FUTURE INSTRUMENTAL CAPABILITIES IN THE ENERGY RANGE OF NUCLEAR TRANSITIONS

P. von BALLMOOS
Centre d'Etude Spatiale des Rayonnements, Toulouse, France

Abstract. Gamma-ray lines are the fingerprints of nuclear transitions, carrying the memory of high energy processes in the universe. Setting out from what is presently known about line emission in gamma-ray astronomy, requirements for future telescopes are outlined. The inventory of observed line features shows that sources with a wide range of angular and spectral extent have to be handled: the scientific objectives for gamma-ray spectroscopy are spanning from compact objects as broad class annihilators, over long-lived galactic radioisotopes with hotspots in the degree-range to the extremely extended galactic disk and bulge emission of the narrow e^-e^+ line.
The instrumental categories which can be identified in the energy range of nuclear astrophysics have their origins in the different concepts of light itself: geometrical optics is the base of coded aperture systems - these methods will continue to yield adequate performances in the near future. Beyond this, focusing telescopes and Compton telescopes, based on wave- and quantum- optics respectively, may be capable to further push the limits of resolution and sensitivity.

Key words: gamma-ray astronomy – instrumentation

1. Introduction

With the Compton Gamma-Ray Observatory and the GRANAT/SIGMA telescope in orbit, high energy astrophysics has for the first time ever the opportunity to study all the facets of celestial gamma-rays side by side. In the energy range of nuclear transitions, the gamma-ray sky has been mapped on various angular scales and a large number of new gamma-ray sources has been discovered (see reviews by Gehrels et al. 1994 and Paul 1995). Maybe the most important scientific potential of the present generation high energy telescopes is their extremely broad common energy coverage. Together with the operating X-ray and high energy gamma-ray telescopes, a quasi-continuous coverage has opened the possibility for multi-wavelength studies of continuum spectra spanning from the keV- to the GeV-range. Figure 1 indicates that the present area once might be called the "golden age of gamma-ray astronomy": never before has the high-energy sky been examined so thoroughly and over such a broad energy range. For many of the high energy sources, multi-wavelength studies may be the only way that leads to an understanding of their complex source mechanisms. A model case is the spectrum of the quasar 3C273 (Lichti et al. 1995) that has been observed - partly simultaneously - from radio to gamma-ray energies. Nevertheless, the gamma-ray telescopes on the Compton Gamma Ray Observatory and on GRANAT also have raised new astrophysical questions and highlighted those which remain unanswered. The future goals of gamma-ray astronomy

Fig. 1. The "golden age of gamma-ray astronomy" ? Never before the high-energy sky has been examined so thoroughly and over such a broad energy range.

must be defined in this context. The progress of SIGMA, BATSE, OSSE and COMPTEL is based primarily on skymaps, excellent timing analysis, and moderate to fair spectral resolution. The observations have revealed certain aspects of the morphology of celestial gamma-ray emitters, yet, the physical processes at work are often only poorly understood. Frequently, the observed spectra do not sufficiently constrain the emission mechanisms: explaining a relatively simple, featureless continuum with a complex multiparameter model can be ambiguous, moreover, different components may blend into one another, each of them can depend on various physical parameters in the emitting region.

In many ways, the present situation resembles the situation of optical astronomy in the beginning of the last century: Back then, the available observational data mainly consisted in images, starcounts, variability's, and colors. Astrophysics was born when G. Kirchhof and R. Bunsen (here at Heidelberg in 1859) developed the spectral analysis and explained the Frauenhofer-lines in the spectrum of the sun. The exploration of atomic and molecular lines has since turned out to be the most powerful tool for the study of the physical conditions in celestial sources.

Up to today, only little advantage has been taken from the fundamental astrophysical information contained in gamma-ray lines. The reason for this is the modest energy resolution of the existing instruments (typically

$\Delta E/E \sim 10\%$). High resolution spectroscopy will therefore be one of the major goals of the next generation of space borne gamma-ray telescopes.

The scientific potential of nuclear gamma-ray astronomy is outlined in section 2. In section 3, different categories of instruments for spectroscopy in the low and medium gamma-ray channel are presented: coded aperture systems, Compton telescopes and diffraction lens telescopes. The three techniques actually reflect our current perception of light itself - they are based on the principles of geometrical optics, quantum optics and wave optics, respectively.

2. The promise of nuclear gamma-ray astronomy

Ultraviolet, visible and infrared-spectroscopy has long become an extremely valuable technique in astronomy. While optical lines reflect structural changes in the electron shell of atoms, caused by collisions with energies of the order of 10 eV ($T \sim 10^3$K), transition between discrete nuclear energy levels imply MeV energies ($T \sim 10^7$ *to* 10^9K), corresponding to the binding energy of nucleons. Collision energies of this order are characteristic for the temperatures inside stars, particles accelerated by electromagnetic fields in solar flares, or interactions of cosmic ray particles with the interstellar medium. Gamma-ray lines are the fingerprints of nuclear transitions, carrying the memory of high energy processes in the universe. High resolution gamma-ray spectroscopy is a unique tool to identify the presence of exited nuclei, quantitatively determine their abundance's, and provide insight into the physical conditions of the source regions (temperature, density, gravitational or cosmological energy shifts).

The scientific potential of gamma-ray spectroscopy includes better understanding of the chemical evolution of the Galaxy by mapping the sites of recent nucleosynthetic activity (novae, SN, massive stars). The observation of supernovae in the galaxies of our local cluster and closeby superclusters (Virgo cluster) will verify our models of nucleosynthesis in massive stars. Spectral features in solar flares, cyclotron lines in gamma-ray bursts and pulsars are among the further challenges of gamma-ray spectroscopy.

An inventory of observed gamma-ray lines is presented in table I, it reflects the current status of nuclear gamma-ray astronomy. Note that most of the knowledge on gamma-ray lines is based on observations made with scintillation detectors that typically feature energy resolutions of 10%. Nevertheless, these elementary spectroscopic measurements already indicate the tremendous potential of gamma-ray line emission. Performance requirements for future spectroscopy missions become conspicuous when the measured/-anticipated line fluxes are compared to the expected angular scales. Figure 2 indicates that emissions with a wide range of angular and spectral extent are expected, varying in intensity by several orders of magnitude. The sci-

TABLE I

Observed celestial gamma-ray line features

Physical Process	**Energy** [keV]	**Source**	**Flux** ph cm^{-2}s^{-1}	**Instrument, Detector**
Nuclear deexcitation				
^{56}Fe(p,p',γ)	847	Solar flares	≤ 0.05	SMM, NaI
^{24}Mg (p,p',γ)	1369	Solar flares	≤ 0.08	SMM, NaI
^{20}Ne (p,p',γ)	1634	Solar flares	≤ 0.1	SMM, NaI
^{28}Si (p,p',γ)	1779	Solar flares	≤ 0.08	SMM, NaI
^{20}12C(p,p',γ)	4439	Solar flares	≤ 0.1	SMM, NaI
	4439	Orion Comp.	$\leq 5{\cdot}10^{-5}$	COMPTEL, sc)
^{16}O(p,p',γ)	6129	Solar flares	≤ 0.1	SMM, NaI
	6129	Orion Comp.	$\leq 5{\cdot}10^{-5}$	COMPTEL, sc)
Radioactive decay				
^{56}Co(EC,γ)^{56}Fe	847, 1238	SN 1987A	$\approx 10^{-3}$ b	Ge det's and
	2598			var. scint's,
	847,1238	SN 1991T	$5{\cdot}10^{-5}$ b	COMPTEL, sc)
^{57}Co(EC,γ)^{57}Fe	122, 136	SN 1987A	$\approx 10^{-4}$	OSSE, NaI-CsI
^{44}Ti(EC)^{44}Sc($\beta^+\gamma$)	1157	Cas A SNR	$7{\cdot}10^{-5}$	COMPTEL, sc)
^{26}Al($\beta^+\gamma$)^{26}Mg	1809	gal. plane	$4{\cdot}10^{-4}$	COMPTEL, sc)
	1809	Vela SNR	1-6$\cdot10^{-5}$	COMPTEL, sc)
e$^-$e$^+$ Annihilation				
	511	Gal. bulge	$1.7{\cdot}10^{-3}$	OSSE, NaI-CsI
	511	Gal. disk	$4.5{\cdot}10^{-4}$	OSSE, NaI-CsI
	480±120 a)	1E 1740-29 c)	$1.3{\cdot}10^{-2}$	SIGMA, NaI
	511	Solar Flares	≤ 0.1	SMM, NaI scint.
	479±18 a)	Nova Muscae	$6.3{\cdot}10^{-3}$	SIGMA, NaI
	400-500 a)	Bursts ? c)	≤ 70	various scint.
	440±10 a)	Crab PSR ? c)	$3{\cdot}10^{-4}$	FIGARO, NaI
Neutron Capture				
^{1}H(n,γ)^{2}H	2223	Solar flares	≤ 1	SMM, NaI
^{56}Fe(n,γ)^{57}Fe	5947 a)	6/10/1974 tr.	1.5 10^{-2}	SMM, NaI
Cyclotron Lines				
	20-58	Hercules X-1	$\leq 3{\cdot}10^{-3}$	various scint.

legend: sc) liquid scintillator/NaI scintillator; a) Redshifted line; b) Maximum emission, c) detection uncertain, the feature has not been confirmed yet

entific objectives for gamma-ray spectroscopy are spanning from compact sources as broad class annihilators, over long-lived galactic radioisotopes with hotspots in the degree-range to the extremely extended galactic disk and bulge emission of the narrow e$^-$e$^+$ line.

Fig. 2. Future spectroscopy missions have to face emissions with a wide range of angular extent, and with intensities different by several orders of magnitude. The anticipated flux for extragalactic SNe of type 1 has been deduced from the COMPTEL detection of SN1991T (Morris et al. 1995) and by scaling its ^{56}Co 847 keV gamma-ray flux with the optical peak magnitude of observed SNIa.

According to our present view of celestial gamma-ray sources in the energy range of nuclear transitions, narrow lines seem to be generally emitted from extended distributions while broad lines tend to be radiated by compact sources.

3. Instruments for gamma-ray spectroscopy

A natural first objective for a future gamma-ray spectroscopy mission is the mapping of the relatively intense sources (on the upper right of figure 2) which are typically emitting 10^{-4} ph cm^{-2}s^{-1} to a few 10^{-6} ph cm^{-2}s^{-1}. Candidate sources of this intensity are mostly galactic and include the sites of recent nucleosynthesis, regions of $e^{-}e^{+}$ annihilation and clouds where nuclear de-excitation by energetic particles takes place. Some of them might appear as extended structures: either because of their apparently diffuse origin - such as the narrow 511 keV line (Purcell et al. 1994) - or because they are relatively closeby as the nucleosynthesis sites in the local spiral arm (del Rio et al. 1994). An instrument that is adequate for this kind of objectives should provide a sensitivity of several 10^{-6} ph cm^{-2}s^{-1}, a wide field of view and an angular resolution in the degree range. Such a profile corresponds to the expected performances of the SPECTROMETER on ESAs INTEGRAL mission and will be discussed in section 3.1.

Besides of the supernovae 1987A (Matz et al. 1988) and 1991T (Morris et al. 1995) the evidence for point like sources of narrow gamma-ray line emission has been mostly implicit at this point. Yet, in the area at the lower left of figure 2 various objects like e.g. galactic novae and extragalactic supernovae are predicted. These sources should have small angular diameters but very low fluxes - mostly because such objects are relatively rare and therefore are more likely to occur at large distances. In order to cover the objectives in this area, experimental gamma-ray astronomy has to find new ways to improve the observational performances after INTEGRAL. For the energies above 500 keV, solid state Compton telescopes (e.g. as proposed by the ATHENA concept) could achieve sensitivities nearly an order of magnitude lower, while providing angular resolutions of a fraction of a degree over a wide field of view. This perspective is presented in section 3.2.

Pushing the performances even further leads to several apparently unsolvable problems. Up to now, better instruments generally were bigger instruments. Yet, physical limits for the size of spaceborne instruments are being attained today. Moreover, achieving sensitivities better than 10^{-6} ph cm^{-2}s^{-1} and resolutions better than fractions of a degree seems to be principally impossible with the presently practiced instrumental concepts: even larger collection areas are synonymous with larger detectors and thus higher background noise. The ensuing mass/sensitivity dilemma can ultimately only be overcome by a radically new type of gamma-ray telescope. In section 3.3, a possible way out of this impasse is presented: a focusing gamma-ray telescope using a tunable crystal diffraction lens.

3.1. SPECTROSCOPY WITH CODED APERTURE SYSTEMS

The underlying concept of coded aperture instruments is geometrical optics since the source photons are considered as traveling on rectilinear paths only. Light is passing through open elements of an otherwise opaque aperture. This aperture system - consisting of masks or collimators - modulates the signal which then reaches the detection plane designed to discern shadow patterns of some kind*. Since the photoelectric effect is the predominant mode of gamma-ray interaction in medium- and high-Z materials, these systems are well adapted to the low energy gamma-ray channel. Pinhole cam-

---

* The basic phenomenon of coded aperture images has first been described by Aristotle in 4th century BC. Noticing that specks of sunlight under a large tree always are rounded, he uses the concept of light traveling along straigt lines through 'peep-holes' to interpret the images (Aristotle, $\pi\rho o\beta\lambda\acute{\eta}\mu\alpha\tau\alpha$). Aristotle also describes and interprets the observation of the crescent-shaped images of the sun during an eclipses produced under different 'masks': eg. using the small spaces between the leaves of plane trees, the small holes of a sieve or the holes made by crossing the fingers of one hand over the other.

eras, rastering collimators, coded masks and modulation collimators belong to this category of instruments.

In gamma-ray astronomy, two main classes of coded aperture systems are used, according to whether the signal is encoded by spatial modulation (coded masks telescopes) or by temporal modulation (modulation collimators). These two types stand for a whole spectrum of devices mixing the basic concepts of spatial and temporal modulation.

Typical coded mask telescopes consist of a planar array of opaque and transparent elements located in front of a position sensitive detection plane (PSD). Scanning collimators or rotating modulating collimators use moving aperture parts in order to time modulate the intensity at a detection plane that does not need to provide spatial resolution. Many of these instruments modulate the signal from an extended region of the sky and thus are able to observe a number of sources simultaneously or quasi simultaneously. The telescopes featuring this multiplex advantage over rastering collimators (such as pure 'on-off' techniques) are sometimes called multiplexing devices.

Our present understanding of the low energy (<1 MeV) gamma-ray sky has been acquired mainly by coded aperture systems. Operational satellite instruments of this type include SIGMA, OSSE and BATSE (Paul et al. 1991, Johnson et al. 1993, and Fishman et al. 1989). While the detection plane of all three of them is based on scintillators, the aperture systems used are a coded mask, a collimator, and the earth, respectively.

High resolution spectroscopy with a coded mask instrument will be available by the beginning of the next decade with ESA's INTEGRAL mission. The INTEGRAL SPECTROMETER described below corresponds to the ESA proposal by a consortium between the CESR (Toulouse), MPE (Garching), CEA (Saclay), IFCTR (Milan), IEEC (Barcelona), Univ. of Louvain, Univ. of Valencia, Univ.of Birmingham and US Institutes. Figure 3a) gives a cutaway view of the SPECTROMETER. The instrument features a compact array of high purity Germanium detectors entirely shielded by a BGO/CSI anticoincidence system (for details see e.g. von Ballmoos et al. 1995).

The Ge detector assembly consists of 19 high purity n-type germanium detectors cooled to 85K via pulsed tubes supplied by two cryogenic compressors. With a total geometric detection area of $\approx$ 500 cm^2 the detection plane is the largest one that could be fitted into the overall constraints of the INTEGRAL mission. The aperture subsystem features a tungsten coded mask (HURA with 127 elements) 171 cm above the detector. The coded mask together with the detector plane defines a fully coded field of view of 16°× 16°.

The narrow line sensitivity shown in Fig. 4 has been obtained by completely modeling the SPECTROMETER for the radiation environment conditions expected outside the magnetosphere. The sensitivity is based on models for the instrument efficiency (GEANT) and background in ^{70}Ge detectors

Fig. 3. 3 instruments

(Naya et al. 1995). The anticipated performance for narrow line spectroscopy is characterized by an energy resolution in the parts per thousand range (typically 2 keV at 1 MeV), an angular resolution of order 2°, and a sensitivity $2\text{-}5{\cdot}10^{-6}$ ph $cm^{-2}s^{-1}$ in the energy range relevant for nuclear astrophysics. The 511 keV line sensitivity is of the order of $2{\cdot}10^{-5}$ ph $cm^{-2}s^{-1}$.

3.2. SPECTROSCOPY WITH COMPTON TELESCOPES

While the total cross section has its minimum at a few MeV, the energy range between several hundred keV and about 30 MeV is dominated by the Compton effect. At these energies coded aperture systems run into several problems: the efficiency of the modulation decreases and various background problems related to heavy shielding become increasingly prohibiting. Hence, making use of the quantum nature of the photon interactions is an inevitable choice for instruments at medium and high energy gamma-rays. The idea to make use of the Compton effect instead of fighting it with thicker shielding and modulators has stimulated several groups and resulted in a distinct class of imaging instruments. With COMPTEL on the Gamma-ray Observatory, the concept has definitely proven its unique potential for MeV gamma-ray astronomy (Schönfelder et al. 1993).

In a Compton telescope the incident gamma-ray is identified by successive interactions in the two detector layers D_1 and D_2. Compton scattering in D_1 is favored when low Z material is chosen. Total absorption of the scattered photon in D_2 can be expected when high Z materials are used. Since the $D_1 \wedge D_2$ coincidence condition discriminates against most of the internal nβ background, a Comptom telescope has an extremely low background. At the same time, this coincidence condition causes the relatively low detection efficiency. In order to further reduce the background due to upward scattered events, the time-of-flight between the two detectors is usually measured in Compton telescopes. Neutron interactions can be identified by measuring the pulse shape of the scintillation pulse.

From the interaction location in D_1 and D_2, the direction χ, ψ of the scattered gamma-ray is obtained; the energy deposits in D_1 and D_2 are E_1 and E_2 respectively. The scatter direction χ, ψ, together with the amounts of energy deposited in the two interactions can be used to reconstruct the arrival direction of the gamma-ray. The Compton equation allows to express the scatter angle φ as a function of the energy-deposits E_1 and E_2:

$$cos\overline{\varphi} \quad = \quad 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2} \qquad \text{with } m_e c^2 = 511\text{keV}$$

If E_1 and E_2 are measured without systematic errors ($E_{tot} = E_1 + E_2 = E_\gamma$), the derived scatter angle $\overline{\varphi}$ equals the true Compton scatter angle φ. The arrival direction of the incident gamma-ray can then be confined to lie on a cone-mantle with axis χ, ψ and opening angle $\overline{\varphi}$ (see fig 3b). The projection of this cone results in a circle on the sky that is generally called the 'event circle'. No information on the azimuth of the incident photon on the circle can be deduced from the measured parameters. The azimuthal information is lost since state-of-the-art Compton telescopes can not measure the direction of the recoil electron in D_1. Consequently, genuine direct imaging is impossible for present Compton telescopes: the image reconstruction process is handicapped by missing information on the scatter angle of the incident photon.

The ATHENA concept (Kurfess et al. 1994, Kröger et al. 1995, Johnson et al. 1995) is based on D_1 and D_2 layers using Germanium planar strip detectors providing 2-3 keV spectral resolution and spatial resolution of ~2 mm. Such detectors, typically 5 cm × 5 cm × 1 cm, are available today and might be integrated into large panels in the future. The ATHENA concept foresees a 1 m^2 D_1 layer consisting of one panel, and a 1 m^2 D_2 layer of four panels, each panel containing 400 Ge strip detectors. Figure 3b) shows a schematic diagram of a solid state Compton telescope combined with a coded mask for low energy gamma-rays. In the Compton mode (300 keV-10 MeV) such an instrument can achieve angular resolutions of 0.2°- 0.3° within a field of view of typically one steradian, and a narrow line sensitivity of several times 10^{-7} ph $cm^{-2}s^{-1}$ above 1 MeV (see fig. 4).

3.3. Spectroscopy with diffraction lens telescopes

Being used to accept that it is 'impossible to reflect or refract gamma rays', high energy astronomy has never considered to make use of the wave-quality of gamma-ray photons. Since focusing was out of question, the detector area of gamma-ray telescopes has always been identical with the photon-collecting area. Consequently, gamma-ray astronomy has come to a mass-sensitivity impasse, since achieving a fair signal to noise ratio is a conflict of trading in signal (~ detector-surface) against background (~ detector-volume).

A new type of gamma-ray telescope featuring a Laue-diffraction lens makes use of the periodic nature of light and its interference with the periodic structure of a crystal. The focusing gamma-ray telescope (Smither et al. 1995, von Ballmoos et al. 1995) is designed to collect gamma-ray line photons on a large effective area and focus them onto a Germanium detector matrix with a small equivalent volume for background noise.

The instrument has first been proposed as a balloon-borne telescope with the lens tuned to diffract 511 keV photons only (von Ballmoos and Smither 1994). Such a configuration makes possible the study of galactic 'micro-quasars' and other broad class annihilators in the light of e^-e^+ annihilation during a balloon flight. As a balloon-borne instrument it can provide high energy- and high angular resolution (2 keV, 15 arc sec, respectively) combined with an excellent sensitivity ($\sim 3 \cdot 10^{-5}$ ph $cm^{-2}s^{-1}$ at 511 keV). The

Fig. 4. Comparison of 3 σ narrow line sensitivities:
HEAO3 (achieved sensitivity). For all other instruments $T_{obs}=10^6$ sec.
The hatched area outlines the sensitivity of the INTEGRAL SPECTROMETER. Lower and upper limits are for an optimistic(o)/pessimistic(p) model: o) including the multiplexing advantage (i.e. sensitivity for any galactcic source during a 10^7 sec survey of the inner galaxy); p) including a β^+ background component.
The shaded area indicates different background estimates for the diffraction lens telescope.

performances of this Ge-lens/Ge-matrix system have been verified in summer 1994 during laboratory measurements with a ground based prototype (Naya et al. 1995).

Ultimately however, the concept should be put to use in space where longer exposures and steady pointing would result in outstanding sensitivities. Yet, as a satellite instrument, a monochromatic lens would clearly be a handicap since its scientific objectives are too exclusive - already e.g. the possible annihilation line of most extragalactic sources (AGNs, quasars) would be inaccessible because of cosmological redshift.

The need of a energy tuning has lead to a ‘tunable crystal diffraction lens’ (von Ballmoos et al. 1995) that permits observation of any identified source at any selected line-energy in the cardinal range of nuclear transitions (200 keV - 1300 keV). The ‘sequential’ operation mode resulting from such a concept makes the sites of explosive nucleosynthesis natural targets for a tunable crystal diffraction telescope.

A space borne telescope using an adaptative crystal diffraction lens will consist of three modules: the lens module, the detector module, and a boom. Optimally the lens module is located directly on the spacecraft, while the detector module is perched on the boom. An artists view of the concept is shown in Fig 3c. The lens module consists of a 90 cm diameter frame accommodating 700 germanium cubes (2 cm × 2cm × 2cm). The crystals are oriented so that they all diffract the incident radiation of a certain energy to the same focal point. Tuning the lens to an energy $E = E_{ref} + \Delta E$ requires that each of the single crystal is rocked by an angle $\Delta\Theta$ with respect to the position of a reference energy E_{ref} (i.e. 511 keV) in order to satisfy the Bragg condition anew.

$$\Delta\Theta \quad = \quad arcsin\left(\frac{hc}{2d(E_{ref} + \Delta E)}\right) \; - \; arcsin\left(\frac{hc}{2dE_{ref}}\right)$$

The precision/repeatability requirements for $\Delta\Theta$ are of the order of ~2 arc seconds. The performance of a device consisting of a piezo-driven actuator and an Eddy-current sensor that measures the displacement complies with these requirements. A miniaturized closed loop system is presently being built and tested at CESR and ANL.

In order to take maximum advantage of the particular properties of a focused gamma ray beam, a germanium matrix will be used for the detector module. These detectors have been found to be ideally adapted to resolve the beam energetically and spatially. A matrix also offers the possibility to monitor the remaining background simultaneously to the astrophysical observation. The low intensity of spacecraft induced background will permit the use of a very light anticoincidence shield.

Since the focal length of the lens is increasing with energy, a retractable boom will be used to the vary the distance between the lens and the detector module. An energy of 200 keV and 1240 keV respectively corresponds to a change in focal length of 3 m to 20 m - for the 511 keV positron annihilation line the distance lens-detector is 8.3 m. Booms have been used for space-borne gamma-ray spectroscopy on Apollo 15 (NaI detector) and on Mars-Observer (Ge detector). Deploying the detector on a boom instead of the diffraction lens has several striking advantages: The mechanical requirements on the mast rigidity are less severe since a Germanium detector array is small and lightweight and thus easy to handle on a boom; moreover, twists and bends of even up to a few cms are tolerable, as the focal spot can wander around on the detector array without significant loss of sensitivity. On the other hand, the stringent requirements for the pointing of the lens (typically $\sim 5''$) can be satisfied on board the pointed and stabilized spacecraft. Finally, moving the detector away from the spacecraft should reduce the background by up to an order of magnitude.

The imaging capabilities of a crystal diffraction telescope are defined by its beamwidth which is identical to the field of view of the lens: for compact sources discrete pointings of the object will be an appropriate observation mode, while extended structures as for example the jets of galactic micro-quasars will be scanned with the narrow beam. The field of view depends on the angular width of the mosaic structure of the diffracting crystals - it will typically be $\sim 15''$ FWHM. Below 1 MeV, the narrow line sensitivity is expected to be a few 10^{-7} ph $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (see figure 4).

4. Conclusion

With the spectrometer on ESA's INTEGRAL mission, a coded mask instrument for gamma-ray spectroscopy will be available by the beginning of the next decade. The foremost objectives of the INTEGRAL spectrometer will be the mapping of gamma-ray line sources emitting 10^{-4} ph $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to a few times 10^{-6} ph $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Many of these potential sources will be galactic. Some of them might appear as extended structures - either because of their truly diffuse origin or because they are relatively closeby as the nucleosynthesis sites in the local spiral arm. An energy resolution of $E/\Delta E \approx 500$, a wide field of view and a mid-scale angular resolution make the INTEGRAL spectrometer adequate for such objectives.

On a more distant horizon, experimental gamma-ray astronomy has to find ways to further push the limits of resolution and sensitivity: At energies above one MeV, Compton telescopes can provide angular resolutions of fractions of degrees and sensitivities of a several 10^{-7} ph $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. At energies below the MeV, tunable crystal diffraction telescopes can achieve sensitivities of a few times 10^{-7} ph $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and angular resolutions of the order of $15''$.

References

Aristotle, 'Problemata Physica' book XV, problems 6 and 11, 4th cent. BC, The Loeb Classical Library, (W. Heineman:London), 1936
del Rio E. et al., 199, AIP Conf. Proc. 304, p. 171, (ed. Fichtel C. et al., New York)
Fishman G. et al., 1989 in Johnson, W.N. (Ed), Proc GRO Science Workshop, p.239
Gehrels N. et al., 1994, ApJ Sup. S., 92, 351
INTEGRAL ESA SCI(93)1, ESA phase A study report, April 1993
Johnson W.N. et al., 1993, ApJ Sup. S., 86, 693
Johnson, W.N. et al., 1995, proc. of workshop 'Imaging in High En. Astron.', Capri 1994
Kurfess J.D. et al., NASA proposal for new mission concepts in Astrophysics, NRA 94-OSS-15, 1994
Kröger R.A. et al., 1995, proc. of workshop 'Imaging in High En. Astron.', Capri 1994
Lichti G. et al., Astron Astrophys 1995, in press
Matz S.M. et al., 1988, Nature 331, 416

Morris D. et al. 1995, proc. 17th Texas Symposium on Relativistic Astrophysics
Murphy R.J. et al. 1990, ApJ ,358, 290
Naya J., et al., 1995a, submitted to NIM
Naya J. et al. , 1995b, proc. of workshop 'Imaging in High En. Astron.', Capri 1994
Paul J. et al., 1991, Adv.Space Res., 11 (6), 289
Paul J. et al., 1995, in Signore M. et al (Ed), The Gamma Ray Sky with Compton GRO and SIGMA, p. 15
Purcell W.R et al., 1994, AIP Conf. Proc. 304, p. 403, (ed. Fichtel C. et al., New York)
Schönfelder, V., Hirner, A. and Schneider, K.: 1973, Nucl.Instrum. Meth., 107, 385.
Smither R.K. et al., 1995, proc. of workshop 'Imaging in High En. Astron.', Capri 1994
von Ballmoos P. and Smither R.K. 1994, ApJ Sup. S., 92, 663
von Ballmoos P. et al, 1995, proc. of workshop 'Imaging in High En. Astron.', Capri 1994
von Ballmoos P., 1995, proc. 17th Texas Symposium on Relativistic Astrophysics