Perspectives of Gamma-Ray Astronomy beyond 2000

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Despite the inherent observational difficulties gamma-ray astronomy has contributed substantially to our knowledge of the universe during the last roughly 20 years. The GRANAT mission and the Compton Observatory have had a remarkable impact with e.g. the discovery of new sources involving stellar or massive black holes, the mapping of gamma-ray line diffuse galactic emissions, the localization of thousands of gamma-ray bursts. Meanwhile the next-generation mission INTEGRAL is scheduled for launch in 2001/2002.

The gamma-ray domain extends from several tens of keV to TeV, covering at least seven decades in photon energy; this is equivalent to the extent of the electromagnetic spectrum starting from the radio to the ultraviolet. The gamma-ray astronomy which includes this huge stretch in wavelength can be separated into two broad domains.

Above several hundred GeV: the very high-energy photons interact with the atmosphere producing Cerenkov light along the photon trajectory. This light can be detected from the ground using large conventional telescopes. The recent progress in the capabilities of the instruments to separate the Cerenkov light associated with gamma rays and high-energy cosmic rays bombarding the atmosphere have permitted a significant breakthrough with the detection of several sources.

Below hundreds of GeV: the photons are absorbed and scattered in the atmosphere and they can be detected only from space with high altitude balloons or satellites. Moreover, as the wavelength of these photons is extremely short they cannot be easily reflected by mirrors as in conventional astronomy. Therefore the collector of photons is also the detector; this explains why the sensitivity of the gamma-ray telescopes is not increasing proportionally to the area of the collector but to its square root. Finally as this domain involves photons with energies large in comparison with optical or even ultraviolet photons, their number is comparatively quite small. All these considerations explain why gamma-astronomy from space is difficult and why the number of sources already detected is still limited even in comparison with its near neighbour, the X-ray domain where the ROSAT satellite is demonstrating the richness of the sky in X-ray objects. In spite of the technical limitations of gamma instruments, recent gamma-ray missions, GRANAT and Compton GRO, have proved the importance of high-energy phenomena at work in our Universe.

In this presentation we will limit ourselves to the low-energy gamma astronomy which concerns gamma rays below a few tens of MeV, where interactions are dominated by photoelectric and Compton processes.

In the first part we will recall briefly the origin of the gamma rays and the type of objects which are mainly concerned by these high energy phenomena.

Afterwards, we will focus first on some discoveries made with the GRANAT γ-ray mission. This Russian satellite includes the French gamma-ray telescope SIGMA which has successfully worked for more than 8 years. We will not consider the remarkable impact of the Compton Gamma-Ray Observatory (CGRO) on the gamma-ray astronomy because it has been extensively covered by a recent paper presented in this journal by V. Schönfelder [1]. Secondly, as we have been involved for more than 15 years in the gamma-ray bursts studies thanks mainly to the French/Soviet space programme, we will recall some recent results in this area. The quality of the results of the Italian Beppo Sax satellite has allowed a big step forward in the understanding of the origin of these mysterious and impulsive emissions.

The third part of this presentation will focus on the coming ESA mission INTEGRAL, indicating some scientific goals which will be of prime importance following GRANAT and Compton GRO.

The last part will indicate some tracks which can be explored to define the next generations of instruments after INTEGRAL.

Extensive analysis of the discoveries by the two major gamma-ray missions still working, GRANAT and Compton GRO, can be found in many papers published in refereed journals or presented at symposia [2–5].

1. Gamma-Ray Origin

Gamma-ray astronomy is the domain of extremely energetic processes involving:
- plasma with temperatures higher than 10^8 K
- high-energy particles accelerated:
  - in strong shock-waves produced by the stellar wind associated with massive stars or by supernovae explosions,
  - in the vicinity of compact objects – neutron stars (NS) or black holes (BH); the energy gained by particles in the strong gravitational field of these objects can reach 100 MeV/nucleon, more than 10 times the nuclear energy which can be produced in stellar cores (for instance the Sun) by proton-proton fusion.

Through these sources of high-energy particles, gamma rays can be produced by:
- Synchrotron emission of electrons in strong magnetic fields near pulsars (10^{12} gauss).
- Bremsstrahlung from electrons in the presence of matter in the interstellar medium or in the accretion disks of binary systems which include a BH or NS.
- Inverse Compton interaction of accelerated electrons with low-energy photons

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(X and UV photons) in the accretion disk around compact objects.

- Nuclear reactions :

– due to the presence of high-energy protons accelerated near BH, NS or active galactic nuclei (AGN).

– in the central furnace of an exploding star with temperatures reaching 10^{10} K. Radioactive elements are produced and injected into the interstellar medium following the explosion of the star. Some of them are gamma-ray line emitters and they can be detected after the envelope of ejected materials has become transparent. After the explosion a compact object is left, a NS or a BH depending whether the mass of the compact object is below or above $\approx$ 3 Solar Masses (1 Solar Mass $\approx 3 \cdot 10^{33}$ g). Such an explosion is the endpoint of the life of stars with masses larger than some 8 Solar Masses and is called a type II supernova. Another kind of stellar explosion is called a type I supernova. It is associated with white dwarfs (M < 1.4 Solar Mass) in binary systems which accrete matter from the nearby companion. When accretion results in a total mass exceeding the Chandrashekar limit (1.4 Solar Mass) the white dwarf cannot be stable and the star explodes. This explosion also produces radioactive elements with some gamma-ray emitters but there is not a large gas envelope around the exploding object which can hide the gamma-ray line emission for some months as in Type II supernova.

– during novae explosions, which correspond to the explosive combustion of accreted material at the surface of a white dwarf. The white dwarf is the end-product of a star which has finished its various nuclear burning phases. Without its sources of energy, the object is cooling and it resists the strong gravitational forces thanks to the presence of degenerate electrons. This quiet end of life for an isolated star applies to stars with initial masses less than about 8 Solar Masses; after the different burning phases which include ejection of matter by stellar winds the final mass is less than the Chandrashekar limit of 1.4 Solar Mass. This is the limit of stability for objects with electron degenerate matter.

2. Some recent results in γ-ray astronomy

The main recent observations have been realized with :

GRANAT (1989) a Russian/French mission with a French gamma-ray telescope SIGMA (CESR Toulouse – Sap Saclay – CNES). The combination of the Russian instruments and SIGMA allowed the imaging of the sky between 3 keV and 1 MeV.

CGRO (1991), a US mission with four instruments: the German telescope COMPTEL, EGRET with an important german participation, OSSE and BATSE. These four instruments allowed the exploration of the 20 keV – 30 GeV energy range. We will not discuss the remarkable results of this mission, already reported in this journal [1].

2.1. Some results from SIGMA on GRANAT

SIGMA has been observing the galactic center region for many years, and has revealed the great variability of the sources. More than ten sources active above 35 keV have been identified in this region, many of them being highly variable (Figure 1a). The contribution of SIGMA to the identification of many sources with for the first time a good localization (at the arc minute level), is remarkable. One source, 1E1740.7-2942, is quite exciting. It exhibited for some hours a very broad and strong feature around 511 keV which can be explained by the presence of a high temperature pair plasma (figure 1b) [6]. It has been called "The Great annihilator". Moreover, correlated observations using the ground based Very Large Array at radio wavelengths have shown a double-sided jet structure emanating from a compact core. This has been considered as the first evidence in our galaxy of an object having a behaviour typical of a quasar. For this reason it has been called "microquasar" [7]. Since this first observation other systems have been observed with the same properties [8].

Another exciting result has been the detection of a transient emission of a possible redshifted annihilation feature in the X-ray nova: Nova Muscae, which has been clearly identified as a blackhole nova (figure 1b) [9]. Other SIGMA sources are suspected to be

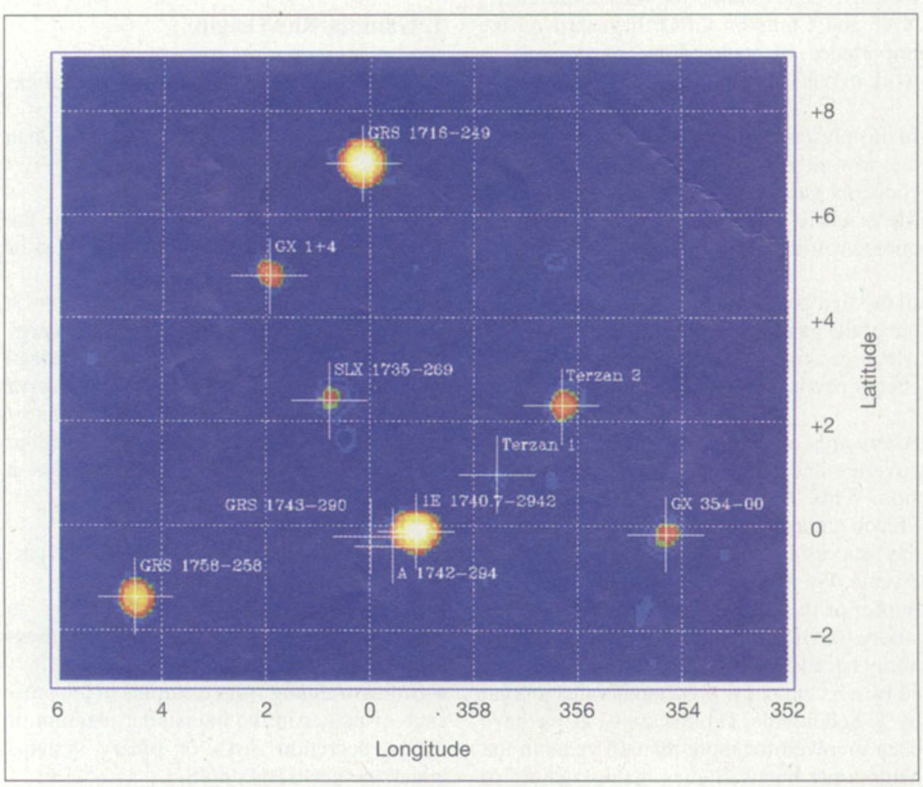


Fig. 1a: Sources observed by the SIGMA team between 1990 and 1996 in the galactic center region (35 – 75 keV). Data have been summed for around 470 days.

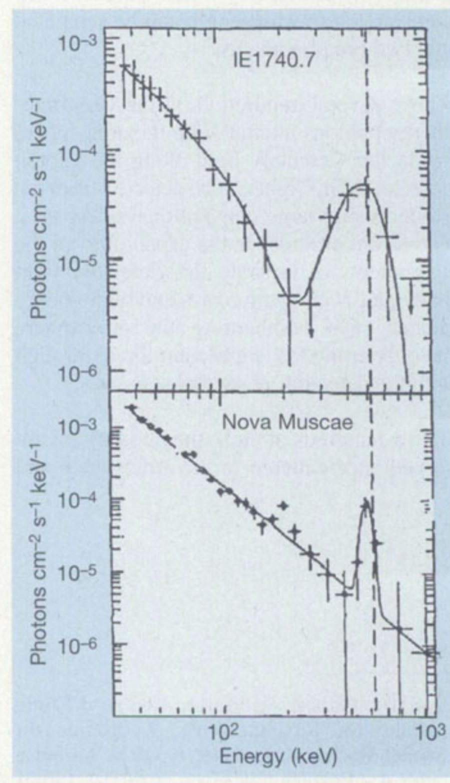


Fig. 1b: SIGMA spectra of 1E1740.7-2942 from Oct. 13, 1993 [6] and X-ray Nova Musca [9]

such blackhole novae even if it has not been possible to determine the mass of the compact object. They produce a variable gamma-ray emission with huge outbursts. These bursts are believed to be connected to variations in the accretion rate from the companion star and instabilities in the accretion disk. More results on the SIGMA mission can be found for instance in the Proceedings of the Toulouse International Colloquium held in 1992 [2].

2.2. Some results on gamma-ray bursts

Gamma-ray bursts (GRB) are flashes of gamma rays lasting from less than one second to minutes and having their energy flux concentrated between few 10 keV and a few MeV. For many years we have tried to discover the source of these emissions, intense but quite unpredictable. We have been the first to localize precisely many GRB using the triangulation method: at least three satellites equipped with GRB detectors are needed, which see the same burst from different locations. The localization of the burst source is obtained knowing the arrival time of the burst at the different satellites positions; if their distance is large the precision of localization can reach a few arc seconds. Since 1972 we have had the benefit for these studies of the French/Soviet space programme. We have installed our GRB detectors on different types of satellites and on probes to Venus or Mars to increase the distance base between the satellites. Many bursts have been localized at the level of a few arc minutes but each time we have looked at the possible counterpart we found nothing convincing inside the error boxes. This has been quite disappointing. The follow-on of this programme has been possible thanks to the Ulysses mission which includes a GRB detector developed in collaboration with MPE. This mission which is out of the ecliptic plan is able to explore the solar poles. Ulysses has been working since 1990. For this period we obtained from our Russian colleagues agreement to put GRB detectors on the Mars missions PHOBOS 1 and 2, launched in July 1988. With this network it would have been possible to localize many GRB with a precision of better than one arc minute. Unfortunately PHOBOS 1 died very soon after launch and PHOBOS 2 a few months later in March 1989, when it reached Mars.

Since this time BATSE on CGRO has been quite successful detecting more than 2000 GRB and showing these GRB are remarkably isotropically distributed. This distribution is in favor of an extragalactic (cosmological) origin even if a large halo around our galaxy (≈ 100 kpc; 1 pc = 3.26 light years) cannot be excluded.

Recently Beppo Sax, an X-ray Italian observatory allowed a very significant breakthrough in the understanding of GRB with the detection, a few hours after a GRB, of an X-ray transient source or afterglow. Many events have confirmed this association. For the first event reported (GRB 970228 – Feb. 28, 1997) ground based telescopes were used to identify a faint optical counterpart which faded quickly in about one week. The New Technology Telescope (NTT) and subsequently the Hubble Space Telescope (HST) which also observed this region found a diffuse emission that might indicate the presence of the host galaxy.

Another important event is GRB 970508 for which a redshift z of 0.8 has been reported thanks to spectroscopic measurements with the 10 m Keck telescope; the extragalactic origin of this GRB seems to be confirmed. If the sources are at Gpc distances, the energy released would be typically 10^{52} ergs. This enormous energy might be liberated during the coalescence of compact objects (neutron stars, black holes, ...).

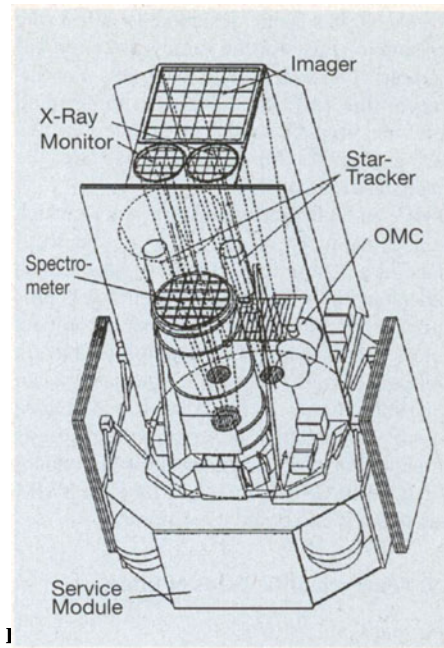
These new exciting results of Beppo Sax and the first detections of counterparts to the GRB also allow us to understand why we have not been able to identify any objects in the GRB error boxes obtained by triangulation. To obtain these error boxes a good time precision in the detection of the GRB at the different satellites is needed and this can take many weeks or months after the detection of the burst. Beppo Sax and the ground observations in optics and radio have shown that the afterglow in the different wavelengths (X, radio, optics) has a short lifetime and cannot be seen (except with Hubble Space Telescope) months after the gamma-ray flash.

3. Next generation of gamma-ray observatories

3.1. The instruments

INTEGRAL is an ESA mission planned to be launched in 2001/2002 (figure 2). Its scientific payload consists of two main instruments and two monitors. The main instruments are an imager, IBIS, and a spectrometer, SPI:

IBIS: The concept of this instrument is the same as SIGMA on GRANAT but the sensitivity due to a significant increase of the area will be higher and it will operate from 20 keV to 10 MeV. The detector uses two planes, a front layer of CdTe pixels of (4×4×2) mm each, for a total area of 2600 cm^2, and a second layer of CsI pixels of (9×9×30) mm each, for a total area of 3100 cm^2. The sides and the rear of the detector planes are surrounded by an active Bismuth Germanate (BGO) veto shield of 2 cm thickness. The tungsten coded aperture mask is placed 3.2 m above the detection plane. The fully coded field-of-view is 9° and the angular resolution is typically 12 arc min Full Width Half Maximum (FWHM).



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SPI: This high spectral resolution gamma-ray telescope works in the same energy range as IBIS. It consists of an array of 19 Germanium detectors surrounded by an active anti-coincidence shield of Bismuth Germanate (BGO) (400 kg) to reduce the background and define the field-of-view. The detectors are cooled to a working temperature ≈ 85 K achieved by an active cooling system using Stirling cycle coolers. Their energy resolution of $E/\Delta E \geq 500$ above 1 MeV is the best that can be achieved now in the gamma-ray domain. The sensitivity is a factor of 10 higher than previous instruments. As in the cases of SIGMA and IBIS, the imaging capabilities of this instrument are obtained with a tungsten coded aperture mask. The mask is 1.7 m above the detection plane. The fully coded field-of-view is 16° and the angular resolution is typically 2.5°.

These two instruments are quite complementary. IBIS has a good sensitivity and a fine angular resolution; SPI has a good sensitivity for spectroscopy and study of narrow lines but its angular resolution is poorer than the IBIS one. Nevertheless SPI will have the capability to map the galactic diffuse emission for two important emissions at 511 keV (annihilation line) and at 1.809 keV (^{26}Al line).

The two monitor instruments are:

JEM-X: an X-Ray Monitor which consists of two identical high-pressure imaging microstrip gas chambers, each viewing the sky through a coded aperture mask situated at a distance of 3.2 m from the detector plane, as for IBIS. This instrument will provide images with arc minute angular resolution on the energy range extending from 2 keV to

60 keV. It has been designed to allow the mission to study for the same source the behaviour at low and high energies. For instance, this will make easier to understand how the nova X transient sources evolve during their outbursts and what are the mechanisms at work.

OMC: an Optical Monitoring Camera which uses a passively cooled CCD in the focal plane of a 30 mm lens. It is now clear that to understand how and where the energy is produced in the vicinity or very near a compact object (BH or NS) it is mandatory to have a multiwavelengths approach. This camera can contribute to this approach but it will also be possible to organize observation campaigns on particular objects, for instance in connection with the ESA cornerstone mission XMM and with ground based telescopes.

3.2. Some scientific fields of interest

The spectrometer SPI

Compared to Comptel and OSSE on CGRO, SPI will have a much better energy resolution ($E/\Delta E = 500$) and a better sensitivity. We can expect this to lead to a more accurate understanding of the origin of the ^{26}Al and annihilation line distributions (see ref. 1).

In the case of the ^{26}Al galactic distribution, the detection of the ^{60}Fe gamma-ray lines at 1.173 MeV and 1.322 MeV would be very helpful in clarifying what is (are) the source(s) of this radioactive element. For instance, if its origin is type II supernovae, as ^{26}Al and ^{60}Fe are co-produced in the same regions they will have the same spatial distribution. It is also very essential to know the profile of the ^{26}Al line, especially after the observations obtained with the GRIS balloon experiment which reported a surprisingly broad line ($\Delta E = 5.4 \pm 1.4$ keV) [10] after removing the instrumental line width. So far such a broadening is not understood but different explanations are possible. With a better sensitivity and good imaging capabilities SPI will be able to measure the broadening of the line for different regions (GRIS had a quite broad field-of-view of 100°). In addition, we can expect to separate foreground sources and to locate them in the galactic disk through the measurement of the centroid of the line at the level of few 0.1 keV which can be achieved (depending on the flux in the line), and which will allow Δv measurements of some tens of kilometers per second. Such foreground sources might have a significant impact on the total ^{26}Al mass which has to be produced in our galaxy to explain the ^{26}Al diffuse emission.

The annihilation line has been mapped by OSSE, which is not an imager and has no fine spectroscopy capabilities. We can expect by the study of the line profiles in different emitting regions of the central galactic radian to better determine the physical conditions of the medium where the annihilations are produced. Depending on the presence of different phases (cold or warm gas, ionized or not, dust...), the broadening of the annihilation line is different. Therefore the spectral resolution and the sensitivity of SPI can help to understand what are the galactic sources of the positrons.

Another interesting open area is connected with the detection by Comptel of the ^{44}Ti gamma-ray line at 1.157 MeV from the supernova remnant Cas A. This element is a source of the galactic ^{44}Ca, but it cannot be produced only by type II supernovae through ^{44}Ti ejecta. The supernova rate seems too small to explain its abundance. Therefore what are the other sources of ^{44}Ca? In any case the production of radioactive ^{44}Ti is important in itself because for core collapse supernovae it is produced in deep regions near the mass cut of the supernova which defines the mass that falls back onto the remnant. Its production is therefore quite sensitive to the SN explosion details, with a strong impact on the models. ^{44}Ti is also important because through its β^+ decay (see table 1 of ref. 1) it can contribute significantly to the existence of positrons in extended regions. This element has a half life long enough to escape from the supernova envelope after a type II explosion, whereas it is certainly not the case for the e^+ produced through the ^{56}Co decay chain, even if these nuclei are more abundant. To understand the rate of SN in our galaxy it is important to look for the most recent SN remnants. From 6 to 24 galactic SN are expected to have occured during the last 300 years [11], but only 2 or 3 nearby galactic supernovae have been identified. ^{44}Ti can be used to detect a significant fraction of these supernovae which are optically obscured. For instance a supernova 100 years old at 10 kpc is quite detectable by SPI.

Another field which remains to be explored concerns gamma-ray lines produced by novae. None have yet been detected; only upper limits have been reported by Comptel [12]. The observation of ^{22}Na gamma-ray line at 1.275 MeV and even ^{7}Be at 478 keV and 511 keV annihilation lines [13] is essential to constrain the present nova models. Today large uncertainties exist in the expected flux from these radioelements, depending particularly on the chemical composition at the onset of the explosion and on the efficiency of the element mixing by convection.

Finally, with a much better energy resolution and sensitivity than the previous instruments,

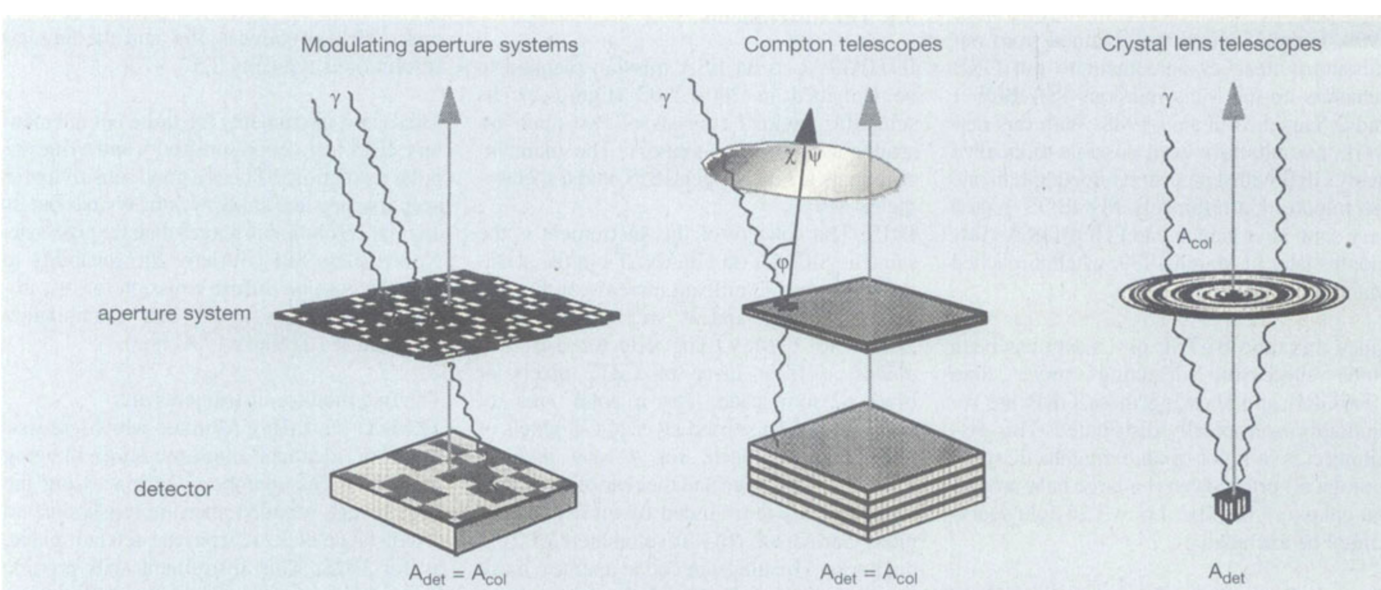

Fig. 3: The possible techniques for low-energy γ-ray astronomy beyond 2000.

SPI will study X- and gamma-ray sources to determine their continuum emission and look for lines which may be superimposed on the continuum spectrum, for instance annihilation lines possibly due to the interaction of electrons jets with the dense clouds which might exist in their vicinity. One interesting candidate is the 1E1740.7-2942 microquasar source. Another example is the transient line at 480 keV discovered by SIGMA in Nova Muscae and which might be explained by a redshifted annihilation line produced in the vicinity of the black hole.

The imager IBIS

This instrument is well adapted for the study of the continuum emitted by gamma-ray sources and also for identifying sources of broad line emission. Below 1 MeV it has a better sensitivity than SPI due to its larger area; it has also a higher angular resolution. For crowded regions as in the galactic center its angular resolution is necessary to avoid source confusion. For instance the Beppo Sax satellite with its wide field camera has been able to study and monitor at the same time as many as 32 sources in the galactic central radian. IBIS for the same region will be able to extend the spectrum of many of these sources above 30 keV. In particular the study of X-ray novae, for which SIGMA has been so successful, will be extended with IBIS thanks to its better sensitivity. A central objective is also to try to separate the binary X-ray sources which include neutron stars and black holes and to find some differentiating signature. This is not an easy task when the mass of the compact object cannot be determined.

The study of microquasars first revealed by SIGMA will also be greatly extended. These galactic systems are very important in better understanding, on a larger scale, active galactic nuclei, thought to harbor massive black holes. It is particularly interesting to study the connections between the inner part of the accretion disk near the BH and the jet which is observed in the radio band. The RXTE satellite (Rossi X-Ray Transient Explorer) has already helped to establish this connection between the inner part of the disk and the jet by simultaneous observations at X-ray, radio and infrared wavelengths of the galactic superluminal source GRS 1915+105 [14].

4. What new techniques and instruments after INTEGRAL ?

For the next generation of instruments after INTEGRAL, we have to think right now of the different ways to: i) increase the sensitivity of the instruments, which is a continuous objective, ii) keep the high energy resolution already achieved with INTEGRAL, iii) increase the imaging capacity of the instruments to allow a better positioning of the sources in the sky.

The technique used for INTEGRAL, detectors inside an heavy shield, cannot be indefinitely extended. The weight would be too large due to the presence of a massive active anticoincidence shield, and the neutron production in this shield would increase dramatically the background of the detectors (nβ and nγ nuclear reactions). The sensitivity increases $\approx \sqrt{S}$ only, and going from a total area of Ge detectors of 500 cm^2 like on SPI to 50 000 cm^2 would not be a realistic approach due to the weight of the ACS which would be tons and the very damaging background it would induce.

Two other techniques might play an important role in the low-energy γ-ray astronomy domain beyond 2000: i) the Compton Telescope Technique, ii) Gamma-Ray Lenses (figure 3).

4.1. The Compton Telescope Technique

This technique has already been used for COMPTEL on CGRO with great success. The principle is illustrated in figure 3. The two detector planes allow one to follow the scattered photon after a first interaction in the upper detector plane. The determination of the photon direction has to be achieved by the best possible positioning of the two interactions and by good energy measurement in the two detector planes. For future instruments, to achieve better energy resolution and better source localization, the scintillator gamma-ray detectors can be replaced by planes of stripped Ge detectors (figure 4).

In these conditions, the energy resolution reaches typically 2.5 keV at 1 MeV. In addition, the localization is improved as the positioning of the interactions in the two detector planes is greatly improved because the strips can be separated by only 1 or 2 mm. Of course the detector plane has to be large enough (1 m^2) to overcome the decrease in efficiency due to a double interaction in the two detection planes. Nevertheless, as observed by COMPTEL, the background is largely decreased compared with the present technique (detectors + active anticoincidence shield), especially if one uses fast timing of the interactions in the two detector planes which constitute the telescope. Another advantage of this approach is the large field-of-view of the instrument (> 30° FWHM) which allows the simultaneous observation of many sources. This field-of-view is also quite useful in measuring extended emissions (for instance ^{26}Al or annihilation line distributions along the galactic plane).

Figure 4 shows that the Compton telescope can be complemented by a coded aperture imager, adding only a mask and a collimator to extend the analysis of the sources between 10 keV to some 200 keV. This is the Athena concept (see ref. 15). For complementary information, the recent Workshop held at Landsdowne (Virginia) in 1996 [16] gives detailed descriptions of such instruments and others.

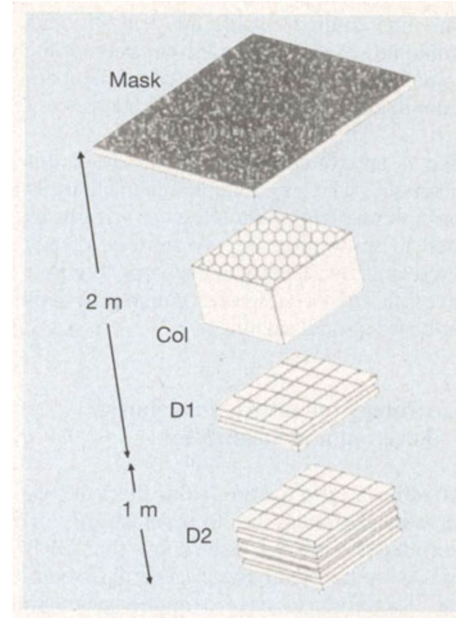

Fig. 4: Conceptual diagram of a combined coded-aperture imager and Compton telescope. The Compton telescope consists of two detector planes (D1 and D2) ≈ 1 m apart. A coded aperture is placed ≈ 2 m above the top detector plane, which forms the coded aperture imager using the top layer of D1. A coarse collimator just above the D1 layer restricts the field-of-view for the image (Athena concept [15])

4.2. Gamma-Ray lenses

Using Laue diffraction it is possible to focus gamma rays (from a few 100 keV to about 1 MeV) for instance on a Ge detector, separating the collector of photons and the detector (figure 3). This concept is being studied at CESR-Toulouse in collaboration with a US team from Argonne laboratory.

Ge crystals are used to diffract the gamma rays. The feasibility of this technique has been proved in the laboratory. The efficiency of diffraction approaches 20 %. The capacity to localize the emission is exceptional compared with other proposed techniques (a few arc seconds) but the focused energy range is quite limited (between 1 and 40 keV). Another disadvantage is the focal length which has to be quite large (10 – 15 m). 511 keV line targets are interesting, for instance exploring the emission from the microquasar 1E1740. The annihilation bump in its spectrum seen by SIGMA might be due to the presence of a e$^+$e$^-$-plasma in the vicinity of the compact object and the two jets (observed in radio) would indicate the ejection of e$^-$e$^+$-plasma. The interaction of this plasma with surrounding dense molecular clouds might give a very narrow line at 511 keV.

This line emitted outside the central object would be separable from the emission of the point source 1E1740 due to the excellent angular resolution of such an instrument.

This is an example of the potential of this technique, which is quite complementary to the first one (Compton telescope). It can be used to study more deeply sources already discovered by a Compton telescope. Figure 5 gives an artist's view of a gamma-ray lens on-board a small satellite.

5. Strategy for future γ-ray burst detection and localization

After the last discoveries in this field, the observational strategy has to be drastically reconsidered since we now know that GRB and X-ray transients are in general associated. Therefore, to have a multiwavelength approach we need to: i) detect GRB in space with a near real time transmission of the position on ground, ii) know the position at the level of the arc minute (this is enough to identify the source due to the large variability of the counterparts).

Beppo Sax clearly demonstrated that optical and radio telescopes can be pointed in the direction of the error box and the identification can be achieved even a few hours after the GRB. Nevertheless, to measure redshifts in the optical counterpart when it exists, a fast localization of the GRB at the arc second level remains a fundamental objective. This can be obtained if the GRB is localized in space at the arc second level or if ground optical telescopes (1 m class) are able to give this localization quickly enough (few minutes after the GRB).

This can be also achieved if at the time of a burst an X-ray telescope specifically designed for the observation of GRB is operative and can be pointed as quickly as possible (few seconds to minutes) in the direction of the GRB error box to follow the X-ray transient and to localize the X-ray emission at the arc second level. A very short time after the GRB this information would be available to the ground.

Among the projects beyond 2000 we may hope that Ulysses (CESR-MPE GRB Detector) will be still working. In this case it will be very useful for precise localization of GRB by triangulation, using at least three satellites in orbit equipped with GRB detectors.

At that time HETE-2 (MIT – CESR – Riken Institute) will have been launched. The objective of this mini satellite is the detection of GRB and their localization at the arc minute level. Moreover, for the first time an alert to the ground observatories will be given in near real time to observe the counterparts.

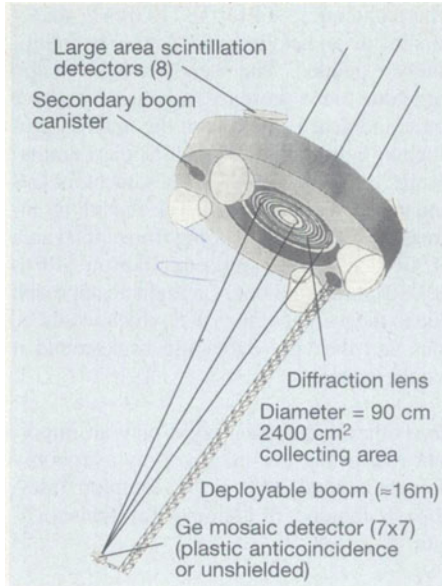

Fig. 5: A gamma-ray telescope using a crystal lens for high angular and spectral resolution

Due to the size of the detectors, the number of bursts which will be seen by ground based telescopes will be limited to few tens each year.

At CESR and in collaboration with MIT new missions are being studied associating GRB detectors and grazing incidence X-ray telescopes. The objective is to study with a multiwavelength approach more than 100 GRB per year extending the pioneering work of Beppo Sax and HETE-2.

6. Conclusions

As a result of the breakthroughs realized by observatories such as GRANAT, CGRO and Beppo Sax for GRB, gamma-ray astronomy is revealing the presence of regions, in our galaxy and beyond, where high-energy processes are at work and enormous quantities of energy are liberated. Objects such as binary systems including a compact object and massive accreting black holes in the centers of galaxies involve physical processes of great importance. For instance, the interplay between the inner part of the disk around a compact object and the compact object itself, or between the inner part of the disk and the jet which is present in microquasars or AGN and blazars, is of prime importance.

Radioactive elements with gamma-ray lines, produced in supernovae and novae explosions, can trace the nucleosynthesis of heavy elements (beyond helium) in the galaxies. This represents an important evidence to help in understanding chemical galactic evolution. The GRB field seems now open for more rapid development than at any time during the last three decades. If the sources are really situated at high redshifts which means at very large distances, it may concern a class of objects important for cosmology.

In all these domains, and others as well, gamma-ray astronomy has clearly become crucial in developing an understanding of our universe. In this field Europe is playing a key role.

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