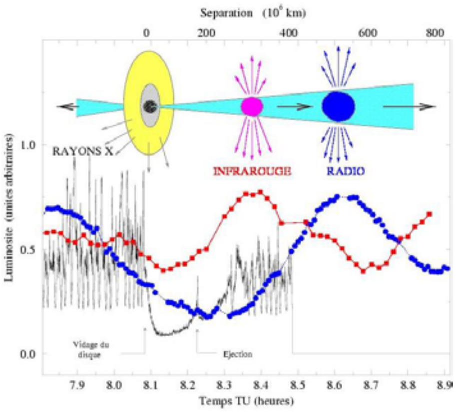
High energy cosmic phenomena

Supernovae, Neutrons stars, Black holes, Cosmic rays



High energy cosmic phenomena

Supernovae, Neutrons stars, Black holes, Cosmic rays

Introduction

The sites of high-energy cosmic phenomena - extreme sources in the universe (Paul & Bignami, 2000), those where the greatest energy transfers occur - are, for the most part, in the grip of the fatal attraction of gravity. It is gravity that regulates supernova explosions producing compact residues - neutron stars and black holes - which are the driving force of a whole range of extreme systems. It is also gravity that forms ultra-massive black holes which are the energy source for the active nuclei of galaxies and a specimen of which is to be found at the heart of each galaxy, including the Milky Way. Extreme stars certainly form an apparently disparate population but all share a high propensity to produce beams of relativistic particles, which occur in the form of cosmic rays. It is therefore hardly surprising that extreme sources have become a byword in the field of astroparticles, a discipline that is emerging at the interface between astrophysics and particle physics.

Unlike the great majority of stars which radiate more in a narrow spectral band (thermal emission), extreme sources more often produce radiation of a non-thermal type over a very wide spectral range. We should therefore observe types of high-energy cosmic phenomena over the whole range of radiations and not only in the high-energy photon bands. Observations in the X-ray and gamma bands, however, remain the best way - and sometimes the only way - of studying and understanding the intimate mechanisms of high-energy cosmic phenomena.

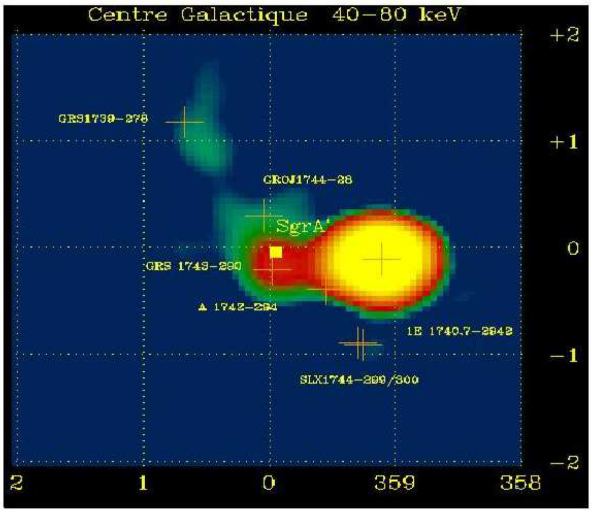


Image of the Galactic nucleus built up from data gathered by SIGMA in the spectral band from 40 to 80 keV during all the observations in the central regions of the Galaxy. The crosses show the precise positions of seven sources detected by SIGMA in this region of the sky.

Having been involved in the study of cosmic radiation as well as of active cosmic sources in the X-ray and gamma ranges from the outset, SAp expanded its approach to extreme stars between 1997 and 2000 by undertaking to investigate the intimate mechanisms of a few of the most representative specimens and focussing, in particular, on the so-called microquasars.

The description of the activities of SAp over the last four years begins with an overview of high-energy data collected by observatories and in experiments involving the participation of SAp and then reviews the multi-wavelength observations and theoretical interpretation work conducted at Saclay.

SIGMA telescope on the GRANAT satellite

The SIGMA telescope was put into service on board the Russian satellite, GRANAT, placed in orbit on December 1, 1989. SIGMA observed the sky from March 1990 until its observations were interrupted following a failure of the satellite solar sensors noticed on November 27, 1998. The research conducted as from 1997 concerned black hole X-ray novae in the Galactic bulge, the inactivity of the Galactic nucleus, bright sources in the Galaxy, remnant emission of gamma-ray bursts and large-scale emission from the Galaxy. Optimised to produce images of the sky in the band between 35 keV and 1.3 MeV, SIGMA proved to be very efficient in tracking accreting stellar black holes. These are not directly detectable but exert a very strong attraction on matter passing within their reach. Some stellar black holes in the binary system are also encircled by a massive plasma disc which is heated by violent friction phenomena to the point where an intense high-energy radiation easily detectable by SIGMA is generated. Many sources of this type are black hole X-ray novae. By analogy with novae observed in the visible range, this description is applied to sources with a brightness which increases by more than two orders of magnitude in a few days and then decreases more or less regularly over the following weeks. The two observation campaigns in the central regions of the Galaxy conducted in March and September 1997 led to the discovery of two new black hole X-ray novae: GRS 1737-31 (Trudolyubov et al., 1999) and XTE J1755-324 (Goldoni et al., 1999). Both show signs of emission produced by an accreting black hole, i.e. a spectrum which extends considerably beyond 100 keV (Laurent & Titarchuk, 1999).

Having conducted 14 campaigns directed at the central regions of the Galaxy, the SIGMA team gathered more than 3,000 hours of data concerning the galactic bulge. No fewer than 15 gamma-ray sources were identified (Vargas, 1997), more than one-third of which bear the spectral signature of black holes. One of the most remarkable discoveries concerns the actual centre of the galaxy where it is believed there is a giant black hole which is thought to have a mass of 2.9 million solar masses, the radio source, Sgr A*, being its radio counterpart. In Figure 1, it can be seen that the SIGMA telescope was unable to detect any source at all at the position of Sgr A* (Goldwurm et al., 2000). The luminosity generated by this possible massive black hole would therefore be less than 100 solar luminosities in the low-energy gamma radiation band.

This limit raises problems for attempts to interpret the emission from Sgr A* in terms of advective processes, but only in-depth observations that will be conducted with the INTEGRAL satellite will make it possible to define effective constraints for this type of modelling (Goldwurm et al., 1999).

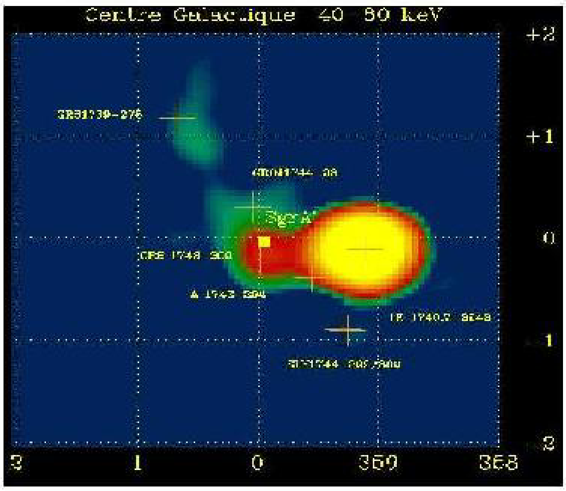


Figure 1. Image of the Galactic nucleus built up from data gathered by SIGMA in the spectral band from 40 to 80 keV during all the observations in the central regions of the Galaxy. The crosses show the precise positions of seven sources detected by SIGMA in this region of the sky.

The SIGMA team conducted a thorough examination of its large database on bright sources in the Galaxy. Firstly, there were two near black hole X-ray novae: GRS 1716-249 (Revnivtsev et al., 1998) and GRS 1009-45 (Goldoni et al., 1998) and, by studying these, we were able to ascertain some specific characters of this type of celestial object. There were then four accreting black holes with persistent emission found in the Galaxy: GX 339-4 (Trudolyubov et al., 1998), GRS 1758-258 (Kuznetsov et al., 1999), 1E 1740.7-2942 and Cygnus X-1, the two latter having formed the subject of a fruitful comparative study (Kuznetsov et al., 1997). There was also GX 1+4, a highly magnetized neutron star, in-depth study of which began on an original model of the high-energy emissive site

(David et al., 1998). In addition, we should mention the studies of GRS 1758-258 (Goldwurm et al., 1997) and of SLX 1735-269 (David et al., 1997) conducted in the X-ray band with the Japanese ASCA satellite in order to learn more about the nature of these sources identified by SIGMA in the Galactic bulge. Discovery, by the Italian satellite BeppoSAX, of remanent emission in the X-ray band of a few gamma-ray bursts led the SIGMA team to reexamine the data collected with the telescope on the four occasions when gamma-ray bursts had been detected through the appliance's secondary lobes. As a result of this new examination, the remanent emission of a gamma-ray burst (GRB 920723) above 35 keV was revealed (Burenin et al., 1999). It should be noted that SIGMA also made a contribution to the study of gamma-ray bursts in the context of the global network which coordinates detections made by a set of satellites and space probes (Hurley et al., 2000).

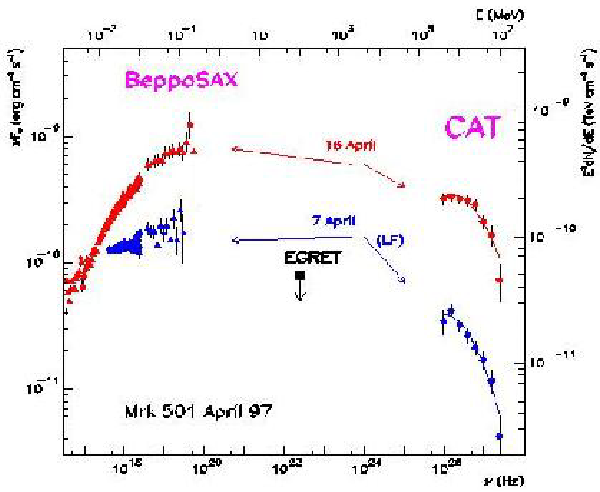
KET experiment on the Ulysses probe

The direct measurement of fluxes of cosmic rays and its interpretation was continued over the four years, with the analysis of data from the KET experiment on the Ulysses probe launched on October 6, 1990, towards Jupiter and placed in orbit practically perpendicularly to the ecliptic plane as from February 1992. Ulysses was thus to overfly the poles of the Sun and, with KET, SAp had the only instrument on board the probe that was capable of measuring the electron component of the cosmic radiation. When it first flew over the Sun's poles in 1994-1995, the KET team showed that the excess flux of cosmic rays above the poles was much weaker than expected and that the modulation of cosmic radiation caused by solar activity did, indeed, depend on the charge sign of the particles. Studies on solar modulation were conducted from 1997 to 2000 according to the position of the probe and the solar activity which, during that period, rose from a minimum to a maximum level. Among the most significant results, it is worth noting the measurement of the variation in the radial and latitudinal gradient of protons according to the distance from the Sun at the solar minimum: unlike the latitudinal gradient, the radial gradient decreases with the distance from the Sun (McDonald et al., 1997). The fact that the effect of charge sign is in direct correlation with the structure of the interplanetary magnetic field was also noted (Heber et al., 1999). Another line of research was interpreting the strong flux of electrons of a few MeV measured since 1996 in terms of electrons released by the tail of the Jupiter's magnetosphere (Ferrando et al., 1999), an interpretation which did not prove to be completely satisfactory in view of the data collected in 2000. Finally, we should mention the finding of a 26-day modulation in the flux of cosmic rays up to the highest latitudes and its amplitude according to the rigidity of particles which shows a peak at about 1 GV (Paizis et al., 1999); It would appear to be difficult to provide a theoretical interpretation for this new effect.

The CAT Telescope

Ground-based gamma-ray astronomy, which provides an observation window which is currently inaccessible to satellites, has undergone rapid development over the past 20 years. It is based on the detection of narrow beams of visible light produced by the Cherenkov effect when bursts of secondary relativistic particles produced by the interaction of gamma photons with an energy exceeding a few GeV are propagated in the upper atmosphere. When they reach the ground, these narrow light beams produce an illuminated circle with a radius of about 100 metres which can be detected with a large conventional mirror. This technique, described as the "Cherenkov atmospheric technique", is well suited to sky observation in the very high-energy gamma photon band. It is in this context that the CAT project (CAT standing for Cherenkov Array at Thémis) was started, and began making observations in September 1996. The result of cooperation between laboratories (including SAp) from France and other countries, the telescope, sited at the old Thémis solar plant in the eastern Pyrenees, consists of a mirror with a 18 m2 collecting area and a focal plane made up of 546 small photomultipliers.

The main research field for CAT is the physics of active galactic nuclei including, in particular, BL Lac objects. Only a few months after it was commissioned, the CAT experiment observed an unprecedented activity of the active galaxy Mkn 501 (Djannati-Ataï et al., 1999). Simultaneous observations made with the Beppo-Sax satellite showed a strong correlation between the flux of very high-energy gamma photons and the flux of photons of a few tens of KeV (see Figure 2)).



Such a correlation favours what is known as a leptonic model, where a single population of electrons causes, by synchroton radiation, the emission observed in the hard X-ray band and, by Compton diffusion on those X-ray photons, the very high-energy emission observed. It should be noted that CAT also revealed remarkable activity of Mkn 421, another active nucleus of the BL Lac type.

Figure 2. Spectra of Mkn 501 during the two especially active states of the source in April 1997, illustrating the correlation between X-ray data (Beppo-Sax) and gamma data (CAT).

EPIC camera on the XMM-Newton satellite

The XMM-Newton team has rights to guaranteed observation time owing to its participation in the construction of the experimental device. Among the seven guaranteed-time programmes, which include participation by SAp, one of the biggest in terms of volume (13 pointings for a total observation time of 210 10^3 s) concerns the study of the Galactic centre where there are a great many extreme sources that SAp teams began to study at the end of 2000 as soon as the first data were received. SAp physicists have also undertaken the analysis of observations made during performance verification phases, such as of the remnants of the Tycho supernova (Decourchelle et al., 2001) whose spectrum, constructed with data collected by the EPIC camera (see Figure 3), demonstrate the spectroscopic performances of this instrument which includes a contribution from SAp which supplied some of the electronics.

Multi-walelength observations and theoretical interpretations

Multi-wavelength studies of supernova remnants

The shock waves created by the propagation of supernova remnants are liable to accelerate charge particles which are then able to interact with the very matter constituting supernova remnants and with interstellar matter located nearby. In the case of electrons only, interactions may also be envisaged with magnetic fields - resulting in non-thermal X-ray emission - and photon fields - resulting in very high-energy gamma emission - which are contained in supernova remnants. In addition to many strong emission lines, as observed in the remnant of Tycho (see Figure 3), the spectrum of young supernova remnants shows a continuum emission above 10 keV, which has been interpreted in terms of electron acceleration. Modelling the 0.5-20 keV X-ray spectrum of Kepler's SNR (combining ASCA and RXTE data) has shown that this high energy tail comes, in fact, from the hot shocked ejecta, while the emission associated to electron acceleration would lie below 5 keV (Decourchelle and Petre 1999). The modelling of supernova remnants performed at Sap (Decourchelle et al. 2000) shows that thermal X-ray emission is extremely sensitive to the retroaction of accelerated particles, which makes it possible to constrain the efficiency of acceleration processes on the basis of observations made in the X-ray band. Observing with Chandra at a supernova remnant shock front, Hughes et al. (2000) put into evidence that to explain the low measured post-shock temperature a large fraction of the shock energy should have gone accelerating particles. While X-ray observations of young supernova remnants give access to the elements synthesised in the explosion, the x-ray study of mature remnants is crucial for investigating shock physics and for understanding the interaction of the blast wave with the interstellar medium. The analysis of ROSAT observations of the Cygnus Loop remnant (Decourchelle et al. 1997) have been complemented by optical Fabry-Pérot observations (with the ESOP instrument developed at SAp), providing access to the kinematics of the remnant (Sauvageot et a. 1999, Bohigas et al. 1999).

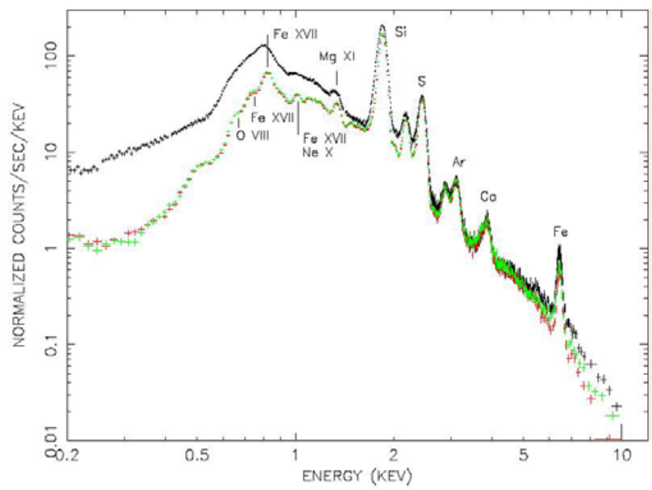


Figure 3:Spectrum of the remnants of the Tycho supernova built up from the data collected by EPIC/MOS1 (in green), EPIC/MOS2 (in red) and EPIC/PN (in black). The spectral lines for the various species are well separated above 1.5 keV. For the same source, the count rate is approximately ten times lower with the fine RGS spectrometer.

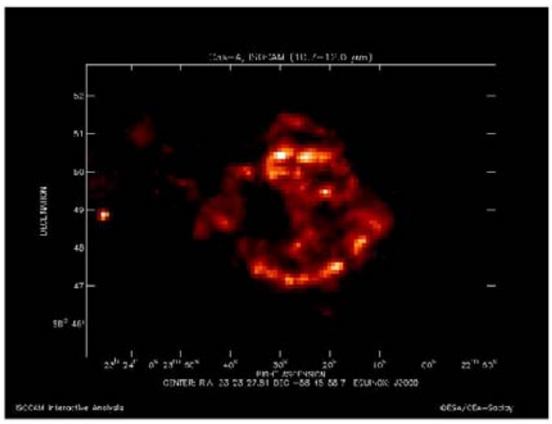


Figure 4: Image of the remnants of the Cas A supernova recorded in the thermal infrared range (11 µm) by ISOCAM on ISO.

The matter ejected during the explosion of a supernova has been studied by radio observation, in the visible and X-ray bands, but very little study has been done in the infrared band. The SAp team, which is responsible for observations of the youngest known supernova remnants in our Galaxy with the ISOCAM camera on the ISO satellite, has shown that, in the case of Cas A, some of the matter ejected by the supernova was condensed to form grains of dust. The images obtained (see Figure 4) have, in fact, revealed a structure in the form of globules, identical to that observed in the visible range, and we know that this structure shows the matter ejected by the supernova. This emission was essentially a thermal emission from dust as confirmed by the spectra obtained with ISO. From this, the SAp team concluded that part of the ejected matter condensed as dust (Lagage, 1998). One of the surprises provided by the study was noting an anticorrelation between the presence of silicated dust in the globules and the presence of neon. Before the explosion, the elements are stratified in layers, with the heaviest towards the deepest parts of the presupernova. Silicated dusts come from the layer where there is oxygen, silicon and magnesium. As for the neon, this is found in another layer situated higher up. The anticorrelation observed means that the layers were not mixed (Douvion et al., 1999). However, we know that the innermost layers (iron, argon and sulphur) were mixed with the upper layers. How could the innermost layers be mixed, in this way, with the upper layers without also mixing together the various upper layers? This question can only be answered by digital simulations or experiments with large lasers.

Multi-wavelength studies of compact objects

Complementary observations in the visible, infrared and radio ranges are indispensable in addition to observations in the high-energy range in order to identify the nature of compact objects. SAp physicists have recorded many significant results in this context, beginning with the identification of counterparts, at long wavelengths, of the hard X-ray sources detected by SIGMA, such as GRS 1739-278 (Martí et al., 1997) and GX 354-0 and Terzan 1 (Martí et al., 1998a). We should also mention identifications of the X-ray binary source at the centre of the globular cluster 47 Tuc with a cataclysmic variable by means of astrometric methods (Geffert et al., 1997) and of the transient X-ray source, Cepheus X-4, with a Be system located in one of the outer arms of the Galaxy by means of spectra obtained in the visible range (Bonnet-Bidaud & Mouchet, 1998). In the same vein, SAp physicists have supplied important information to allow a better understanding of the sources of repetitive bursts of low-energy gamma rays, such as the estimation of the distance between two of them: SGR 1627-41 and SGR 1806-20 (Corbel et al., 1997; 1999), and the indication that the latter is probably an isolated neutron star on the basis of observations conducted in the infrared band with the ISOCAM camera on the ISO satellite (Fuchs et al., 1999). Physicists from SAp have conducted detailed multi-wavelength studies on what are known as "polar" binary systems where the compact object is a highly magnetized white dwarf. Observations of the AM Her source conducted in the X-ray band with Beppo-Sax and in the visible band have revealed a very great variability in low accretion states. Sudden increases in luminosity have been interpreted as being the result of instabilities in the accretion column (de Martino et al 1998; Matt et al., 2000; Bonnet-Bidaud et al., 2000a). Thanks to detailed spectroscopic observations conducted in the visible band and to the reanalysis of UV data collected by the IUE satellite, it has been possible to confirm that BY Cam, a polar type system where the astonishing oddity of an abundance of heavy elements (CNO) had already been noticed, showed a slight desynchronization which has now strongly backed up the hypothesis that the source was affected by a nova type explosion (Mouchet et al., 1997). The source was included in the initial programme of observations from the FUSE satellite. Observation in the far ultraviolet range revealed that the resonance line of oxygen was much weaker than that for other sources (Szkody et al., 2000) which is in keeping with predictions for the abundance of novae. Until now, it had been considered that the strong magnetic field prevented any "nova" phenomenon. This conclusion could have important consequences regarding the evolution of polar systems and the possible progenitors of novae and supernovae of type I.

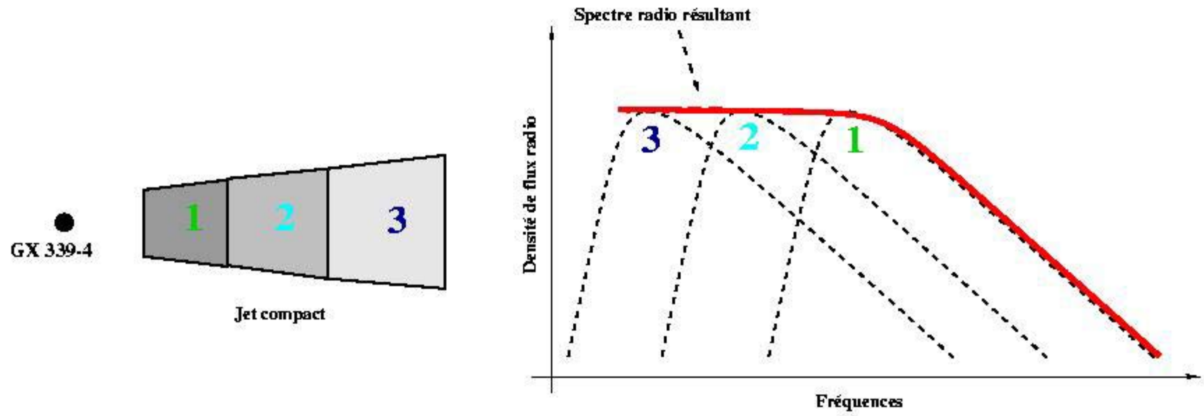


Figure 5. Origin of radio emission in the context of a compact jet model. The radio emission is believed to be the sum of several different optical thickness components. The highest frequency radiation is emitted in the zones located at the base of the jet (which are therefore the most opaque).

The multi-wavelength study of GX 339-4 has revealed a certain number of new properties of the X-ray binary source with persistent emission containing a black hole and studied in detail at high energy but which is little known in the radio range. Following interferometric observations, Stephane Corbel and his colleagues discovered that, in the low accretion state, GX 339-4 appeared in the radio range with a quasi-constant flux density with a flat or slightly inverted spectrum (Corbel et al., 2000), this emission being characteristics of the synchrotron radiation from an optically thick medium, which can be explained by means of a compact jet model (see Figure 5). In 1998, GX 339-4 was the site of a transition to a high accretion state characterized by the increase in soft X-ray emission from the accretion disc. It should be noted that the accompanying disappearance of radio radiation and hard X-ray emissions can only be explained by the disappearance of the compact disc (Fender et al., 1999). This result shows the importance of a simultaneous study at more than one wavelength.

Multi-wavelength studies of microquasars

Microquasars are X-ray binaries where a black hole, which accretes the matter from the neighbouring star via an accretion disc, cause the ejection of jets of matter at speeds near the speed of light. Microquasars were discovered following a multi-wavelength campaign conducted in 1991 and 1992 by the SAp SIGMA team for gamma rays and by Félix Mirabel and his colleagues for radio radiation with the Very Large Array. They are morphologically similar to quasars but are considerably smaller with regard to length and mass (see Figure 6). The scientific progress which followed (Mirabel & Rodriguez, 1999) was, above all, owing to a series of multi-wavelength campaigns with which SAp was closely associated. The most fruitful of these concerned GRS 1915+105, the first microquasar known for ejections at speeds apparently faster than the speed of light. Félix Mirabel and his colleagues thus revealed, for the first time, the link between accretion phenomena and the ejection of matter that occurs in GRS 1915+105 in the vicinity of the same compact star. At a first stage, they observed the expansion of relativistic plasma clouds after their ejection, which was detected in the form of synchroton radiation firstly in the infrared range and then in the radio range. At a second stage, observations conducted in the X-ray band, the infrared band and the radio range showed the connection between the emptying of the inner part of the accretion disc and the ejection of relativistic plasma clouds (Figure 7). These observations jointly show that the morphological similarities between quasars and microquasars are subtended by the same dynamic and physical phenomena (Mirabel et al., 1998).

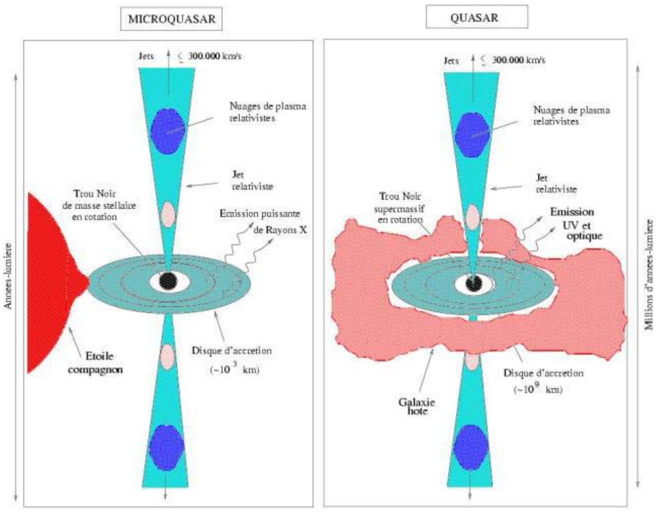


Figure 6: Schematic representation of a microquasar, the miniature replica of a quasar at stellar scale.

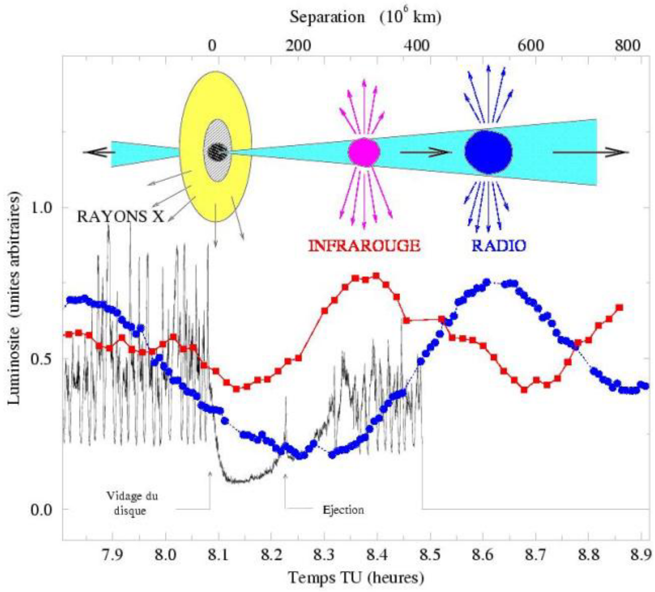


Figure 7: Multi-wavelength observation of a typical relativistic plasma ejection sequence by the microquasar GRS 1915+105.

SAp physicists also took part in many multi-wavelength campaigns for the follow-up of other microquasars and the discovery of new specimens. In this context, we should note the observations of the GRS 1758-258 field conducted at the southern European observatory (Observatoire Européen Austral), initially with a 2.2 m telescope and then with the New Technology Telescope (see Figure 8) with the purpose of searching for the counterpart of that microquasar both in the visible range and in the near infrared range (Martí et al., 1998b). We should also mention the discovery of the radio counterpart of the massive X-ray binary LS 5039 (Martí et al., 1998c), which has recently been shown to be of the microquasar type.

In spite of this remarkable progress, many questions remain unanswered. In particular, where does the energy required to accelerate matter at such speeds come from? Furthermore, how can we explain the behaviour of the disc which, in many cases, shows quasi-periodic oscillations? Answering these questions calls for a theoretical model (see below) in combination with studies of the time-related evolution of the emission from microquasars. It was in this way that Jérôme Rodriguez undertook to correlate the size of the disc with the frequency of the quasi-periodic oscillations in the case of GRS 1915+105 and GRO J1655-40, which are two microquasars where observation results confirm the theoretical predictions (Rodriguez et al., 2000). Knowing more about the processes at work in microquasars also calls for observations such as those conducted by Yael Fuchs in the infrared spectrum with the ISOCAM camera on the ISO satellite on the western lobe of W 50, the nebular surrounding SS 433 (Fuchs et al., 2000). SS 433 is an X-ray binary harbouring a neutron star, which, like microquasars, is a source of jets, although they are more weakly relativistic.

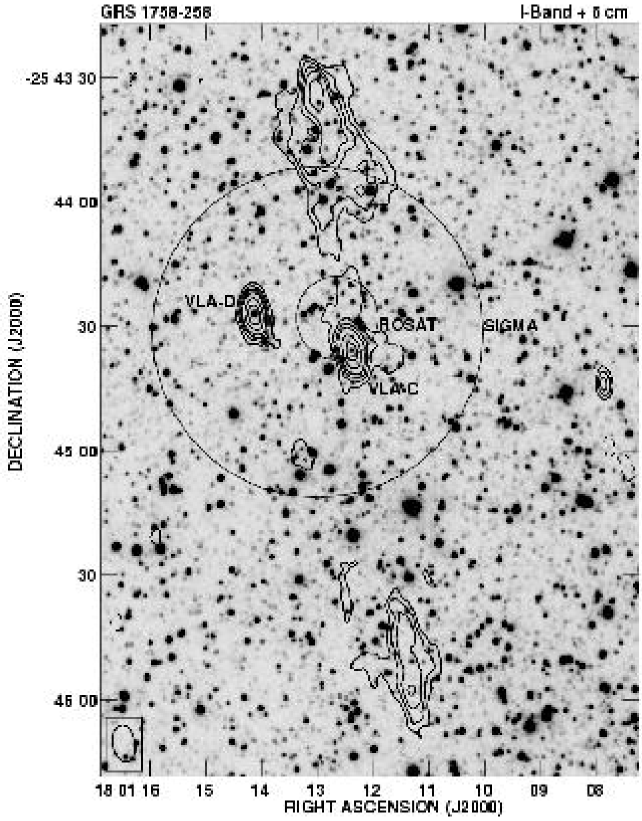


Figure 8. Image of the field of microquasar GRS 1758-258 recorded at the wavelength of 0.9 µm with the NTT SOFI camera. The contours show the intensity of the radio emission at 6 cm recorded with VLA. The SIGMA and ROSAT error circles are indicated.

The 15-micrometre mapping of the western section of W 50 reveals more probable sites of interaction between jets and that nebula, but what is the nature of the emission observed? Could it be, for example, of the synchrotron type, as in the radio range? This would justify an extremely efficient mechanism for the re-acceleration of electrons in order to emit in the infrared range and, thus, a new facet of the analogy between the quasar and the microquasar since the latter process has already been observed in radio-galaxies.

Modelling of Bondi-Hoyle-Lyttleton type accretion

Bondi-Hoyle-Lyttleton accretion refers to the falling of gas onto a compact object in supersonic motion. This mechanism concerns, in particular, X-ray binaries of large mass, in which a compact object is in orbit around a giant star capable of generating a dense stellar wind. To explain this type of accretion, Thierry Foglizzo pursued an initial research direction which consisted in evaluating the effectiveness of Kelvin-Helmholtz and Rayleigh-Taylor instabilities between the shock region and the accreting star (Foglizzo & Ruffert, 1999). Indeed, there is, along the shock region, a region where the vorticity produced by the impact is maximal and where the entropy gradients are the greatest. But these mechanisms, on their own, do not explain the instability observed as their growth time is comparable with the falling time from the shock region to the accreting star. A decisive step towards understanding the instability of Bondi-Hoyle-Lyttleton entailed understanding the role of the entropy-acoustics cycle (Foglizzo & Tagger, 2000) in the subsonic portion of the flow, between the shock region and the accreting star.

Modelling of gamma emission on the horizon of a black hole

Observations made in the hard X-ray band and the low-energy gamma-ray band indicate that all X-ray binaries known to harbour a black hole produce an abundant flux of low-energy gamma photons which is attributed to the Compton diffusion of X-ray photons radiated by the disc with a population of energetic electrons confined to the vicinity of the black hole. It is in this context that Philippe Laurent, in collaboration with Lev Titarchuk and his team, developed a radiation transfer code by the Monte-Carlo method with the purpose of modelling the Compton spectrum emerging from a binary system harbouring a black hole of stellar origin, in the hypothesis where the accreted electrons are accelerated owing to their free-fall motion on the horizon of the black hole (Laurent & Titarchuk, 1999). As can be seen in Figure 9, this digital simulation program, when used in the context of the Schwarzschild metric, produces emerging spectra that are remarkably comparable with those recorded during observations of black hole type X-ray binaries conducted in the low-energy gamma-ray band.

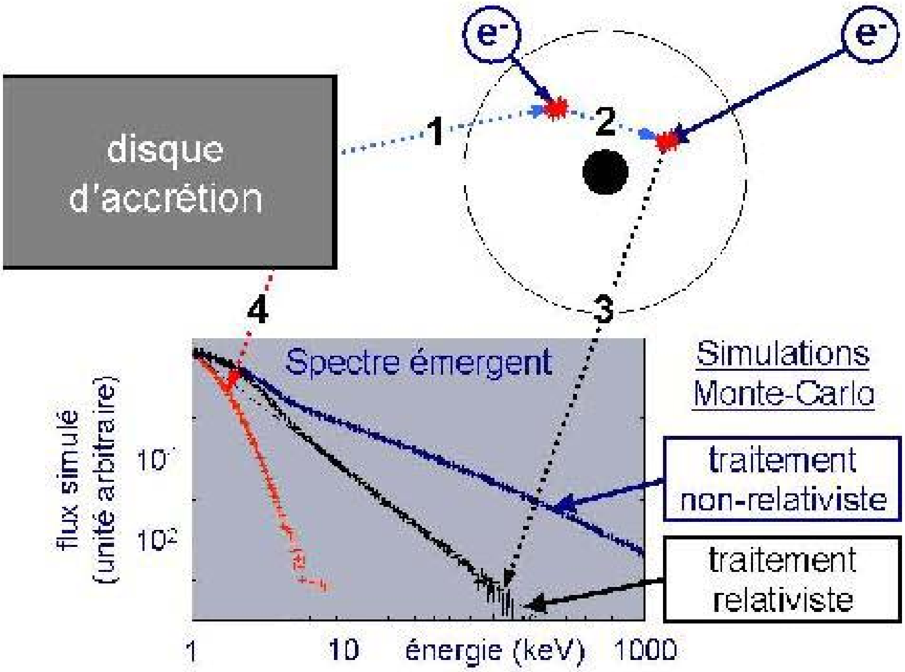


Figure 9. Sequence of multiple Compton diffusion at the edge of an accreting stellar black hole. An X-ray photon (1) emitted by the accretion disc diffuses a first time on a falling electron in free fall which passes some of its energy to it. The photon (2) diffuses again with another electron in free fall. The photon (3) then escapes from the grip of the black hole to reach the observer, so contributing to the luminosity measured in the low-energy gamma-ray band. The X-rays (4) emitted directly towards the observer contribute to the luminosity measured in the X-ray band. It should be noted that the calculated spectrum is too "hard" if the relativistic effects are not taken into account but perfectly reproduces observations when these effects are incorporated in the code.

Modelling of accretion-ejection phenomena in microquasars

In order to learn more about the phenomena at work in microquasars, Peggy Varnière and Michel Tagger undertook an analytical and digital study of the instability of accretion-ejection allowing extraction of the kinetic moment of the disc, thus causing the accretion of gas (Tagger & Pellat, 1999). In the internal section of the disc, this instability forms a spiral structure which is thought to be the origin of the quasi-periodic oscillations observed in the X-ray range. As shown diagrammatically in Figure 10, the kinetic moment of the disc is transported by the spiral to the zone where the gas rotates at the same speed as the wave and where it is stored in a Rossby eddy (Varnière & Tagger 2000). This eddy then allows the angular moment to be evacuated to the disc rim by emission of an Alfvén wave. When the inner edge of the disc remains far from the black hole, the relativistic effects are negligible and the frequency of the accretion-ejection instability varies with the inner radius of the disc to the power -3/2, which is observed. But, when the disc is close enough to the black hole, the relativistic effects can inverse that correlation and the frequency of the quasi-periodic oscillations decreases along with the radius. This tallies with recent observations of the microquasar GRO J1655-40.

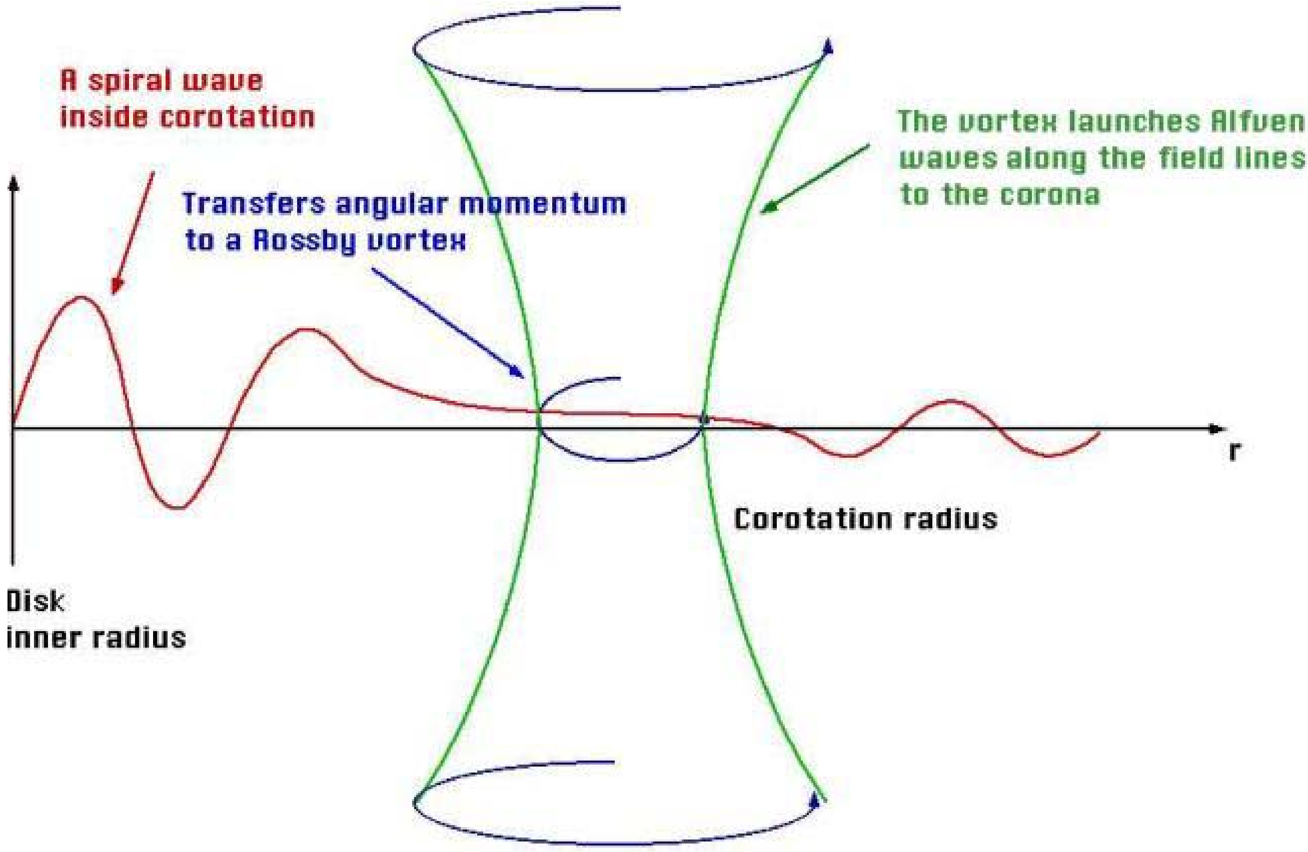


Figure 10: Diagrammatic representation of the accretion-ejection phenomena at work in microquasars.

Galactic Cosmic Ray sources, and the galactic evolution of Beryllium and Boron

The abundances of the elements in Galactic Cosmic Rays (GCRs) seems controlled by their volatility and their charge-to-mass ratio in the source medium (rather than by their first ionization potential, as was earlier accepted). These features are best interpreted in terms of an acceleration of gas ions and of entire dust grains in interstellar and/or circumstellar media, by Supernova (SN) shock waves (Meyer et al., 1997; Ellison et al. 1997). On the other hand, the presumably "primary" type of evolution of the Beryllium and Boron (Be, B) abundances in the early galaxy has been interpreted as implying that GCRs are accelerated directly out of fresh SN ejecta. Jean Paul Meyer and co-workers have shown that this hypothesis is certainly not valid for current GCRs, and is actually not even required for the early galaxy GCRs. The composition of the bulk of the source material of current GCRs, indeed, resembles that of the average galactic medium or of the Sun, and is inconsistent with that of SN ejecta. The (Fe+Ni) / (Mg+Si+Ca) ratio is solar in GCRs, while these elements are synthesized in different types of SNe (SN Ia and SN II) exploding in very different environments; s-process elements, which are never synthesized in any SN of any type, are not underabundant, relative to elements synthesized in SNe (Figure 11); all GCR isotopic ratios are solar (except for $^{22}Ne/^{20}Ne$ and $^{12}C/^{13}C$, probably indicating the acceleration Wolf-Rayet star wind material). In addition, the lack of ^{59}Ni in GCRs tells us that the material has been accelerated more than 10^5 years after its nucleosynthesis, therefore after dilution of the ejecta. Further, only the forward shock of a SN remnant (SNR), which can accelerate only the interstellar and/or circumstellar material outside the remnant, has enough energy and a long enough lifetime to accelerate the particles (Meyer & Ellison 1999; Ellison & Meyer 1999).

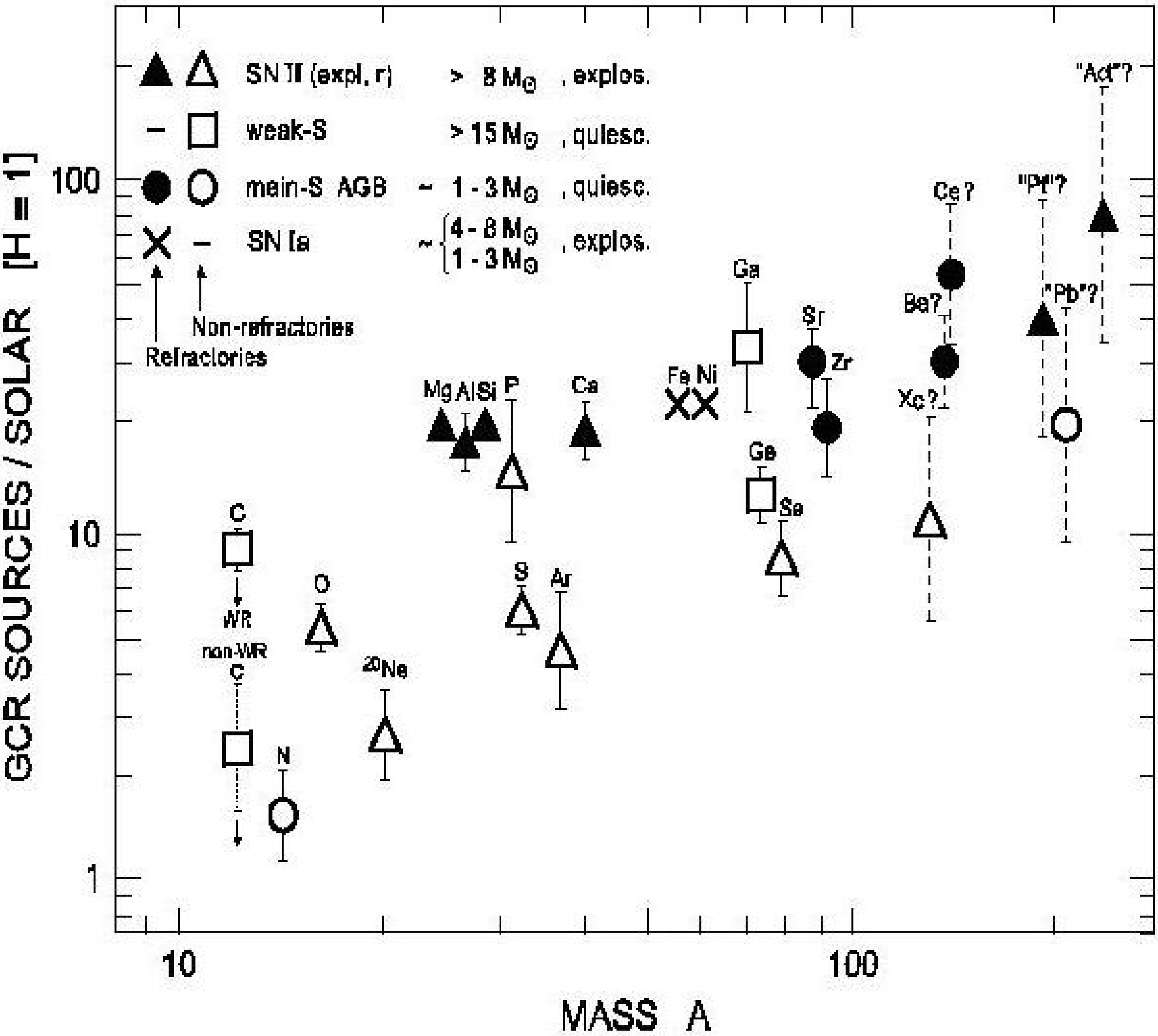


Figure 11: Heavy element abundance anomalies in the Galactic Cosmic Ray (GCR) sources, relative to Solar abundances, vs. mass A. In this figure, consider only the refractory elements (full symbols, and crosses), for which there seems to be no significant chemical or atomic selection effect during the acceleration. Among those refractory elements, there is no abundance bias in GCRs between elements synthesized explosively in Type-II SNe (Mg, Al, Si, Ca, Pt ?, Actinides ?), in Type-Ia SNe (Fe, Ni), and those formed quiescently by the s-process in low-mass AGB stars (Sr, Zr, Ba ?,Ce ?).

These conclusions do not conflict with a possible "primary" evolution of the Be and B abundances in the early Galaxy. Many SNe, indeed, explode in bursts within hot Superbubbles (SB) made of a mixture of material evaporated from surrounding dense clouds (dominant !), of Wolf-Rayet wind material, and of ejecta of earlier, local SNe. The forward shock of any SNR within the SB thus accelerates a material moderately enriched in products of recent nucleosynthesis, a modest enrichment that does not conflict with the current GCR composition. Now, Be and B are made by the spallation of heavier nuclei. But, in the early Galaxy, the average interstellar medium was virtually devoid of these heavier nuclei, so that any GCRs accelerated out of locally enriched SB material, however weakly, will have a predominant contribution in the synthesis of Be and B, giving it a "primary" type of evolution (Meyer & Ellison 1999).