.

A precise determination of the 1.809 MeV latitude profile by SPI will provide important information about the dynamics and the mixing of $^{26}$Al ejecta within the interstellar medium. High velocity $^{26}$Al has been suggested by measurements of a broadened 1.809 MeV line by the GRIS spectrometer (Naya et al., 1996), although this observation is at some point inconsistent with the earlier observation of a narrow line by HEAO 3 (Mahoney et al., 1984). In any case, the propagation of $^{26}$Al away from its origin should lead to a latitude broadening with respect to the scale height of the source population, and the observation of this broadening may allow the study of galactic outflows and the mass transfer between disk and halo of the Galaxy. Actually, COMPTEL 1.809 MeV observations restrict the scale height of the galactic $^{26}$Al distribution to $z < 220$ pc (Knödlseder, 1997; Oberlack, 1997; Diel et al., 1997), which certainly excludes a ballistic motion of $^{26}$Al at a speed of 500 km s$^{-1}$ (as suggested by GRIS), and which could even be in conflict with the reacceleration scenario, discussed by Sturmer (these proceedings) to explain the GRIS observations. The excellent energy resolution of SPI will easily allow to decide whether the 1.809 MeV line is broadened or not, and the improved angular resolution and sensitivity with respect to COMPTEL will allow to determine the scale height of the galactic $^{26}$Al distribution.
The expected energy resolution of SPI of ~2.5 keV at 1.809 MeV converts into a velocity resolution of ~400 km s\(^{-1}\), allowing for line centroid determinations of the order of 50 km s\(^{-1}\) for bright emission features. Thus, in the case of an intrinsically narrow 1.809 MeV line, line shifts due to galactic rotation should be measurable by SPI (Gehrels & Chiu, 1999). Although this objective figures certainly about the most ambitious goals of SPI observations, a coarse distance determination of 1.809 MeV emission features based on the galactic rotation curve seems in principle possible.

Complementary to the study of the large-scale distribution of the 1.809 MeV emission by SPI will be observations of nearby, localised 1.809 MeV emission regions, such as Vela, Cygnus, Carina, or Orion. The aim of these observations will be the identification of emission counterparts at other wavelengths in order to associate the nucleosynthesis activity to individual objects or specific groups such as OB associations or young open clusters. Already with COMPTEL data, such studies have proven to provide important insights in the nature of the 1.809 MeV emission by SPI will be helped to overcome this problem. Deep exposures of the Vela region, which is part of the INTEGRAL core program, a detection of the Wolf-Rayet star \(\gamma\)-Vel is awaited, and the contributions of the Vela SNR, the new RX J0852.0-4622 supernova remnant, and OB star associations should be measurable. In the Cygnus region, the young globular cluster Cyg OB2 should be detectable by SPI, allowing the study of nucleosynthesis in an individual massive star association (Knödlseder et al., these proceedings). In Carina, the point-like 1.809 MeV emission feature detected by COMPTEL (Knödlseder et al., 1996) may be resolved, and the contributions from individual young massive star clusters identified. And in Orion, hints for 1.809 MeV emission from a nearby OB association (Oberlack, 1997) may be confirmed, enabling the study of nucleosynthesis in one of the closest and best studied star forming regions in the Milky Way.

To illustrate the potential of SPI, a contour map of the 1.809 MeV emission in the Vela region obtained by COMPTEL is shown in Fig. [1]. There is a wealth of potential \(^{26}\)Al sources in this field, but the limited angular resolution of COMPTEL does not allow for a clear identification of the dominant contributors. Additionally, the sensitivity of COMPTEL is not sufficient to clearly separate diffuse \(^{26}\)Al flux from point-like emission (Knödlseder et al., 1999b), leading to an additional uncertainty in the association of emission structures with \(^{26}\)Al sources. With improved sensitivity and angular resolution, SPI will help to overcome this problem. Deep exposures of localised emission features will sufficiently constrain the 1.809 MeV morphology to associate the structure with candidate sources in the field. In the Vela region, which is part of the INTEGRAL core program, a detection of the Wolf-Rayet star \(\gamma\)-Vel is awaited, and the contributions of the Vela SNR, the new RX J0852.0-4622 supernova remnant, and OB star associations should be measurable. In the Cygnus region, the young globular cluster Cyg OB2 should be detectable by SPI, allowing the study of nucleosynthesis in an individual massive star association (Knödlseder et al., these proceedings). In Carina, the point-like 1.809 MeV emission feature detected by COMPTEL (Knödlseder et al., 1996) may be resolved, and the contributions from individual young massive star clusters identified. And in Orion, hints for 1.809 MeV emission from a nearby OB association (Oberlack, 1997) may be confirmed, enabling the study of nucleosynthesis in one of the closest and best studied star forming regions in the Milky Way.
has been observed by numerous instruments (see Harris et al. (1998) and references therein). At least two galactic emission components have been identified so far: an extended bulge component and a disk component. Indications of a third component situated above the galactic centre have been reported (Purcell et al., 1993; Harris et al., 1998), yet still needs confirmation by more sensitive instruments (see also Milne et al., these proceedings).

The galactic disk component may be explained by radioactive positron emitters, such as $^{26}$Al, $^{44}$Sc, $^{56}$Co, and $^{22}$Na (Lingenfelter & Ramaty, 1989). Although all these isotopes are also gamma-ray line emitters, only $^{26}$Al will lead to correlated gamma-ray line and 511 keV emission since the typical annihilation time scale of some $10^7$ yrs considerably exceeds the lifetime of the other isotopes. Consequently, 511 keV line-emission is a potential tracer of extinct short-lived galactic radioactivities.

The origin of the galactic bulge component is much less clear. The observation of an abrupt turn off of the 511 keV emission from the galactic centre by HEAO 3 at the beginning of the eighties has led to the idea that a compact object might be responsible for the galactic bulge emission (Riegler et al., 1989). However, a re-analysis of the same data by Mahoney et al. (1994) has shown that the reported flux variation is not significant. Also, contemporaneous observations with the SMM satellite (Share et al., 1988) and latest observations by OSSE (Purcell et al., 1993) and TGRS (Teegarden et al., 1994) show no evidence for any time-variability. Lingenfelter & Ramaty (1989) therefore proposed a two component model for the galactic bulge emission which is composed of a variable compact source near the galactic centre and a steady diffuse interstellar annihilation source. The flux level of the variable point source, however, is limited by the observations to less than $4 \times 10^{-4}$ ph cm$^{-2}$s$^{-1}$, and indeed, time-variability is not required by the data (Share et al., 1988; Purcell et al., 1993; Teegarden et al., 1994). On the other hand, the observation of broadened and red-shifted annihilation features from 1E 1740.7-2942 (Bouchet et al., 1991) and Nova Muscae (Goldwurm et al., 1992) has been considered as evidence for positron production in compact objects (but see Section 2.8). However, the contemporaneous observation by OSSE and SIGMA of an outburst of 1E 1740.7-2942 in September 1992 gave contradictory results (Jung et al., 1993), casting some doubt on the contribution of compact objects to the galactic positron budget.

The origin of the galactic bulge positrons will be one of the key-questions addressed by SPI. Narrow-line transient features with fluxes of $4 \times 10^{-4}$ ph cm$^{-2}$s$^{-1}$ should be detectable by SPI within less than one hour. If the feature is broadened by 300 keV (as observed for example in 1E 1740.7-2942) the required observation time $t_{\text{broad}}$ increases like $t_{\text{broad}} = t_{\text{narrow}} \Delta E_{\text{broad}} / \Delta E_{\text{GeV}}$. resulting in a detection within $\sim 12$ hours. Hence, the weekly galactic plane scan together with the central region deep exposure performed during the INTEGRAL core program (Winkler, these proceedings) will provide a unique survey of the galactic bulge, capable of detecting even faint transient 511 keV emission events.

In addition to the detection of transient events, SPI will also provide a detailed map of 511 keV emission from the Galaxy. Using this map, the morphology of the galactic bulge can be studied in detail, and the question on the contribution of point sources to the galactic bulge emission can be addressed. In particular, the ratio between bulge and disk emission, which is only poorly constrained by existing data (see Milne et al., these proceedings), will be measured more precisely, allowing for more stringent conclusions about the positron sources of both components. The 511 keV map will also answer the question about the reality of the positive latitude enhancement, which may provide interesting clues on the activity near to the galactic nucleus (Dermer & Skibo, 1997).

Additionally, the 511 keV line shape carries valuable information about the annihilation environment which will be explored by SPI. The dominant annihilation mechanism sensitively depends on the temperature, the density, and the ionisation fraction of the medium, and the measurement of the 511 keV line width allows the determination of the annihilation conditions (Guessoum et al., 1991). Observations of a moderately broadened 511 keV line towards the galactic centre indicate that annihilation in the bulge mainly occurs in the warm neutral or ionised interstellar medium (Harris et al., 1998). By making spatially resolved line shape measurements, SPI will allow to extend such studies to the entire galactic plane, complementing our view of galactic annihilation processes.

With its good continuum sensitivity, SPI will also be able to detect the galactic positronium continuum emission below 511 keV. The intensity of this component with respect to that of the 511 keV line carries complementary information about the fraction $f$ of annihilations via positronium formation, probing the thermodynamic and ionisation state of the annihilation environment (Guessoum et al., 1991).

### 2.5. Observation of novae

Novae explosions are potential sources of various radioactivities, of which the nuclei $^7$Be, $^{13}$N, $^{19}$F, $^{22}$Na, and $^{26}$Al are the most important ones (Gómez-Gomar et al., 1998a). $^7$Be decays by electron capture into $^7$Li, and the observation of the accompanying decay line at 478 keV will be an irrefutable prove of cosmic $^7$Li enrichment by novae (Starrfield).  

---

3The expected narrow line sensitivity of SPI at 511 keV is limited by a strong instrumental line to $2 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$ for an observation time of $10^6$ seconds; however, if the line is substantially broadened, the sensitivity of $7 \times 10^{-6}$ ph cm$^{-2}$s$^{-1}$ that is found adjacent to 511 keV energies should be applied.

4The expected narrow line sensitivity of SPI at 511 keV is limited by a strong instrumental line to $2 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$ for an observation time of $10^6$ seconds; however, if the line is substantially broadened, the sensitivity of $7 \times 10^{-6}$ ph cm$^{-2}$s$^{-1}$ that is found adjacent to 511 keV energies should be applied.
et al., 1978). Although $^{13}\text{N}$ and $^{18}\text{F}$ are no gamma-ray emitters they decay under positron emission, and their annihilation in the nova envelope may lead to a prominent 511 keV line feature accompanied by a low-energy Compton continuum (Hernanz et al., 1997). $^{22}\text{Na}$ maybe produced in the subclass of oxygen-neon (ONE) rich novae, and the observation of the 1.275 MeV gamma-ray decay line holds valuable information about the dredge-up of white-dwarf core matter during the explosion (Weiss & Truran, 1997). Finally, $^{26}\text{Al}$ produced in ONE novae may contribute to the galactic $^{26}\text{Al}$ budget, although both theory and observations do not suggest a large contribution (Kolb & Politano, 1997; Knödlseder, 1999).

Neither of the nova lines has been detected so far (Harris et al., 1997; Iyudin et al., 1995; Harris et al., 1999), hence any positive detection by SPI would be a great piece of information for understanding the nova phenomenon and the implied nucleosynthesis processes. Observationally, novae are situated at the border between diffuse and point-like emission sources. Assuming a galactic nova rate of 35 yr$^{-1}$ (Shafter, 1993) and an one type proportion of 22% (Livio & Truran, 1994), an average of 29 such objects should be visible during one lifetime of the $^{22}\text{Na}$ isotope. For carbon-oxygen (CO) novae, which are the dominant sources of $^7\text{Be}$, an average of 6 objects emitting the 478 keV line should be always present in the Galaxy. Since novae are believed to occur dominantly in the inner Galaxy, the limited angular resolution of SPI will recognize them as diffuse emission from the central galactic radian (Jean et al., 2000). After two years of operations, the core programme exposure of the central radian will allow SPI to detect diffuse 478 keV and 1.275 MeV fluxes of about $10^{-5}$ ph cm$^{-2}$s$^{-1}$, considerably fainter than actual upper limits (Harris et al., 1999; Iyudin et al., 1995; Leising et al., 1998).

The detectability of individual novae by SPI will, of course, depend on the ejected masses of radioisotopes, and the intrinsic width of the decay lines (see Eq. 4). Classical CO novae show ejection velocities of 250 – 2500 km s$^{-1}$, corresponding to Doppler-broadenings of 0.8 – 8 keV (FWHM) at 478 keV (Cohen, 1983). ONE novae explode more violently, with ejection velocities ranging from 1000 – 5000 km s$^{-1}$, leading to line-widths of 10 – 40 keV (FWHM) at 1.275 MeV (Smits, 1997; Hayward et al., 1991). However, the ejecta may considerably slow-down during the lifetime of $^{22}\text{Na}$ (e.g. Austin et al., 1996), and the most opportune situation for SPI to detect the 1.275 MeV line may occur only 1 – 2 years after the actual nova explosion.

Estimates of nova nucleosynthetic yields by Hernanz et al. (1999a) suggest that $^7\text{Be}$ decay from individual CO novae within 500 pc should be detectable by SPI, $^{22}\text{Na}$ in ONE novae may be visible out to 2 kpc, and the 511 keV line from $^{13}\text{N}$ and $^{18}\text{F}$ positrons could be observed for novae within 3 kpc from the Sun. Within the quoted distances, the expected event frequencies are 0.01, 0.2, and 0.6 yr$^{-1}$ for 478 keV, 1.275 MeV, and 511 keV line detections, respectively. Note, however, that the 511 keV emission lasts only for about one day (Hernanz et al., 1997), hence despite the relatively high event frequency, a direct detection within the field-of-view of SPI would be extremely fortuitous.

However, the short-lasting 511 keV emission with the accompanied Compton-continuum from novae could be detected as an increase in the counting rate of the SPI BGO collimator and anticoincidence shield (Jean et al., 1999). In fact, the 91 BGO crystals (making a total detector mass of 512 kg) which define the SPI field-of-view and shield the detector array against background radiation, provide a formidable large-area detector, that will also be inserted in the third interplanetary network to allow burst localisations to within ~ 10 arcmin (Hurley, these proceedings). Estimations based on the revised $^{13}\text{N}$ and $^{18}\text{F}$ yield predictions by Hernanz et al. (1999b) suggest that SPI should be able to detect massive ONE novae up to distances of 7 – 8 kpc, leading to an event frequency of 3 yr$^{-1}$. However, only limited localisation capabilities are provided by the BGO shield, and the search for a counterpart in the visible or the near-infrared will be challenging.

2.6. $^{44}\text{Ti}$ – unveiling recent supernova

Until recently, the census of recent galactic supernova events was exclusively based on historic records of optical observations and amounted to 6 events during the last 1000 years. Due to galactic absorption and observational bias, this census is by far not complete. Gamma-ray line observations of the $^{44}\text{Ti}$ isotope have the potential to considerably increase the statistics. $^{44}\text{Ti}$ is believed to be exclusively produced by $^{44}\text{Ti}$-rich freeze-out in supernova events, and the existence of its decay product $^{44}\text{Ca}$ makes this production mandatory. Due to the penetrating power of gamma-rays, $^{44}\text{Ti}$ lines from recent supernova events throughout the Galaxy can reach the Earth, and therefore, unveil yet unknown young supernova remnants.

The prove of principle was achieved by the observation of a 1.157 MeV gamma-ray line from the 320 years old Cas A supernova remnant using the COMPTEL telescope (Iyudin et al., 1994). Evidence for another galactic $^{44}\text{Ti}$ source was found in the Vela region where no young supernova remnant was known before (Iyudin et al., 1998). Triggered by this discovery, unpublished ROSAT X-ray data showing a spherical structure at the position of the new $^{44}\text{Ti}$ source were reconsidered and lead to the discovery of a new supernova remnant, now called RX J0852.0-4622 (Aschenbach, 1998). In the meanwhile, the remnant has also been discovered at radio wavelengths (Combi et al., 1999; Duncan & Green, 2000). Although the $^{44}\text{Ti}$ observation is only marginal (Schönfelder et al., 1999), it is the first time that gamma-ray line observations triggered the discovery of a new supernova remnant. From the X-ray data, an age of less than 1500 yrs and a distance...
Given the marginal detection of the 1.157 MeV line from RX J0852.0-4622, a confirmation of $^{44}\text{Ti}$ decay by SPI will be crucial for the further understanding of this object. Recall, however, that the SPI sensitivity limit depends on the intrinsic line width, and substantial Doppler-broadening could hamper a convincing detection. On the other side, the hard X-ray lines at 68 and 78 keV may also be detected by IBIS and possibly SPI (Ilyudin et al., these proceedings), and indeed, detecting $^{44}\text{Ti}$ may be more easily achieved in these lines in case of substantial broadening (Georgii et al., these proceedings). Finally, $^{44}\text{Ti}$ line-profile measurements will provide complementary information on the expansion velocity and dynamics of the most inner layers of the supernova ejecta.

The regular galactic plane scans and the deep exposure of the central radian will lead to a substantial exposure build-up, enabling the detection of further hidden young galactic supernova remnants through $^{44}\text{Ti}$ decay. The observed supernova statistics may then set interesting constraints on the galactic supernova rate and the $^{44}\text{Ti}$ progenitors. Indeed, actual observations already indicate that some of the galactic $^{44}\text{Ca}$ may have been produced by a rare type of supernova (e.g. Helium white dwarf detonations) which produces very large amounts of $^{44}\text{Ti}$ (Hes et al., 1999).

Finally, we want to mention that a detection of the $^{44}\text{Ti}$ lines from SN 1987A could be feasible, and any non-detection will impose interesting constraints on $\alpha$-rich freeze-out nucleosynthesis in this event (Woosley & Hoffman, 1991). Fits to the bolometric light curve indicate the presence of $10^{-4} \, M_\odot$ of $^{44}\text{Ti}$ in SN 1987A (Fransson & Kozma, 1993), and values twice as high are not excluded by nucleosynthesis theory (Woosley & Hoffman, 1991) and probably also not by the observations. Thus, assuming a high $^{44}\text{Ti}$ yield of $2 \times 10^{-4} \, M_\odot$ and a distance of 45 kpc to the LMC (as suggested by recent observations of eclipsing binaries; Guinan et al., 1998; Fitzpatrick et al., 2000), a 1.157 MeV line flux of $8 \times 10^{-6} \, \text{ph cm}^{-2} \, \text{s}^{-1}$ is expected, of the same order as the SPI sensitivity limit for a narrow line. Again, line-broadening will worsen the detectibility, but the possibility of a detection is certainly worth a deep exposure of the LMC by INTEGRAL.

### 2.7. Type Ia supernovae

The possibility of detecting gamma-ray lines from supernova remnants has been first suggested by Clayton & Craddock (1963) to identify transbismuth rays. Additional sensitivity may be achieved in these lines in case of substantial broadening, requiring possibly a supernovae as tracer of spontaneous $^{254}\text{Cf}$ fission, capable to explain the light-curves of type Ia supernovae. After recognising that the subsequent radioactive decays of $^{56}\text{Ni}$ and $^{56}\text{Co}$ may also explain the light-curves, Clayton et al. (1963) suggested that gamma-ray telescopes should search for their decay lines from type Ia supernovae within a few Mpc. Observationally, type Ia events are favoured over the other supernova classes because they produce an order of magnitude more radioactive $^{56}\text{Ni}$ than the other types, and they expand rapidly enough to allow the gamma-rays to escape before all the fresh radioactivity has decayed. Nevertheless, the first and only direct prove of $^{56}\text{Co}$ and $^{57}\text{Co}$ radioactivities in a supernova were obtained from observations of SN 1987A in the LMC, a type II event. However, it must be clear that such a nearby event is extremely rare, and the chance of observing a type II supernova during the INTEGRAL lifetime is extremely low (Timmes & Woosley, 1997).

Nevertheless, CGRO observations have taught us that supernovae are intriguing objects, and even at the detection threshold, their observation may provide interesting implications on the progenitor nature or explosion mechanism. For example, Morris et al. (1993, 1997) report the detection of the unusually bright SN 1991T in NGC 4527 (at a distance between $13 - 17$ Mpc) by COMPTEL, implying a $^{56}\text{Ni}$ mass of $1.3 - 2.3 \, M_\odot$, although an earlier analysis of COMPTEL data by Lichti et al. (1994), and a search of Leising et al. (1993) in OSSE data gave only upper limits. Assuming that COMPTEL indeed detected SN 1991T, the derived $^{56}\text{Ni}$ mass exceeds all theoretical expectations, requiring possibly a supernovae with $\sim 1 \, M_\odot$ to explain the observations. Indeed, high ($\sim 1 \, M_\odot$) $^{56}\text{Ni}$ masses have also been inferred by Spyromilio et al. (1992) from the strength of forbidden transitions of Fe II and Fe III in late-type spectra, by Mazzali et al. (1993) from modelling early-type spectra with a Monte Carlo code, and by Cappellaro (1997) from fitting the long term luminosity evolution by a Monte-Carlo light curve model. Using premaximum spectra, Ruiz-Lapuente (1992) inferred a peculiar chemical composition structure where a shell of intermediate-mass elements is sandwiched between a core and an outer-layer composed of Fe-peak elements. In addition, Fisher et al. (1999) recognised that the Fe-rich core and outer layer are moving faster than the intermediate unburned carbon-rich region, a chemico-dynamical configura-

---

<1 kpc has been inferred. Adding the $^{44}\text{Ti}$ observations further constrains the age and distance to $\sim 680$ yrs and $\sim 200$ pc, respectively (Aschenbach et al., 1999). Interestingly, nitrate abundance data from an Antarctic ice core provide evidence for a nearby galactic supernova $680 \pm 20$ yrs ago, compatible with the $^{44}\text{Ti}$ data (Burgess & Zuber, 1999).
tion that can not be reconciled with classical type Ia supernova models. They suggest that SN 1991T was the result of a white-dwarf merger, which exploded by the action of huge tidal forces at the onset of the merger due to synchronous rotation [Iben, 1997], which eventually may lead to a super-Chandrasekhar $^{56}$Ni mass. Although this scenario is certainly quite speculative, it illustrates that gamma-ray line observations of type Ia supernova may play a decisive role in identifying such peculiar events.

Another interesting example is SN 1998bu in M96, which shows the characteristics of a rather typical type Ia event at a distance of about 11 Mpc. Theoretical nucleosynthesis models predict that the radioactive decay of $^{56}$Co in SN 1998bu should lead to a peak flux of $(1 - 5) \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$ in the 847 keV line, where the upper value corresponds to Helium detonation models and the lower value represents deflagration models [Gómez-Gomar et al., 1998; Höflich et al., 1998]. However, SN 1998bu was observed by OSSE for over 140 days and by COMPTEL for almost 90 days without any positive detection [Leising et al., 1999; Georgii et al., 2000]. The upper time-averaged 847 keV flux limit of OSSE amounts to $3 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$, the COMPTEL limit of $4 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$ is comparable. For the 1.238 MeV line, COMPTEL imposes an even more stringent flux limit of $2 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$. Thus, the observations start to constrain type Ia supernova models, excluding for example the Helium cap model for SN 1998bu [Georgii et al., 2000].

Observing SN 1998bu by SPI would probably have been a major breakthrough for observational gamma-ray line astrophysics. Even if the 847 keV line would have been broadened to 50 keV, which is probably rather pessimistic [Isern et al., 1999], SPI would have achieved a sensitivity of $10^{-5}$ ph cm$^{-2}$s$^{-1}$ within a comparable exposure time (100 days). At this level, either SN 1998bu would have been clearly detected or the non-detection would have ruled out all existing thermonuclear supernova models. Assuming that SN 1998bu was indeed close to detection (at a 847 keV flux of say $3 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$), SPI would have detected the 847 keV line at a significance of about 10$\sigma$, allowing for valuable line profile studies.

2.8. Radioactivities from Accretion Disks around Black Holes

Another interesting site of nucleosynthesis has been proposed by Chakrabarti (1986) who considers the formation of elements in sub-Keplerian thick disks around black holes. Prantzos (1999) recently presented exploratory calculations for nucleosynthesis of radioactive isotope in thick disk models with viscosity parameter $\alpha$ in the $10^{-2} - 10^{-4}$ range. The short timescale of a few $10^{5}$ s and the relative low temperatures of a few $10^{5}$ K allow for only limited Hydrogen burning to take place through the hot CNO, NeNa and MgAl chains. In such conditions, radioactive isotopes familiar from e.g. nova nucleosynthesis ($^{7}$Be, $^{22}$Na, $^{26}$Al) are produced, along with the release of positrons by $^{13}$N and $^{15}$O. Assuming that $\sim 50\%$ of the accretion flow is ejected upon arrival in the inner disk (by e.g. radiation pressure or some other mechanism), he derived SPI detection distances of 2 kpc, 100 pc, and 1 kpc for $^{7}$Be, $^{22}$Na, and $^{26}$Al for a 10 $M_\odot$ black hole that is fed by a massive companion at a rate of $2 \times 10^{-5}$ $M_\odot$/yr for $\sim 10^{6}$ yrs.

Indeed, observations of high Li abundances in the secondaries of black hole binaries may indicate nucleosynthesis during explosive accretion events. Martin et al. (1996) suggest that the transient emission line observed by SIGMA during the 1991 outburst of Nova Muscae [Goldwurm et al., 1992] may be due to de-excitation of $^7$Li following the radioactive decay of freshly produced $^7$Be. Although it remains difficult to explain the high observed flux in the 478 keV feature [Yi & Narayan, 1997] and the short duration of the event ($\sim 13$ hours; Goldwurm et al., 1992), the search for signposts of nucleosynthesis in accretion disks around black holes presents an exciting exploratory field for SPI (see also Isern, these proceedings).

3. INTERACTION LINES

The second fundamental process (after radioactive decay) that leads to gamma-ray line emission is nuclear de-excitation following energetic particle reactions [Ramaty et al., 1979]. These gamma-rays exhibit a great wealth of spectral features, ranging from very narrow lines to broad features, depending on the composition and energy spectrum of the energetic particles, and on the composition and physical state of the ambient medium. Observable gamma-ray line emission is expected from many astrophysical sites, including solar flares, the interstellar medium, neutron stars and black holes, supernova remnants, and active galactic nuclei (see Bykov, these proceedings). Ramaty et al. (1979) calculated detailed gamma-ray spectra arising from energetic particle interactions with the interstellar medium for various abundance compositions. The most prominent features they predict are a broadened line at 4.438 MeV from excited states in $^{12}$C and $^{13}$B, a broadened line with a narrow component at 6.129 MeV from excited $^{16}$O, and a number of narrow or very narrow lines at lower energies, among which is the 847 keV line from excited $^{56}$Fe. They estimated 4.438 MeV and 6.129 MeV line fluxes from the central radial of the Galaxy of the order of $10^{-5} - 10^{-4}$ ph cm$^{-2}$s$^{-1}$rad$^{-1}$, rather optimistic for the potential detection with existing gamma-ray telescopes (or with SPI). However, the normalisation of the spectra was rather arbitrary, and indeed, observations by SMM [Harris et al., 1995] and OSSE [Harris et al., 1999] suggest that the line fluxes should be below $10^{-3}$ ph cm$^{-2}$s$^{-1}$rad$^{-1}$.

Relying on the observation that the Be/Fe abundance ratio is independent of metallicity, Ramaty
et al. (1997) proposed to use the current epoch galaxywide Be production rate to normalise the gamma-ray line intensities. With this approach, they predict that the nuclear line emission in the energy interval $3 - 7$ MeV from the central radius of the Galaxy should not exceed $2.5 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$rad$^{-1}$. From a similar calculation, Tatischeff et al. (1999) find an upper limit of $5 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$rad$^{-1}$ (see also Tatischeff et al., these proceedings).

Can SPI detect gamma-ray lines at this level? Following the discussion of Jean et al. (2000), the SPI sensitivity to diffuse emission may be estimated by multiplying the point-source sensitivity by $\sqrt{2}$. Assuming that the galactic plane emission has a latitude extent of less than $\pm 8^\circ$ (i.e. it fits entirely in the SPI fully-coded field of view), SPI is able to observe 0.28 radians of the galactic ridge within the fully coded field-of-view of $16^\circ$ with a single pointing. Thus, the SPI sensitivity in units of ph cm$^{-2}$s$^{-1}$rad$^{-1}$ for diffuse galactic plane emission is obtained by multiplying the point-source sensitivity by a factor of 5. For narrow lines in the $3 - 7$ MeV range, a sensitivity of $2.5 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$rad$^{-1}$ seems feasible.

If the excited nuclei are in the gas phase of the interstellar medium, the recoil following excitation will lead to a considerable Doppler-broadening of typically $\sim 100$ keV (FWHM). Following Eq. [1] it seems unrealistic that such lines are detectable by SPI. If, however, a large fraction of nuclear de-excitations appear within interstellar grains, the nuclei may lose their recoil energy before emitting gamma-rays, leading to much narrower lines. The 3$\sigma$ localisation error box of this source, $\sigma = (300.5^\circ, -29.6^\circ)$ with a $2.223$ MeV flux of $1.7 \times 10^{-4}$ ph cm$^{-2}$s$^{-1}$. Among the 11 objects catalogued by the ROSAT all-sky survey that coincide with the 3$\sigma$ localisation error box of this source, none corresponds to any known X-ray binary, cataclysmic variable, or active galactic nucleus. The most interesting of the ROSAT sources is RE J0317-853, which is identified as a nearby (35 pc) peculiar white dwarf. RE J0317-853 is one of the hottest known white dwarfs (50 000 K) and shows a magnetic field between 180-800 MG, one of the strongest known for white dwarfs. Regular white light variations indicate an anomalous high rotation period of 12 minutes, which is difficult to explain for an isolated white dwarf (indicating either an unidentified binary companion or a white dwarf merger).

With the aim of testing this hypothesis, McConnell et al. (1998) assembled an all-sky map for $2.223$ MeV line emission from 5 years of COMPTEL data. However, instead of detecting signatures from X-ray binaries within the galactic plane, they found only one significant (3.7$\sigma$) point-like source located at $(l, b) = (300.5^\circ, -29.6^\circ)$ with a $2.223$ MeV flux of $1.7 \times 10^{-4}$ ph cm$^{-2}$s$^{-1}$. Among the 11 objects catalogued by the ROSAT all-sky survey that coincide with the 3$\sigma$ localisation error box of this source, none corresponds to any known X-ray binary, cataclysmic variable, or active galactic nucleus. The most interesting of the ROSAT sources is RE J0317-853, which is identified as a nearby (35 pc) peculiar white dwarf. RE J0317-853 is one of the hottest known white dwarfs (50 000 K) and shows a magnetic field between 180-800 MG, one of the strongest known for white dwarfs. Regular white light variations indicate an anomalous high rotation period of 12 minutes, which is difficult to explain for an isolated white dwarf (indicating either an unidentified binary companion or a white dwarf merger).

McConnell et al. (1998) suggest flaring activity on RE J0317-853 may lead to $2.223$ MeV line emission, similar to the processes observed in solar flares. Indeed, a strong, highly polarised radio flare has been observed from this object in 1996, but more recent radio observations did not show evidence for any flaring activity (Barrett et al., 1999). Also optical spectroscopy showed no flaring behaviour or evidence for a low mass companion, hence Barrett et al. (1999) conclude that RE J0317-853 is not a strong candidate for the $2.223$ MeV counterpart.

In any case, the $2.223$ MeV emission feature remains intriguing, and SPI observations should shed new light on the nature of this object. SPI should easily allow to detect the $2.223$ MeV line, even if it would be broadened to 1 MeV (FWHM) – which however is excluded by the COMPTEL observations. Even IBIS should detect the $2.223$ MeV source if the flux is as high as reported by McConnell et al. (1999), and the good angular resolution should allow to improve the counterpart identification considerably.

4. NEUTRON CAPTURE SIGNATURES

Nuclear reactions within the accretion flow of compact objects may not only produce radioisotopes (see Section [2.8]), but can also release neutrons that may subsequently be captured by protons to form $^2$H (Deuterium). The neutron capture is accompanied by emission of a $2.223$ MeV photon that eventually may be observable by gamma-ray telescopes (Brecher & Burrows, 1980). The detection of the $2.223$ MeV line would provide evidence for this nuclear reactions, and would allow for a detailed study of the heating processes within the accretion flow. Note, however, that the line may eventually be broadened or shifted (Brecher & Burrows, 1986; Alaronian & Sunyaev, 1984) and emission at $2.223$ MeV is only expected if the neutrons can encounter a medium that is denser and cooler than the hot accretion disk plasma (Guessoum, 1989).
5. CONCLUSIONS

With this review, we tried to illustrate that SPI has been designed to address an extremely wide range of research topics, reaching from massive star nucleosynthesis over supernova physics to accretion flows in compact objects. Since SPI is the spectrometer on INTEGRAL we deliberately excluded topics related to continuum emission – those will be addressed by the corresponding paper of the IBIS collaboration (Ubertini, these proceedings). Nevertheless, topics like the diffuse gamma-ray background (Lichti et al., these proceedings), the diffuse galactic gamma-ray emission (Valinia et al., these proceedings), pulsars (Dyk et al., these proceedings), active galactic nuclei (Collmar, these proceedings), or gamma-ray bursts (Mereghetti et al., these proceedings), are equally important for SPI, which has a continuum sensitivity comparable to IBIS, but which is optimised for large-scale emission (IBIS provides a much better angular resolution but is less sensitive to extended emission features). On the other hand, IBIS may also detect gamma-ray lines and can help to identify counterparts by means of the high localisation accuracy. Thus, SPI and IBIS are complementary instruments on INTEGRAL, which, when combined, will explore the gamma-ray sky far beyond the established horizon.

ACKNOWLEDGMENTS

The authors want to thank M. Hernanz, P. Jean, G. Meynet, N. Mowlavi, N. Prantzos, and V. Tatischeff for helpful discussions.

REFERENCES

Aharonian, F.A, and Sunyaev, R.A. 1984, MNRAS, 210, 257
Arnett, W.D. 1977, Ann. NY Acad. Sci., 302, 90
Arnould, M., Paulus, G., and Meynet, G. 1997, A&A, 321, 452
Aschenbach, B., Iyudin, A.F., and Schönhelder, V. 1999, A&A, 350, 997
Aschenbach, B. 1998, Nature, 396, 141
Austin, S.J., Wagner, R.M., Starrfield, S., et al. 1996, AJ, 111, 869
Barrett, P., McConnell, M., Drake, S., et al. 1999, AAS HEAD meeting 31, 33.10
Bloemen, H., Morris, D., Knödlseder, J., et al. 1999, ApJ, 521, L137
Bloemen, H., Wijnands, R., Bennett, K., et al. 1994, A&A, 281, L5
Bouchet, L., Mandrou, P., Roques, J.-P., et al. 1991, ApJ, 383, L45
Brecher, K., and Burrows, A. 1980, ApJ, 240, 642
Burgess, C.P., and Zuber, K. 1999, New Scientist, 163, 2204, p. 7
Cappellaro, E., Mazzali, P.A., Benetti, S., et al. 1997, A&A, 328, 203
Cerviño, M., Knödlseder, J., Schaerer, D., et al. 2000, A&A, in press
Chakrabarti, S.K. 1986, in: Accretion Processes in Astrophysics, eds. J. Audouze, J. van Tran Thanh, p. 155
Clayton, D.D., and Craddock, W.L. 1965, ApJ, 142, 189
Clayton, D.D., Colgate, S.A., Fishman, G.J. 1969, ApJ, 155, 75
Cohen, J.G. 1985, ApJ, 292, 90
Comb, J.A., Romero, G.E., and Benaglia, P. 1999, ApJ, 519, L177
Dame, T.M., Ungerechts, H., Cohen, R. S., et al. 1987, ApJ, 322, 706
Dermer, C.D., and Skibo, J.G. 1997, ApJ, 487, L57
Diehl, R., & Timmes, F.X. 1998, PASP, 110, 637
Diehl, R., Oberlack, U., Knödlseder, J., et al. 1997, in: Proc. 4th Compton Symposium, eds. C.D. Dermer, M.S. Strickman, and J.D. Kurfess, p. 1114
Duncan, A.R., and Green, D. A. 2000, A&A, in press
Fisher, A., Branch, D., Hatano, K., and Baron, E. 1999, MNRAS, 304, 67
Fitzpatrick, E.L., Ribas, I., Guinan, E.F., et al. 2000, AAS meeting 196
Fransson, C., and Kozma, C. 1998, in: SN 1987A: Ten Years After, eds. M.M. Phillips and N.B. Suntzeff, ASP, in press
Gallino, R., Busso, M., Wasserburg, G.J., et al. 1999, in: Astronomy with Radioactivities, eds. Roland Diehl and Dieter Hartmann, p. 95
Gehrels, N., and Chen, W. 1996, A&AS, 120C, 331
Georgii, R., Plüschnke, S., Diehl, R., et al. 2000, in: Proc. 5th Compton Symposium, eds. M.L. McConnell and J.M. Ryan, p. 49
Goldwurm, A., Ballet, J., Cordier, B., et al. 1992, ApJ, 389, L79
Gómez-Gomar, J., Hernanz, M., José, J., and Isern, J. 1998a, MNRAS, 296, 913
Gómez-Gomar, J., Isern, J., and Jean, P. 1998b, MNRAS, 295, 1
Guessoum, N., Ramaty, R., Lingenfelter, R.E., 1991, ApJ, 378, 170
Guessoum, N. 1989, ApJ, 345, 363
Guinan, E.F., Fitzpatrick, E.L., Dewarf, L.E., et al. 1998, ApJ, 509, L21
Harris, M.J., Naya, J.E., Teegarden, B.J., et al. 1999, ApJ, 522, 424
Harris, M.J., Teegarden, B.J., Cline, T.L., et al. 1998, ApJ, 501, L55
Harris, M.J., Purcell, W.R., Grabelsky, D.A., et al. 1996, A&A, 120C, 343
Ramaty, R., Kozlovsky, B., Lingenfelter, R.E., and Reeves, H. 1997, ApJ, 488, 730
Ramaty, R., Kozlovsky, B., and Lingenfelter, R.E. 1979, ApJS, 40, 487
Ramaty, R., and Lingenfelter, R.E. 1977, ApJ, 213, L5
Riegler, G.R., Ling, J.C., Mahoney, W.A., et al. 1981, ApJ, 248, L13
Ruiz-Lapuente, P., Cappellaro, E., Turatto, M., et al. 1992, ApJ, 387, L33
Shafter, A.W. 1997, ApJ, 487, 226
Schönfelder, V., Bloemen, H., Collmar, W., et al. 1999, in: Proc. 5th Compton Symposium, eds. Mark L. McConnell and James M. Ryan, p. 54
Share, G.H., Leising, M.D., Messina, D.C., and Purcell, W.R. 1990, ApJ, 358, L45
Share, G.H., Leising, M.D., Messina, D.C., et al. 1988, ApJ, 326, 717
Smits, D.P. 1991, MNRAS, 248, 20
Spyromilio, J., Meikle, W.P.S., Allen, D.A., and Graham, J.R. 1992, MNRAS, 258, 53
Starrfield, S., Truran, J.W., Sparks, W.M., Arnould, M. 1978, ApJ, 222, 600
Tatischeff, V., Ramaty, R., and Valinia, A. 1999, in: LiBeB, Cosmic Rays and Gamma-Ray Line Astronomy", ASP Conference Series, eds. R. Ramaty, E. Vangioni-Flam, M. Casse, and K. Olive, in press
Teegarden, B.J., Cline, T.L., Gehrels, N., et al. 1996, ApJ, 463, L75
The, L.-S., Diehl, R., Hartmann, D.H., et al. 1999, in: Proc. 5th Compton Symposium, eds. Mark L. McConnell and James M. Ryan, p. 64
Timmes, F.X., and Woosley, S.E. 1997, ApJ, 489, 160
Timmes, F.X., Woosley, S.E., Hartmann, D.H., et al. 1995, ApJ, 449, 204
Watanabe, K., Hartmann, D.H., Leising, M., The, L.-S. 1999, ApJ, 516, 285
Weiss, A., and Truran, J.W. 1990, A&A, 238, 178
Woosley, S.E., and Heger, A. 1999, in: Astronomy with Radioactivities, eds. Roland Diehl and Dieter Hartmann, p. 133
Woosley, S.E. 1997, ApJ, 476, 801
Woosley, S.E., and Hoffman, R.D. 1991, ApJ, 368, L31
Yi, I., and Narayan, R. 1997, ApJ, 486, 363