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The Impact of Multifrequency Observations on Our Knowledge of the Physics of the Universe

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Abstract This paper has the purpose of introducing and bounding this workshop about *Multifrequency Behaviour of High Energy Cosmic Sources*. With the sole object of reaching such a goal we will point out several current problems and in order to stress the importance of multifrequency observations on the development of our knowledge of the Physics of the Universe we will discuss several examples taken from our direct experience and knowledge.

Key words: multifrequency astrophysics: high energy astrophysics — T Tauri stars — X-ray binary systems — jets — GRBs — cosmic background — astroparticle

1 INTRODUCTION

Multifrequency observations are a typical collaboration task between different kinds of astronomers. The idea of collecting them together was born some time ago, in 1984, when the first workshop about *Multifrequency Behaviour of Galactic Accreting Sources* was organized in order to discuss the whole behaviour of cosmic sources from experimental and theoretical points of view (Giovannelli 1985). The history of such a workshop was renewed in 1995 as *Multifrequency Behaviour of High Energy Cosmic Sources*, and since then with biennial cadence it is still alive and kicking.

A multitude of high quality data across practically the whole electromagnetic spectrum came at the scientific community's disposal a few years after the beginning of the Space Era. With these data we are attempting to explain the physics governing the Universe and, moreover, its origin, which has been and still is a matter of the greatest curiosity for humanity (e.g. Giovannelli & Sabau-Graziati 2004).

Traditional observations with a single instrument, sensitive to a given frequency, give only partial knowledge of the observed object. To obtain a complete picture of the object, we need multifrequency observations. They are fundamental both in imaging and in spectroscopy. Figure 1 shows a composite image of the Crab Nebula by using data from three of NASA's Great Observatories. The Chandra X-ray image is shown in light blue, the Hubble Space Telescope optical images are in green and dark blue, and the Spitzer Space Telescope's infrared image is in red. The neutron star is the bright white dot in the center of the image.

Figure 2 shows the energy flux versus energy of the 197 ms radio pulsar PSR B1 055–52 (Nel & De Jager 1994). It appears evident the importance of multifrequency observations: indeed, the temptation of an extrapolation of EINSTEIN data toward higher energies would produce a clear wrong spectrum of the pulsar, as well as that of EGRET data toward lower energies.

Among celestial objects, high energy cosmic sources are especially interesting from the point of view of multifrequency observations. Collapsed objects, close binaries, SNRs, pre-main-sequence stars, AGNs,

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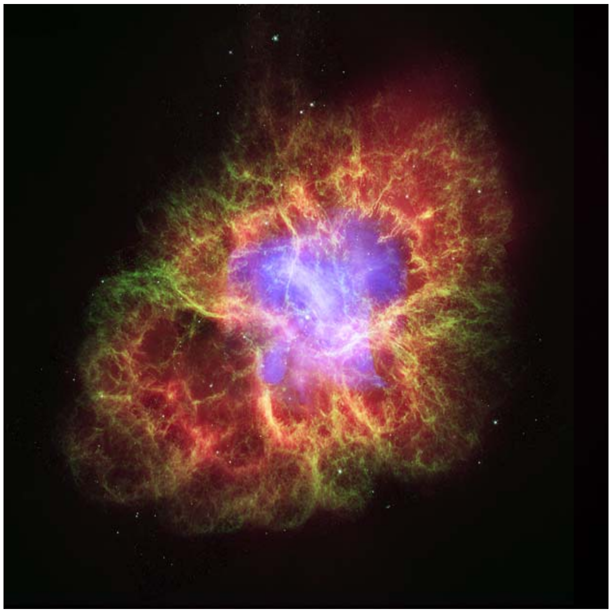

Fig. 1 Crab Nebula composite image: X-ray in blue (Chandra), optical in green and dark blue (HST), infrared in red (Spitzer Space Telescope).

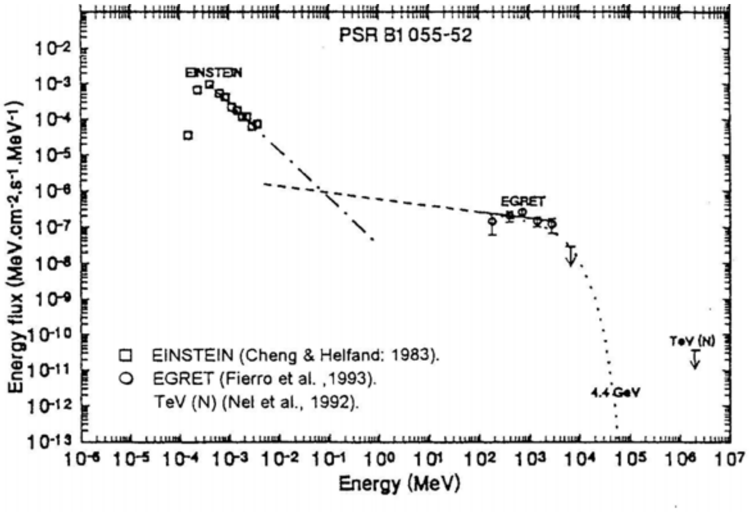

Fig. 2 Spectrum of the 197 ms radio pulsar PSR B1 055–52 (Nel & De Jager 1994).

GRBs experience particularly violent phenomena of high complexity, and emit radiation over the whole electromagnetic spectrum. A ‘simple’ massive early type star emits energy along a large part of the electromagnetic spectrum, as shown in Figure 3: thermal radio-IR is the free-free radiation of the hot wind; thermal X-ray emission is from shocks in the winds; non-thermal radio, IR, X-ray and γ-ray emissions are produced by relativistic particles accelerated by the shocks.

Therefore, it appears evident the importance of multifrequency observations, possibly simultaneous, of cosmic sources for a better understanding of the physics governing their behaviour.

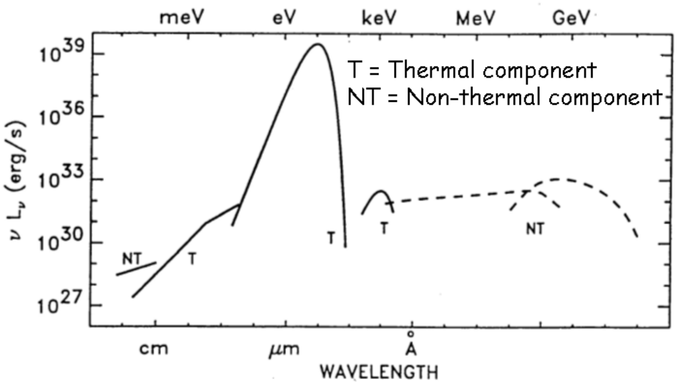

Fig. 3 The multifrequency spectrum from radio to γ-ray for a typical massive early-type star.

In the following sections we will briefly comment some examples of multifrequency observations and their impact on our knowledge of the physics governing the behaviour of different classes of cosmic sources.

2 T TAURI STARS

The study of pre–main sequence stars (PMSSs) is of great interest as it provides crucial information on stellar evolution and, particularly, on the role of magnetic fields, angular momenta, accretion of matter and mass loss processes, as well as indirect information on the formation processes of the Sun and Solar system.

With the nowadays knowledge of PMSSs, we can say that they are sites of a variety of extraordinary astrophysical processes, including accretion discs and outflows. The former have been detected by means of observations of molecular lines in cold gas. The best known class of PMSSs is that of the T Tauri stars (TTSs), identified by strong H_α line in emission, which is believed to be generated in an extended circumstellar envelope, indicating a continuous mass accretion process. The presence of an accretion disc have been strengthened by the observation of nearly Keplerian differential rotation (Hartmann & Kenyon 1987a,b) in the optical and near- IR (NIR) spectra of FU Ori, a young stellar object (YSO) whose spectral energy distribution can be explained by the presence of a disc.

TTSs are young contracting stars which are going to the main sequence with masses $< 3\,M_\odot$ and luminosity in the range 2–5 $L_\odot$. They show broad emission lines, strong and variable UV excesses and mass loss. Most of them have absorption spectra of K-M spectral type, on which emission lines of H, He, Ca II, Fe I and Fe II are superimposed. They show also additional continuum emission in UV and IR regions with respect to a MSS of the same type. Most of them show X-ray emission, whose flux is correlated with the rotational period. Whether this radiation forms is still controversial. Depending on their evolutionary status, TTSs can be surrounded by an accretion disc or not. The rotational period ($P_{\rm rot}$) is correlated with the spectral type of TTSs. The 'radiative track' stars with accretion disc signature show shorter $P_{\rm rot}$, on average, than those 'convective track' stars. This means that the efficiency with which accretion disc systems regulate stellar angular velocities may be different between stars on convective and radiative tracks. Those stars without accretion disc signature (Weak TTSs), among each spectral-type range, rotate more rapidly than those Classic TTSs of the corresponding range. For a review see the paper by Giovannelli (1994 and the references therein).

RU Lupi was selected by many groups as a convenient target in order to study the behaviour of TTSs. In particular Giovannelli's group performed a long campaign of coordinated ground and space–based multifrequency observations — often simultaneous — of RU Lupi in order to obtain a large set of physical parameters to be used in understanding the physics governing the correlated processes occurring in this system. The methodology of the multifrequency observations of highly variable cosmic sources (Giovannelli & Sabau-Graziati 1996) is now very well accepted by the international community, thanks also to the pioneers who clearly demonstrated its feasibility, in spite of the many objective difficulties in organizing coordinated campaigns of simultaneous observations (e.g. Giovannelli 1985). A large amount of data coming from many multifrequency campaigns of observations were collected. Their availability makes RU Lupi an excellent probe to test the goodness of the current models of TTSs. For these reasons Giovannelli (1994) wrote a long and exhaustive review paper.

Here we present some results coming from multifrequency observations of RU Lupi which improved its knowledge and gave also good inputs for an unusual methodology for progressing the science in general. Indeed, multifrequency simultaneous observations allowed to solve the problem of the total energy distribution in 'quiescence' and during 'Flare-like Events (FLEs)', whilst multifrequency no–simultaneous observations allowed to solve the controversial problem of the rotational period.

Starting from the two FLEs detected from UV to IR bands and searching in the literature all the FLEs reported mostly in the optical, Giovannelli (1994) (see Table XXVI) found that FLEs have a periodicity $P_{\rm FLE} = 27.686 \pm 0.002\,{\rm d}$. Several X-ray measurements gave only upper limits to the fluxes, while in one occasion, the X-ray flux was positively detected (Giovannelli et al. 1984a). Such a detection is in phase with the $\sim 27.7\,{\rm d}$ periodicity. Moreover, with such a period, if were the rotational one, the rotational velocity would be $\approx 5.5\,{\rm km\,s^{-1}}$ and would contrast the formation of a huge convective zone between the star surface and the inner boundary of the accretion disc. However, with such a rotational velocity, the relationship:

$$\log L_{\rm x} = 27.2 + 2 \log v_{\rm rot} \tag{1}$$

similar to that of Pallavicini et al. (1981), updated with the TTSs, as well as late–type dwarfs and RS CVn systems (Bouvier 1990) is roughly verified. Indeed, $L_{\rm x} = 4.76 \times 10^{28}$ erg s^{-1}, which is consistent with the upper limits found during 'quiescence'. Therefore 27.7 d is very probably the rotational period of RU Lupi, contrary to what is wrongly reported in the current literature ($P_{\rm rot} = 3.7$ d) (Boesgaard 1984 and the references therein), as clearly shown in Figure 5.

If this 27.7 d periodicity should be confirmed by direct measurements as the rotational period, a deeper analysis of the problem of angular momentum transfer and associated phenomena would be necessary.

3 GALACTIC ACCRETING SOURCES

Galactic accreting sources are close binary systems in which a compact star is accreting material from an optical star. Close binary systems: High Mass X-ray Binaries (HMXBs), Low Mass X-ray Binaries (LMXBs), Anomalous X-ray Pulsars (AXPs), Soft Gamma-ray Repeaters (SGRs), and Cataclysmic Variables (CVs) are the sites in which the physics of the matter accretion onto compact objects manifest in all the possibilities: from pure disc–fed to pure wind-fed transfer. Since these processes reveal themselves along a large part of the electromagnetic spectrum, these accreting sources are good targets for a number of measurements in different energy ranges, from the IR to VHE γ-ray.

Interaction processes between optical and compact companions produce effects which are measurable through physical quantities accessible to our detectors in different energy ranges. Low energy processes, mainly developing at the optical companion, influence the high energy processes, mainly occurring at the compact star, and vice versa (e.g. reviews by Becker 2000; van der Klis 2000; Giovannelli & Sabau-Graziati 2001, 2003, 2004; Mereghetti 2001a,b; Verbunt & Bassa 2003 – and references therein).

In spite of a robust knowledge of binary systems, many open problems still survive, and caution deserves in their study.

Our Galaxy contains an adequate number of X-ray binaries (XBs) whose emissions are the highest measurable; this renders such systems the most powerful laboratories for testing theories of collapsed objects and plasma physics, which can be used also for extragalactic systems by scaling distances and dimensions.

The number of XBs is 280 (Liu et al. 2000, 2001). Among them 131 are high mass XBs (HMXBs) being the optical companions giant or supergiant OB or Be stars. Mass transfer via excretion disc (Be stars) or via strong wind or Roche-lobe overflow; 149 are low mass XBs (LMXBs) being the optical companions low mass stars with spectral type later than B. Mass transfer occurs via Roche-lobe overflow. However, although the current classification considers XBs only systems with neutrons stars or black holes, we suggest to include in this class also the cataclysmic variables (CVs) – and in more general sense also the RS Canum Venaticorum (RS CVn) type systems — simply because they are binary systems emitting X-rays (e.g. Giovannelli & Sabau-Graziati 2003, 2004). An excellent review on the formation and evolution of compact X-ray sources have been published by Tauris & van den Heuvel (2003).

Among XBs there are 43 radio emitting X-ray binaries (REXBs) which constitute $\sim 15\%$ of the total: 8 are HMXBs and 35 LMXBs. 15 of REXBs are microquasars (Paredes 2007 and references therein).

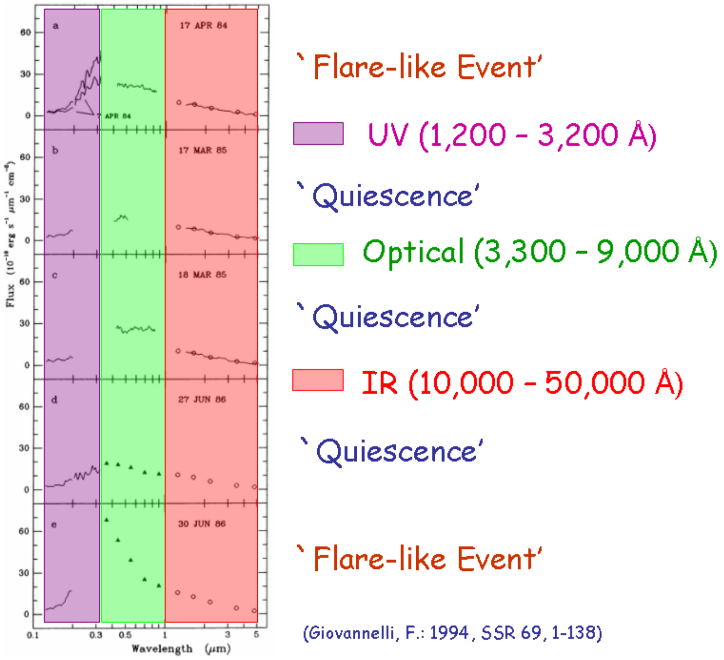

Fig. 4 Simultaneous multifrequency observations – from UV to IR – of RU Lupi in different epochs. Two FLEs and three 'quiescent' states were detected (Giovannelli 1994).

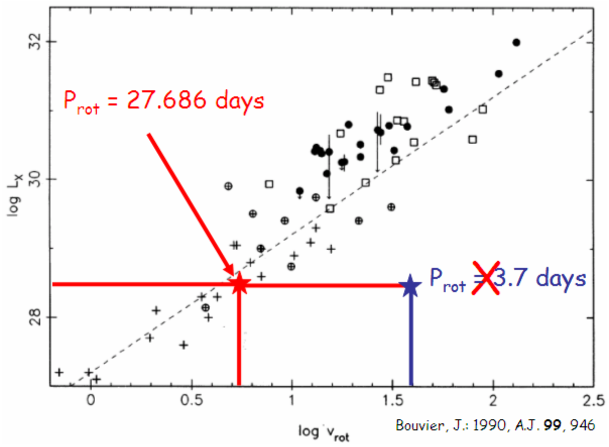

Fig. 5 X-ray luminosity versus rotational velocity of TTSs (●), late-type dwarfs (+), dKe–dMe (⊕), and RS CVn systems (open squares) (Bouvier 1990). RU Lupi ($\star$) is reported in red (correct $P_{\rm rot}$) and in blue (wrong $P_{\rm rot}$) (Giovannelli 1994).

The number of XBs is rapidly increasing thanks to the numerous operative high energy experiments ground– and space–based.

In the last couple decades a huge amount of multifrequency data, sometimes simultaneous, have been obtained from ground– and space–based experiments for a multitude of systems. So, the analysis is not far to be complete. In order to derive a synthesis, a change in the philosophy of the experiments is mandatory:

a continuous long term monitoring of a ‘few’ targets, representative of homogeneous classes of systems, is then necessary. In this way it will be possible to clarify what is happening during the different phases in which the physical processes occur.

3.1 High Mass X-ray Binaries

Close binary systems were the first objects to be detected in the X-ray energy region because of their intense emission, high enough to exceed the thresholds of detection even of the first generation X-ray detectors, which were simple proportional chambers, whose sensitivity level was of $\sim 10^{-4}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$ in the range 2–50 keV (e.g., Tananbaum 1973; Peterson 1973).

In the 1970s the study of X-ray pulsars stimulated many fields of astrophysics. The measurements of the neutron star masses were especially important as well as their relationships with the nuclear physics and high energy physics, gravitation theory and stellar evolution. It was possible to obtain detailed information about the optical companions of the collapsed objects, and therefore to develop in a coherent framework the evolution of close binary systems (e.g., van den Heuvel 1976). Through the study of the X-ray pulsars it was possible also to improve the knowledge of matter transfer processes in binary systems. Moreover, X-ray pulsations were used as probes of the internal structure of neutron stars and optical companions (e.g., Rappaport, Stothers & Joss 1980).

By using the data bank of the many X-ray satellites launched since 1970s it was possible to improve considerably the knowledge of binary systems both in soft and hard X-ray regions, with strong consequences also on the knowledge of extragalactic objects.

It has been demonstrated that HMXBs are good targets for a number of measurements in different energy ranges, from the IR to VHE γ-ray, in order to understand many crucial problems on the physics of the collapsed objects and their interactions with the optical companions. For these purposes two of the most significant energy ranges are the optical and X-ray ranges. Simultaneous measurements in these ranges can solve, in a first approximation, most of the problems still open in understanding the physics of the accretion of matter onto collapsed objects, the interactions with the stellar winds from the optical companions, the mechanisms triggering the X-ray emission and outbursts, and others.

In spite of the many space and ground based multifrequency experiments and the multitude of data of excellent quality obtained and partially still not analyzed, the question of the nature of the accretion flow to the neutron star and the resultant accretion torque in X-ray/Be binaries is still open.

The X-ray source in HMXBs provides a unique active probe of the winds of massive stars. In fact, the binary system orbits around its center of mass, then our line of sight continuously changes, allowing the map of the distribution of X-ray absorbing gas in the system. Meanwhile the strong X-ray flux alters the local dynamics of the wind, then it is possible to study the physics of radiatively driven winds, and thanks to X-ray variability in different time scales, it is also possible to study the dynamics of radiatively driven winds. Thus the study of winds provides precious information also about the accretion of matter onto the collapsed objects for systems clearly wind–fed. In the opposite case, in systems where the accretion is completely disc–fed we do not know completely the dynamics of the Roche lobe overflow process, and in particular, the fraction of matter and angular momentum lost from the binary system is still poorly known. And, moreover, wind accretion and Roche lobe overflow are the extreme cases of the same accretion process. An increase of the number of systems deeply studied simultaneously in different energy regions is then necessary in order to improve the statistics of the different cases of accretion, from ‘pure’ wind–fed to ‘pure’ Roche lobe overflow.

For this purpose we are rather lucky, since our Galaxy contains an adequate number of HMXBs whose emissions are the highest measurable; this renders such systems the most powerful laboratories for testing theories of collapsed objects and plasma physics. In order to go on in such a sense, a change in the philosophy of the experiments is mandatory. A continuous long term monitoring of a ‘few’ systems, representative of homogeneous class of systems, is then necessary. In this way it will be possible to clarify what is happening during the different phases in which the physical processes occur. These processes can be influenced by the rotation of the X-ray pulsars, the orbital period of the system, transit time of the matter from the primary to secondary star via wind, or disc, or intermediate, and so forth.

Moreover, all the results obtained can be scaled to extra-galactic distances and dimensions. The relative ease in performing multifrequency measurements of HMXBs suggests that they can be useful targets even for small satellites.

3.1.1 Historical Multifrequency Observations of A 0535+26/HDE 245770

The most studied HMXB system, for historical reasons and concomitant favourable causes, is the X-ray/Be system A 0535+26/HDE 245770 (see review by Giovannelli & Sabau-Graziati 1992). By means of long series of coordinated multifrequency measurements, very often simultaneously obtained it was possible to solve:

- the identification of the optical counterpart of the X-ray pulsar (Flavia' star);
- the identification of different X-ray outbursts triggered by different states of optical companion and influenced by the orbital parameters of the system;
- the identification of the presence of a temporary accretion disc around the neutron star at periastron.

Multifrequency observations of this system started soon after its discovery as X-ray pulsar by the Ariel-5 satellite (Rosenberg et al. 1975). The error box of the X-ray source contains 11 stars up to 23rd magnitude; among them there is the 9 mag Be star HDE 245770. The a priori probability of finding a 9 mag star in such a field is 0.004, so that Margon et al. (1977) suggested this star as probable optical counterpart of A0535+26. But in order to really associate this star with the X-ray pulsar, it was necessary to find a clear signature proving that the two objects would belong to the same binary system. This happened thanks to a sudden insight of one of us (FG), who predicted the fourth X-ray outburst of A 0535+26 around middle December 1977. For this reason Giovannelli's group was observing in optical HDE 245770 around the predicted period for the X-ray outburst of A 0535+26. Figure 6 shows the X-ray flux intensity of A 0535+26 as deduced by different measurements available in that time, with obvious meaning of the symbols used (Giovannelli 2005). FG's intuition happened looking at the rise of the X-ray flux (red line) and at the 24th May 1977 measurement (red asterisk): he assumed that the evident rise of the X-ray flux would have produced an outburst similar to the first one occurred in 1975. Then with a simple extrapolation he predicted the fourth outburst, similar to the second: and this happened!

Optical photoelectric photometry of HDE 245770 showed significant light enhancement of the star relative to the comparison star BD +26 876 during Dec. 17–21 and successive fading up to Jan. 6 (Bartolini et al. 1978), whilst SAS-3 satellite was detecting an X-ray flare (Chartres & Li 1977). The observed enhancement of optical emission during the flare-up of the X-ray source gave a direct argument strongly supporting the identification of HDE 245770 with A 0535+26.

The pulse period behaviour of A0535+26 (e.g. Giovannelli & Sabau-Graziati 1992) indicates that in its normal state the pulsar becomes 'slow' ($P_{\rm spin} < P_{\rm eq}$) during the active phases, i.e. close to periastron, and 'fast' ($P_{\rm spin} > P_{\rm eq}$) during the quiescent phase, i.e. close to apoastron. The alternation between the slow and fast phases is due to the oscillatory behaviour of the instantaneous equilibrium period, which in turn tracks the variable accretion rate. The value of the equilibrium period $P_{\rm eq}$ is related directly to the instantaneous accretion rate $\dot{\rm M}$ by $P_{\rm eq} \propto \dot{\rm M}^{-3/7}$ (Davidson & Ostriker 1973; Ziółkowski 1985).

The spin period of the X-ray pulsar is varying even during the same outburst. This behaviour is consistent with the *saw–tooth* model: a spin–up of the X-ray pulsar, on time scale of $\approx 100\,$yr, detected during active phases is roughly cancelled by the spin–down, on time scale of $\approx 1000\,$yr, occurring during quiescent phases (e.g. Ziółkowski 1985). Figure 7 shows the variations of the spin period during the 1977 December outburst (left panel) (Giovannelli & Sabau-Graziati 1992 and the references therein) and the long term pulse period history (Giovannelli et al. 1990). The mean secular spin–down is $\overline{\dot{P}/P} \sim -6.8 \times 10^{-4}$ yr^{-1} (Giovannelli et al. 1984b).

Soon after, with spectra taken at the Loiano 152 cm telescope with Boller & Chivens 26767 grating spectrograph (831 grooves/mm II-order grating: 39 Å mm^{-1}) onto Kodak 103 aO plates, it was possible to classify HDE 245770 as O9.7IIIe star. This classification was so good that it survives even to the recent attempts of dispute made with modern technology. The mass and radius of the star are 15 $M_\odot$ and 14 $R_\odot$, respectively; the distance to the system is $1.8 \pm 0.6\,$kpc (Giangrande et al. 1980).

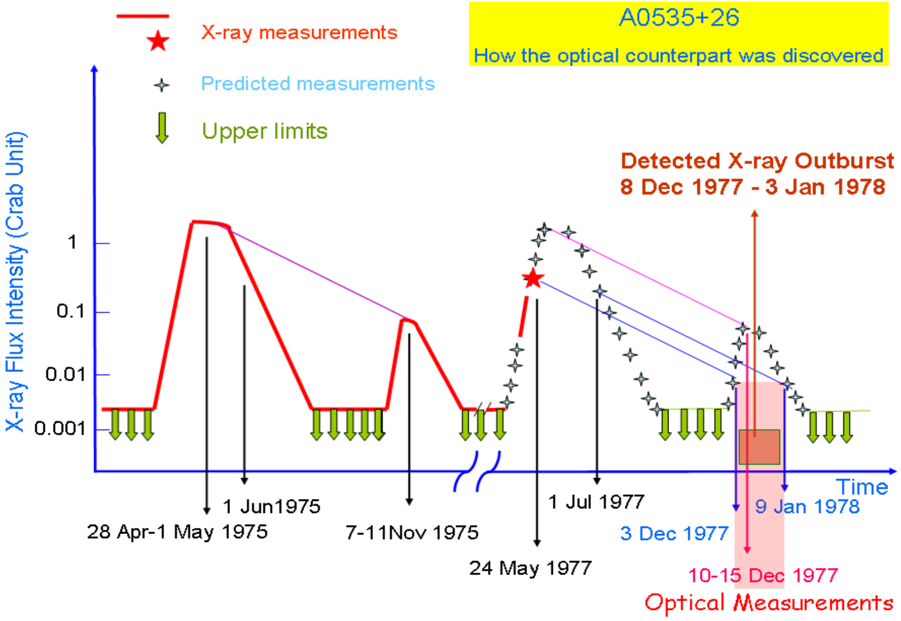

Fig. 6 X-ray flux versus time of A 0535+26. X-ray measurements are reported with red lines and asterisk, upper limits with green arrows, and predicted fluxes with light blue stars. Periods of real detected X-ray outburst and optical measurements are marked too (Giovannelli 2005).

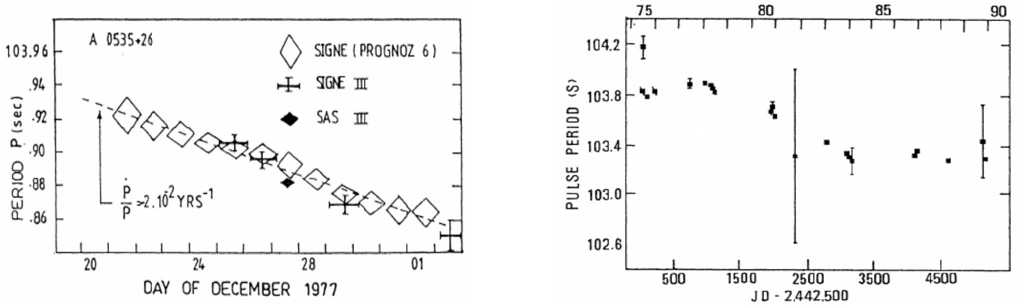

Fig. 7 A 0535+26 – Left panel: spin period variations during the December 1977 outburst (Giovannelli & Sabau-Graziati 1992 and references therein). Right panel: long term spin period history (Giovannelli et al. 1990).

UV spectra taken with the IUE allowed to determine the reddening of the system as E(B-V) = 0.75 ± 0.05 mag, the rotational velocity of the O9.7IIIe star ($v_{\rm rot} \sin i = 230 \pm 45$ km s^{-1}), the terminal velocity of the stellar wind ($v_\infty \simeq 630$ km s^{-1}), the mass loss rate ($\dot{\rm M} \sim 10^{-8}\, M_\odot$ yr^{-1} in quiescence (Giovannelli et al. 1982). During the October 1980 strong outburst, the mass loss rate was $\dot{\rm M} \sim 7.7 \times 10^{-7}\, M_\odot$ yr^{-1} (de Martino et al. 1989).

Analysis of a long series of X-ray outbursts as well as the behaviour of the O9.7IIIe star for the A 0535+26/HDE245770 system (Giovannelli & Sabau-Graziati 1992) allowed to understand the reasons of different kinds of outbursts in general in X-ray/Be systems. Figure 8 shows the three kinds of X-ray outburst, namely *normal*, *anomalous (or noisy)*, and *casual* for a generic X-ray/Be system with e ≈ 0.9 and $P_{\rm orb} \approx$

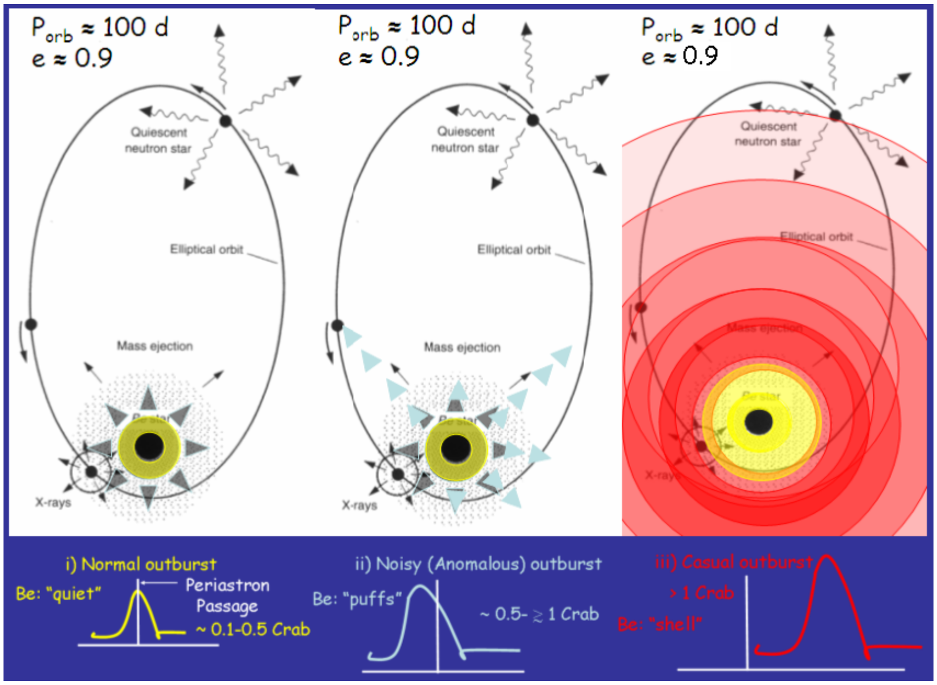

Fig. 8 Sketch of three kinds of X-ray outbursts of an X-ray/Be system with high eccentricity, and long orbital period, induced by the interactions between the Be star, in different states of activity, and the neutron star.

100 d. Normal outburst occurs at the periastron passage of the neutron star when the Be star is ‘quiescent’: only the ‘quiescent’ stellar wind is escaping from the Be star. Anomalous outburst occurs around — not necessarily at — the periastron passage of the neutron star when the Be star is experiencing an emission of ‘puffs’ of material superimposed to ‘quiescent’ stellar wind. Casual outburst occurs in principle at any orbital phase when the Be star expels a shell (repetition time of order thousand days). The intensity of X-ray outbursts is $\sim 0.1-0.5$, $\sim 0.5-1$, and > 1 Crab for normal, anomalous and casual outbursts, respectively.

3.1.2 Relevant Recent Results

Recently, many VHE γ-ray sources have been detected. HEGRA (High Energy Gamma Ray Astronomy) observations, from 1997 to 2002, of the CRAB Nebula between 500 GeV and 80 TeV have provided a good experimental spectrum whose best fit is given by $dN/dE = (2.83 \pm 0.04) \times 10^{-11}(E/\mathrm{TeV})^{-2.62\pm0.02}$ photons cm^{-2} s^{-1} TeV^{-1} (Aharonian et al. 2004). A new TeV HEGRA source J2032+4130 has been detected, being its flux $F(E > 1\mathrm{TeV}) = (5.9 \pm 3.1) \times 10^{-13}$ photons cm^{-2} s^{-1}, which is ~ 0.03 Crab (Horns & Rowell 2004). HESS (High Energy Stereoscopic System) discovered 8 new VHE galactic sources. These 8 sources plus J1745–290 and SNR RX J1713.7–3946, already known, can form a new population of VHE gamma-ray sources in the Galaxy (Aharonian et al. 2005). For a review about HESS results see the papers by Santangelo (2007).

These new experimental facts triggered also many theoretical works about the possibility of explaining such VHE emissions from massive close binary systems (Bednarek 2006a,b, 2007a; Bednarek & Giovannelli 2007) and other cosmic sources both galactic and extragalactic, such as young open clusters (Giovannelli, Bednarek & Karakuła 1996; Bednarek 2007b), OB associations (Bednarek & Giovannelli 2005; Bednarek 2007b), globular clusters (Bednarek & Sitarek 2007) pulsar wind nebulae (PWNe) interacting with dense molecular clouds (Bartko & Bednarek 2007), Propagation of gamma-rays in massive binaries and interactions of cascade gamma-rays with the massive star (Bednarek 1997, 2001; Bednarek & Giovannelli 1999; Giovannelli, Bednarek & Sabau-Graziati 2001), blazars (Bednarek 1999; Beall &

Bednarek 1999; Bednarek & Protheroe 1999a,b). Many of these sources are also VHE neutrinos emitters (e.g. Bednarek 2002, 2003, 2005; Beall & Bednarek 2002; Bednarek, Burgio & Montaruli 2005). Recent results from MAGIC (e.g. Albert et al. 2007a,b,c,d,e,f,g,h,i) and HESS are superbly confirming theoretical predictions.

Such detections from XBs allowed to consider γ-ray binaries as a new class very high energy sources, very well discussed by Dubus (2007). They are compact PWN (pulsar wind nebula) objects. A common scenario is that the pulsar spin–down powers a relativistic wind. VHE emission arises from containment of this relativistic wind (plerion). VHE emission occurs close to pulsar/star ($\gamma\gamma$ absorption should modulate TeV flux as for instance in LS 5039).

A renewed interest about X-ray/Be systems has originated from the possibility that HDE245770 /A0535+26 system may be identified with the otherwise unidentified variable EGRET gamma ray source 3EG J0542+2610, assuming the existence of a temporary accretion disc around the neutron star, i.e. during the February 1994 X-ray outburst. The gamma-ray emission seems to have been quenched exactly when the accretion disc was well-formed and rotating maximally (Romero et al. 2001).

As discussed by Giovannelli & Ziółkowski (1990) it is possible for a temporary accretion disc to form in the system A0535+26/HDE245770. The possibility of the formation of accretion discs round the neutron stars in X-ray/Be binaries has been thoroughly debated for several decades, and in recent times this possibility is a well accepted one within the working community (e.g. Ushomirsky & Routledge 2001; Hayasaki & Okazaki 2004).

Doubts about this idea came from the theoreticians (Davies & Pringle 1980; Livio et al. 1986a,b; Anzer, Borner & Monaghan 1987) who suggested that matter accreted directly from the stellar wind of the Be star should have very low specific angular momentum with respect to the neutron star, which would make the formation of an accretion disc impossible. However the observations suggested a different scenario: that the matter accreted by X-ray pulsars associated with Be stars (and therefore accreted from their winds) has in fact very high specific angular momentum compared to that required by a Keplerian disc (Rappaport & Joss 1977; Ziółkowski 1985).

Indeed, during X-ray outbursts, (when spin-up times are measured), the accretion onto the pulsar A0535+26 is disc–fed, so that (at least temporarily) an accretion disc must be present during the X-ray active phases (see e.g. Finger, Wilson & Harmon 1996). Whether remnants of the disc are still present near apoastron remains an open question.

An experimental support of the presence of a temporary accretion disc around the neutron star has been presented and discussed by Giovannelli et al. (2007) by means of optical spectroscopy. They detected a doubling in the HeI lines in emission close to the periastron passage of the neutron star. Such a splitting disappeared in a time scale of about a month, indicating that the presence of the accretion disc is temporary.

Once again it is compulsory to remark the importance of multifrequency observations of a number as large as possible of X-ray/Be systems, spread over entire orbital periods, in order to definitively clarify the physics governing their behaviour, including the production of different X-ray outbursts and possible VHE emissions. Such an emission renders these systems good targets for the new generation γ-ray experiments both space– and ground–based.

Relevant experimental results in the past two decades have provided crucial inputs for theories and better comprehension of the physics of compact objects. Cyclotron lines from HMXBs (Dal Fiume et al. 1998), and in particular the four cyclotron features from the pulsating transient X 0115+63 (Santangelo et al. 1999) have been detected. Then it was possible the derivation of the magnetic field at the neutron star: $B = (1-4) \times 10^{12}\,\mathrm{G}$ for the known X-ray pulsars. This is an important track for the investigation on magnetic field evolution of neutron stars.

Gamma-rays from the massive binaries Cyg X-3, LSI 303°, Cen X-3, and Vela X-1 have been detected by the COMPTEL and EGRET detectors of the CGRO. These detections provoked a discussion on their propagation inside such binary systems (Bednarek 1997; Bednarek & Giovannelli 1999). If VHE γ-rays have been injected somewhere inside HMXBs, they may initiate the inverse Compton pair cascade in the anisotropic radiation of the massive companion, provided that the inverse Compton scattering (ICS) losses of secondary cascade $e^{\pm}$ dominates over other energy losses. The spectra of the escaping secondary cascade γ-rays depend on the angle of observation, but in a quite broad range of the angles this dependence is not strong. This may create problems with the detection of orbital modulations of γ-ray signals from such massive binaries.

A significant fraction of energy escaping from a HMXB ($\geq 80\%$) — the other part is absorbed by the HMXB — produces a continuum γ-ray spectrum, and annihilation and nuclear γ-ray lines generated on the surface of the primary star by the infalling secondary γ-rays.

The measurement of such spectra and their features is one of the open problems for γ-ray satellites, such as AGILE and the future GLAST. MAGIC and HESS can solve experimentally such problem. SPI and IBIS on board the INTEGRAL could perform such measures too, but only with different philosophy of the scheduling.

3.2 Low Mass X-ray Binaries

Milestones on the study of LMXBs have been the RXTE and BeppoSAX satellites. The importance of these systems resides mainly in the fact that they are containing neutron stars (or black holes), which are objects of fundamental physical interest. Their study allows the derivation of information about the equation of state of high density matter and to test the general relativity in the presence of very strong field régime.

When the matter is descending into the neutron star's very deep gravitational potential well (GM$_{\rm NS}$/$R_{\rm NS}$ $\sim$ $0.2c^2$), the temperature of the inner flow increases a great deal because of the release of a large amount of gravitational energy. The characteristic velocities near the NS are of order (GM$_{\rm NS}/R_{\rm NS})^{1/2}$ $\sim 0.5c$. Therefore the time scale for the motion of the matter through the emitting region, namely, the dynamical time scale, is as short as $\tau_{\rm dyn}$ = r^3/GM$_{\rm NS}^{1/2}$ ~ 0.1 ms for r = 10 km, and $\sim$ 2 ms for r = 100 km.

NSs in LMXBs display a complex variety of quasi-periodic oscillation (QPO) modes in their X-ray flux (van der Klis 1989). The discovery of the KHz QPOs, made with the RXTE satellite (Strohmayer et al. 1996; van der Klis et al. 1996), provided experimental evidence of the crude phenomenology, occurring in the vicinity of the neutron stars.

What is clear at this moment is that, for the first time, rapid X-ray variability phenomenon, directly linked with the NS's most distinguished characteristic, namely its compactness, have been detected. This is particularly evident if the phenomena are in some way related to the orbital motion. Indeed, a Keplerian orbital frequency $\nu_{\rm K} = P_{\rm orb}^{-1}$ = (GM$_{\rm NS}/4\pi^2 r_{\rm K}^3)^{1/2}$ of 1200 Hz around a 1.4 $M_\odot$ NS as seen from infinity corresponds to an orbital radius $r_{\rm K}$ = (GM$_{\rm NS}/4\pi^2\nu_{\rm K}^2)^{1/3}$ of 15 km directly constraining the equation of state of the bulk matter of nuclear density, and only just outside the general relativistically marginally stable orbit (van der Klis 2001).

Whatever the model, for the first time one has to seriously worry about general relativistic effects in describing the observable dynamics of the physical systems.

With the new generation X-ray satellites, when accretion disc will be seen, the physics of the accretion processes will have experimental supports for testing all the circulating models.

3.3 Anomalous X-ray Pulsars and Soft Gamma-ray Repeaters

Anomalous X-ray Pulsars (AXPs) constitutes a subclass of the LMXBs, characterized by lower luminosities, higher magnetic fields and smaller ages than non-pulsating LMXBs. Recent measurements of the spin down rates of soft gamma-ray repeaters (SGRs) and AXPs have been interpreted as evidence of very strong magnetic fields at the collapsed object poles, roughly two orders of magnitude greater than those of the 'normal' X-ray pulsars. If this interpretation is correct, the justification of such high values of magnetic fields constitutes one of the hottest problem in modern astrophysics.

Models based on strongly magnetized neutrons stars (B $\sim$ 10^{14}–10^{15} G) have been developed in the last decade just in order to explain the behaviour of the SGRs (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). Dar (2006) argue that, instead, the observations support the hypothesis that SGRs and AXPs are neutron stars that have suffered a transition into a denser form of nuclear matter to become, presumably, strange stars or quark stars. Internal heat and slow gravitational contraction long after this transition can power both their quiescent X-ray emission and their star quakes, which produce 'soft' gamma ray bursts.

But, if magnetic fields in AXPs and SGRs (‘magnetar’) are of $\sim 10^{15}$ G, an almost ‘obvious’ consequence can be derived: the correspondent dimension of the source must be of ~ 10 m. This could be the dimension of the acceleration zone in a supercompact star. Is this a quark star? *If you construct a trap, the rat falls into it!* (Giovannelli & Sabau-Graziati 2006).

3.4 Cataclysmic Variables

CVs renewed their importance because of the detection of TeV emission from a few of them, as well as softer γ-ray emission detected by the INTEGRAL observatory from a consistent number of them. CVs are very similar to LMXBs: one just has to replace the central white dwarf with a neutron star.

The detection of several systems SW Sextantis-like, whose orbital periods are inside the historical ‘period gap’ of CVs (2–3 hr) (Rodríguez-Gil 2003), opened a ‘new’ problem in the study of the evolution of CVs. SW Sex systems are probably the missing link between the intermediate polars ($P_{\rm orb} > 3$ hr) with magnetic fields of $\sim 10^6 - 10^7$ G, still experiencing magnetic bremsstrahlung, and polars ($P_{\rm orb} < 2$ hr) with magnetic fields of $\sim 10^7 - 10^8$ G, subject to gravitational radiation.

The exciting problem is to prove the evolutionary continuity of all the magnetic CVs and their relationship between HE emission and magnetic field intensity. This problem can be faced also looking at the low energy behaviour of CVs, which correlate with high energy behaviour: e.g. emission lines from the accretion disc are witness of its morphological and physical evolution; and this is correlated with the magnetic field intensity (e.g. Martinez-Pais et al. 1994; Giovannelli & Sabau-Graziati 2004 and references therein). For a recent review on CVs see Giovannelli (2008).

3.5 Accretion Models

Models of soft X-ray transient (SXT) outbursts are closely similar to those developed for dwarf nova (DN) outbursts. It is now generally accepted that SXT and DN outburst are owed to a sudden increase of the mass accretion onto the compact object.

Now far a few critical words on the problem of accretion of matter and on the bursts in the case of binary systems containing a neutron star, where the accretion of matter is often disc–fed. The disc itself is rotating, so that the accreted material adds angular momentum to the neutron star. Thus, unlike radio pulsars — which are spinning down — accreting neutron stars in X-ray binaries should spin up as time passes. There is a strong funnelling of the accretion onto the poles and the local confinement of the accretion mound, at least until the ignition, most often results in stable burning. For this reason thermonuclear X-ray bursts are not seen from X-ray pulsars, with the exception of the SAX J1808.4–3658.

All of the observed regular X-ray bursting neutron stars accrete at $\dot{\rm M} < 10^{-9}\, M_\odot$ yr^{-1} and show no evidence of magnetic fields strong enough to focus the accretion onto an area small enough to stabilize the burning. The thermonuclear instability forces the star to burn the fuel in a time-dependent manner (the fuel accumulated for a few hours until the instability set in, and then fuel is burned in about 10 seconds when T$> 10^9$ K).

The burning processes are quite complicated: most of the hydrogen is burned in a series of rapid proton captures followed by β-decays of the heavy nuclei — the rp process (Bildsten & Strohmayer 1999).

Modelling the burning requires knowledge of the thermonuclear reaction rates for nuclei far on the proton-rich side of the valley of stability, but most of these rates have not yet been experimentally measured.

4 JETS IN ASTROPHYSICS

Relativistic jets have been found in numerous galactic and extragalactic cosmic sources at different energy bands. They can be formed by electrons and protons — accelerated up to relativistic energies — which through interactions with the matter and/or photons generate high energy radiation. The spectra of such a radiation are strongly dependent on the angle formed by the beam axis and the line of sight, and obviously by the Lorentz factor of the particles (e.g. Bednarek et al. 1990 and the references therein; Beall, Guillory & Rose 1999; Beall 2002, 2003; Beall et al. 2006, 2007).

Jets are thought to be produced by the powerful electromagnetic forces created by magnetized gas swirling toward a collapsed object (i.e. black hole). Although most of the material falls into the collapsed object, some can be ejected at extremely high speeds. Magnetic fields spun out by these forces can extend over vast distances and may help explain the narrowness of the jet.

Several examples of jets can be seen in the Chandra X-ray images. Such jets are coming from different sources, such as the radio galaxies Pictor A, Cyg A and Cen A, the Crab and Vela pulsars and nebulae, and several Herbig Haro objects: HH 30, HH 34, HH 47, as shown in Figure 9.

Probably, the most astonishing example is that of Pictor A (Figure 9, left upper panel), in which a spectacular one-sided jet that emanates from the center of the galaxy (left) and extends across $\sim$110 kpc toward a brilliant hot spot is shown. The hot spot is at least $\sim$240 kpc (8 times the diameter of our Milky Way galaxy) away from where the jet originates. The hot spot is thought to represent the advancing head of the jet, which brightens conspicuously where it plows into the tenuous gas of intergalactic space. One possible explanation for the X rays is that shock waves along the side and head of the X-ray jet are boosting electrons and possibly protons to ultra-relativistic energies. Jets are thought to be produced by the powerful electromagnetic forces created by magnetized gas swirling toward a black hole. Although most of the material falls into the black hole, some can be ejected at extremely high speeds. Magnetic fields spun out by these forces can extend over vast distances and may help explain the narrowness of the jet. For details on the X-ray jet, detected by the CHANDRA satellite, see the paper by Schwartz et al. (2000). For the extended X-ray emission from the eastern radio lobe of Pic A, detected by XMM-Newton satellite, see the paper by Grandi et al. (2003).

Therefore, following the very interesting paper by Beall et al. (2007), astrophysical jets are a remarkable laboratory for a number of important physical processes. They provide a confirmation of special relativity in terms of relativistic Doppler boosting, superluminal motion, and time dilation effects. When coupled with their black-hole/neutron-star origins, jets have implications for testing general relativity. Over the course of two decades of astrophysical research, we have become aware that jets are ubiquitous phenomena in astrophysics. Extended linear structures now associated with jets can be found in star–forming regions, galactic binaries, microquasars, active galaxies and quasars, clusters of galaxies, and γ-ray bursts. The presence and evolution of these jet–like structures is of course a testament to the principle of conservation of angular momentum.

The association of jets with accretion discs strengthens the case for similar physical processes in all these phenomena (e.g., Beall 2003; Marscher 2005), and it has become plausible that essentially the same physics is working over a broad range of temporal, spatial, and luminosity scales. Jets have, therefore, become a ‘laboratory’ or perhaps an anvil, that we can use to help us forge our understanding of the physical processes in the sky.

In 1992 the first so-called microquasar, *annihilateur*, was identified (Mirabel et al. 1992). This source was exhibiting bipolar radio jets spread over several light-years. This was the first such observation in our Galaxy, however jets had been already observed emanating from distant galaxies. Therefore this observation made clear the existence of a morphological analogy between quasars and microquasars. Indeed, Mirabel & Rodríguez (1994) detected from the black hole candidate GRS 1915+105 — discovered by Castro Tirado et al. (1994) — apparent superluminal motions, while frame velocity was v$\sim$ $0.92c$. It became then rapidly clear that the advantages of microquasars compared to quasars were that i) they are closer, ii) it is possible to observe both (approaching and receding) jets, and iii) the accretion/ejection timescale is much shorter. After this observation of superluminal motions, the morphological analogy with quasars became stronger, and the question was then: is this morphological analogy really subtended by physics? If the answer is yes, then microquasars really are “micro”–quasars. For instance, there should exist microblazars (microquasar whose jet points towards the observer), in order to complete the analogy with quasars.

Although there is no clear definition of a microquasar, we can characterize it as a galactic binary system — constituted of a compact object (stellar mass black hole or neutron star) surrounded by an accretion disc and a companion star — emitting at high-energy and exhibiting relativistic jets. A schematic view of a microquasar, compared with quasars, is given in Figure 10 (Chaty 1998). Taking this broad definition, nearly 20 microquasars in our Galaxy have been observed.

Microquasars are among the best laboratories for high energy phenomena and astroparticle physics. They are good candidates to be emitters of astroparticles: very high energy photons, cosmic rays and neutrinos. For these reasons the study of microquasars is one of the main goal of current space missions. Since each component of the system emits at different wavelengths, it is necessary to undertake multifrequency observations in order to understand phenomena taking place in these objects.

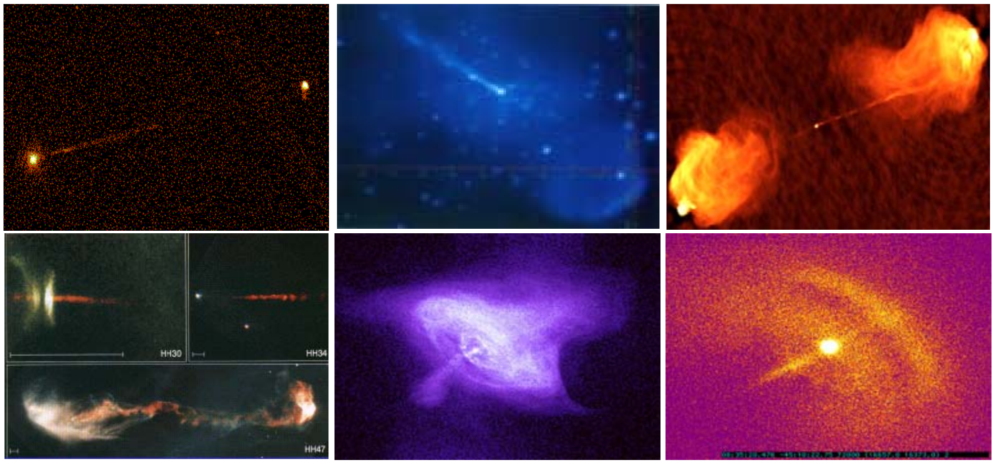

Fig. 9 Clockwise from left upper panel the spectacular jets emanate from i) the center of the radio galaxy Pictor A; ii) Cen A radio galaxy; iii) Cygnus A radio galaxy; iv) Vela pulsar; v) Crab Nebula; vi) Herbig Haro objects: HH 47, HH 34, and HH 30 (NASA/Chandra X-ray Observatory ACIS Images).

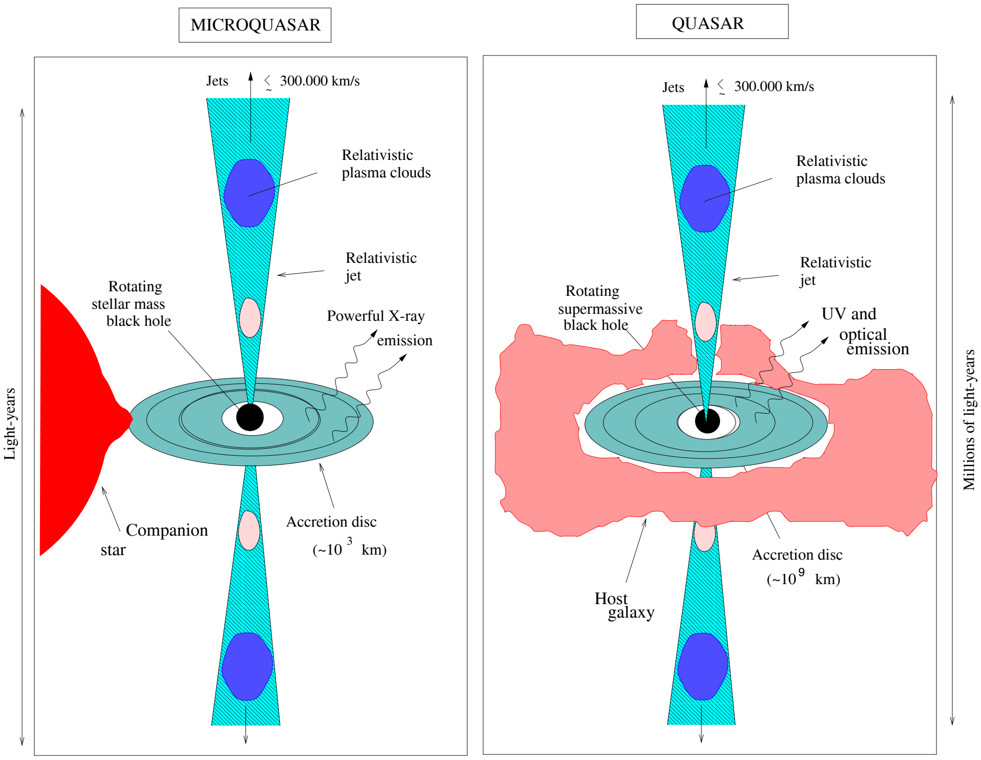

Fig. 10 Sketch showing analogies between quasars and microquasars. Note the different mass and length scales between both types of objects (Chaty 1998).

Chaty (2007) remarks the importance of multifrequency observations by means of the measurements of GRS 1915+105, taken in 1997. The link between accretion and ejection is visible examining Figure 11. We can see the disappearance of the internal part of the accretion disc, shown by a decrease in the X-ray flux, followed by an ejection of relativistic plasma clouds, corresponding to an oscillation in the near-infrared (NIR) and then in the radio, the cloud becoming progressively optically thin.

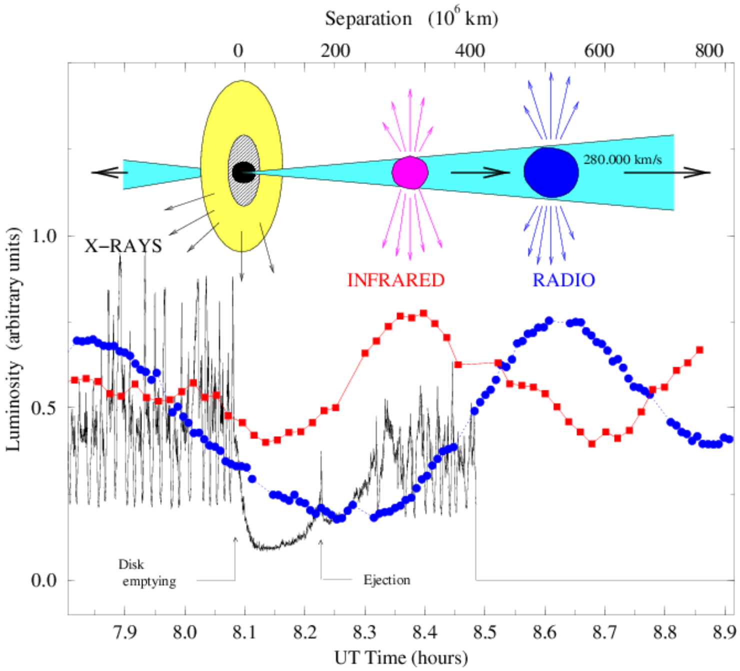

Fig. 11 Observation of the link between accretion and ejection. X-ray, NIR and radio light curves of GRS 1915+105 during the 1997 September 9 multifrequency observation campaign. The disappearance of the internal part of the accretion disc (decrease in the X-ray flux) is followed by an ejection of relativistic plasma clouds oscillation in the NIR and radio (Chaty 2007 and the references therein).

As excellently discussed by Chaty (2007), the quasar/microquasar analogy became rapidly very fruitful, the field of quasars benefiting of microquasars, and vice versa. For instance, because accretion/ejection timescale is proportional to black hole mass, it is easier (because faster) to observe accretion/ejection cycles in microquasars than in quasars On the other hand the understanding of ejection phenomena in microquasars have largely benefited from jet models developed for active galaxies.

High energy emission from microquasars and AGNs have been clearly discussed from experimental and theoretical points of view by Paredes (2007). In his paper he presented the complete list of microquasars and discussed about these sources as γ-ray emitters from observational point of view and the possible models fitting the multifrequency data. Bosch-Ramon, Romero & Paredes (2006) developed a model based on a freely expanding magnetized jet, in which internal energy is dominated by a cold proton plasma extracted from the accretion disc. The model was applied to the microquasar LS 5039 (Paredes, Bosch-Ramon & Romero 2006) to reproduce qualitatively the spectrum of radiation produced in the jet from radio to VHE. Indeed, LS 5039 has recently been detected as a source of VHE γ-rays. This detection, that confirms the previously proposed association of LS 5039 with the EGRET source 3EG J1824.1514, makes of LS 5039 a special system with observational data covering nearly all the electromagnetic spectrum.

Figure 12 shows the spectral energy distribution (SED) predicted for LS 5039 and the data obtained with several instruments. The effects of the absorption are evident in the SED, where there is a minimum around few 100 GeV.

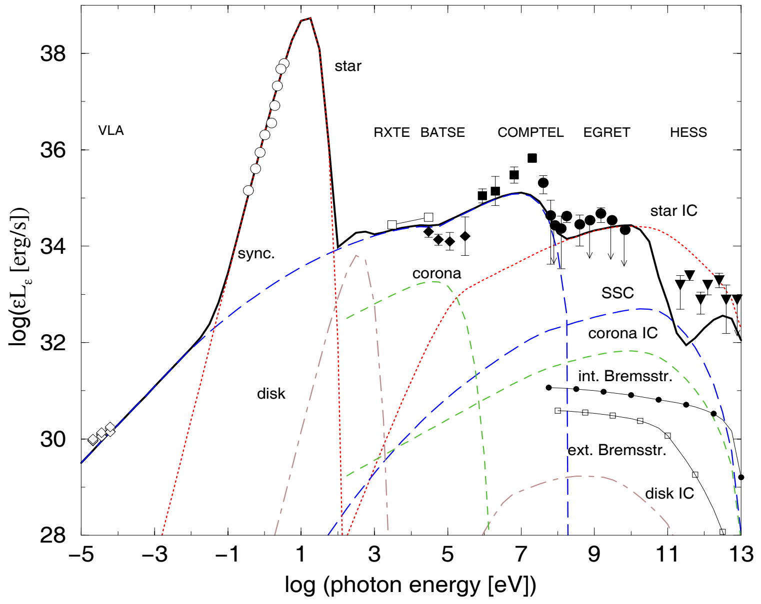

Fig. 12 SED of LS 5039. The main radiation components are shown, altogether with the total emission, which suffers attenuation by photon photon absorption above 10 GeV (Paredes, Bosch-Ramon & Romero 2006).

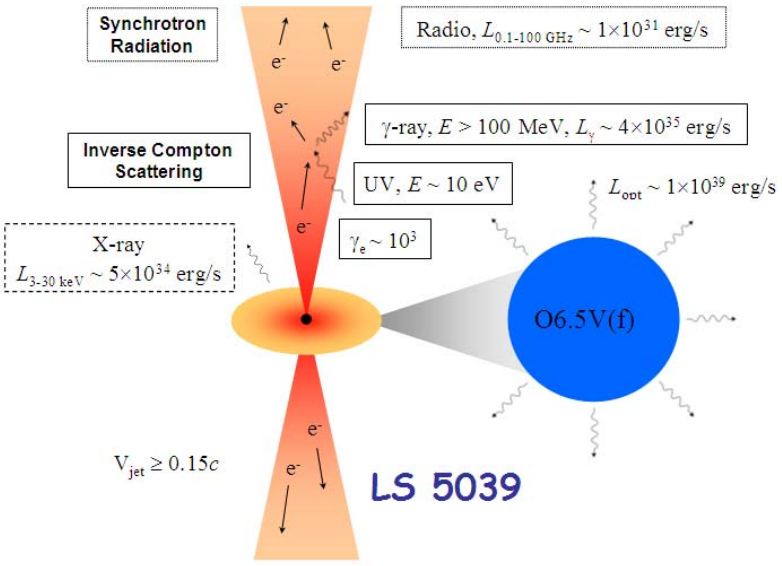

Fig. 13 Sketch of the general model of LS 5039. The main radiation components are shown with their relative emissions (Paredes 2006).

Figure 13 clearly represents in a sketch what is the general model of the source LS 5039 that allowed to fit the multifrequency data reported in Figure 12 (Paredes 2006).

5 GAMMA-RAY BURSTS

Gamma-ray burst (GRBs) were discovered in 1967 – thanks to the four VELA spacecrafts, originally designed for verifying whether the Soviet Union abided the 1963 Limited Nuclear Test Ban Treaty – when 16 strong events were detected (Klebesadel, Strong & Olson 1973). Since then GRBs have remained a puzzle for the community of high energy astrophysicists. For this reason the problem of GRBs originated thousands articles most of them devoted to their physical interpretation (e.g. the review by Mazets & Golenetskii 1988; the review by Giovannelli & Sabau-Graziati 2004 and the references therein). BATSE/CGRO experiment detected 2704 GRBs from 1991 to 1999. This number increased with new generation satellites (BeppoSAX, RossiXTE, HETE, INTEGRAL, and SWIFT). In spite of this, the problem of their origin is still alive, at least for a part of them.

Up to date there are more than 100 claimed association of GRBs with the host galaxies at high redshift. This fact strongly push toward the extragalactic origin of GRBs. However, extragalactic origin would necessitate an extremely high amount of energy for each event, that probably only invoking *ad hoc* models could be justified. If a γ-ray burst should produce a very high collimated relativistic beam in the direction of us, the amount of energy associated ($\approx 10^{53}$ erg) could be justified.

Critics to this origin have been discussed by several authors, such as Kundt (2001, 2002, 2003) and Bisnovatyi-Kogan (2003a,b). Indeed, some points need to be clarified, namely: i) Redshift is measured only in long-duration bursts. Do short bursts have different nature? ii) Origin of hard gamma ray (20–20000 MeV) afterglow, lasting up to 1.5 hours. iii) Hard X-ray absorption features. iv) Influence of a strong GRB explosion on the host galaxies, which is not (yet) found. v) Absence of the expected correlations connected with properties of GRBs at large and small redshifts.

In order to settle the controversy, it is crucial to monitor the sky with the goal of searching for the behaviour of GRBs in the whole electromagnetic spectrum, possibly with simultaneous measurements.

The SWIFT observatory is strongly improving our knowledge about GRBs. The average redshift of the host galaxies for the long GRBs is $\bar{z} = 2.3$, which is a factor of ~ 2 greater than the average redshift for the GRBs detected in the pre–SWIFT era. Moreover, this spacecraft has detected few dozens short bursts at cosmological distances at average redshift $\bar{z} = 0.5$. They are located mostly in elliptical galaxies outside of the star formation regions. Therefore, they must be connected to the old population and not to the young massive stars (as the long bursts are). The most likely explanation is that at least large part (majority?) of these events are due to mergers of compact objects (e.g. Ziółkowski 2007).

Theoretical description of GRBs is still an open strongly controversial question. Fireball (FB) model (Meszaros & Rees 1992; Piran 1999), cannon ball (CB) model (Dar & De Rújula 2004), spinnin-precessing jet (SPJ) model (Fargion 2003a,b) are the most popular, but each one against the others. Dar (2006) critically discussed the FB and CB models. He concluded that the CB model is incredibly more successful than the standard FB models of GRBs. Fargion & Grossi (2006) support the validity of SPJ model declaring that it is even more general than the CB one. About this controversy, I invite the colleagues to read the very interesting scientific-social remark made by Arnon Dar at the end of the paper discussed by Guido Barbiellini at the Vulcano Workshop 2002 (Barbiellini & Longo 2003).

6 BACKGROUND IN THE UNIVERSE

After the Big Bang the Universe started to expand with a fast cooling. The cosmic radiation observed now is probably a melting of different components which had their origin in different stages of the evolution as the results of different processes. This is the Diffuse Extragalactic Background Radiation (DEBRA), which, if observed in different energy ranges, allows the study of many astrophysical, cosmological, and particle physics phenomena.

The first component of this radiation was detected in the microwave region. Its spectrum is best fitted to that of a black body at 2.7 K. The temperature is uniform in all the sky to a precision of $\sim 10^{-4}$. This is the residual radiation, predicted by the theory of the Big Bang, in a phase in which the entire Universe was warm, dense, and opaque. The Universe became transparent $\sim 10^{5}$–10^{6} years later (cosmological redshift $\sim$ 1100–1000) when the temperature decreased below 3,000 K and hydrogen recombined. Some theories about the formation of complex structures predicted the existence of a background radiation also in the IR and optical spectral regions originating during the formation of the first stars in the first galaxies, at a cosmological redshift of $\sim$ 4–5 (Partridge & Pebles 1967a,b). Also in the X-ray and γ-ray ranges a diffuse background radiation exists, but it is not yet completely understood, although the new generations of detectors of numerous satellites are improving knowledge of it. Also each class of residual particles, with the relative radiative decay, should contribute to the cosmic diffuse background. Therefore it is possible to use measurements of the diffuse radiation in order to evaluate the masses (or at least some limits) and couplings of each class of particles.

COBE results from FIRAS instrument give for the CMBR a best fit to a black body spectrum within 3.4×10^{-8} erg cm^{-2} s^{-1} sr^{-1} cm over the range 5–0.5 mm (2–20 cm^{-1}). These measurements imply stringent limits on energy release in the early Universe after $t \sim 1$ yr and redshift $z \sim 3 \times 10^6$. The deviations are less than 0.03% of the peak brightness. The temperature of the CMBR is 2.726 ± 0.010 K at 95% confidence level. Such a value is corresponding to redshift equal zero in a Big Bang model of the Universe (Mather et al. 1994).

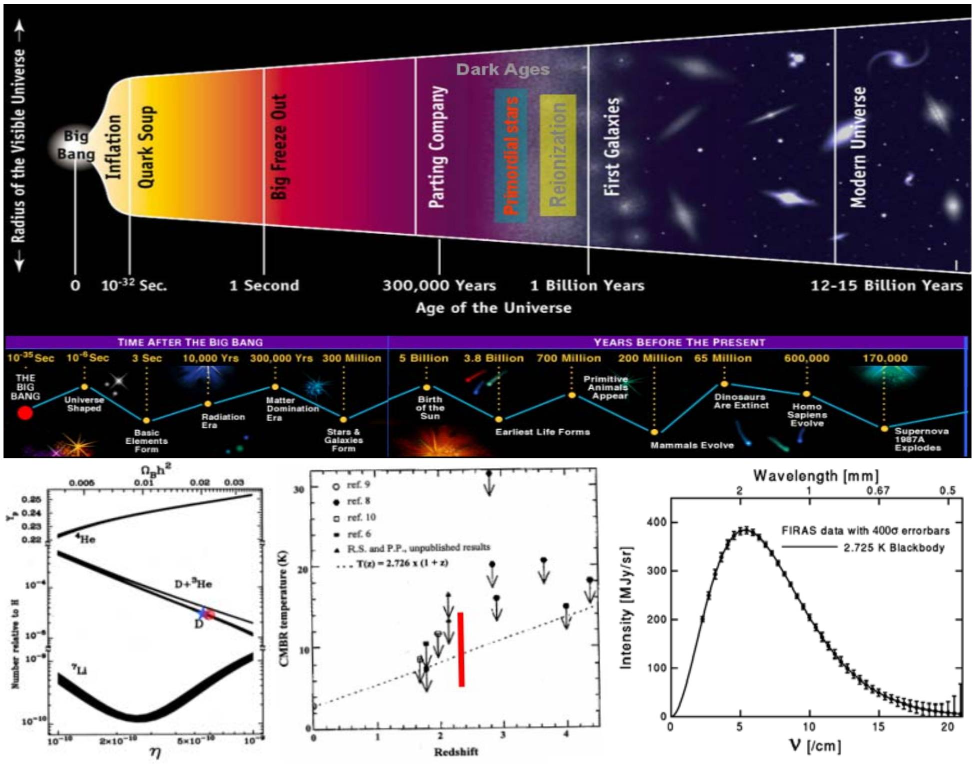

Fig. 14 Upper panel: Sketch of the evolution of the Universe with the main steps (adapted from Board of Trustees, University of Illinois 1995, and Nino Panagia 2006). Lower panel: Left - Light element abundances (Burles, Nollett & Turner 2001). Derived points from experiments are overlapped: $\star$ (Netterfield et al. 2002), $\circ$ (de Bernardis et al. 2000). Center - CMBR temperature versus redshift (Srianand, Petitjean & Ledoux 2000). Right - COBE–FIRAS 2.725 K black body spectrum.

Figure 14 shows in the upper panel a sketch of the evolution of the Universe from the Big Bang to present time; in the lower left panel: the light element abundances (Burles, Nollett & Turner 2001); in the lower center panel: the CMBR temperature at various redshifts as determined by Srianand, Petitjean

& Ledoux (2000), and the references therein. The point at $z = 0$ is the result of COBE ($T_{\rm CMBR}(0) = 2.726 \pm 0.010$ K), which is well fitted by a black body spectrum, as shown in the lower right panel (Mather et al. 1994). At $z = 2.1394$ there is an upper limit. At $z = 2.33771 \simeq 2.34$, the CMBR temperature is: 6.0 K $< T_{\rm CMBR}(2.34) < 14.0$ K (vertical bar). The dashed line is the prediction from the Hot Big Bang: $T_{\rm CMBR} = T_{\rm CMBR}(0) \times (1 + z)$. Such a prediction gives $T_{\rm CMBR}(2.34) = 9.1$ K, which is consistent with the measurement.

However, the background radiation is present not only in the microwave band, but practically across all the electromagnetic spectrum. It is possible to consider the DEBRA as a radiation produced by a cosmic source: the whole Universe. Such a background radiation from radio to HE γ-ray energy bands has been deeply discussed by Ressel & Turner (1990), Henry (1999, 2002), Hasinger (2000), and in the review paper by Giovannelli & Sabau-Graziati (2004). The analysis of the different components of DEBRA leads to the Grand Unified Photon Spectrum (GUPS), covering 29 orders of magnitude of the electromagnetic spectrum, from 10^{-9} to 10^{20} eV, as shown in Figure 15.

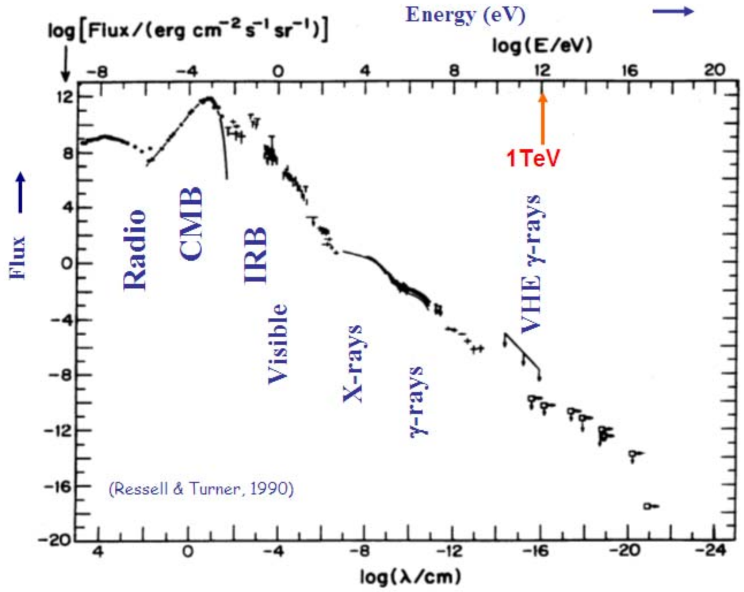

Fig. 15 The Grand Unified Photon Spectrum of the Diffuse Extragalactic Background Radiation (Ressel & Turner 1990).

The GUSP is continuously being updated, thanks to results coming from the many experiments in different energy regions. Henry (1999) thoroughly discussed the updated experimental situation of the cosmic background, and Henry (2002) discussed — by means of his and new results reported in the references therein — about units for use in the display of spectra *without* the compression used in 1999. So the material is much more readable:

If one is interested in *energy content* the most meaningful units in which to display the spectrum of diffuse radiation are, remarkably enough, photons s^{-1} cm^{-2} sr^{-1} nm^{-1}. If there is an *equal* amount of energy present in every logarithmic interval of frequency, then these units have the virtue of assuming *constant* value.

The results are shown in Figure 16, where is reported the updated spectrum of DEBRA:

1) Radio background; 2) Microwave background; 3) Firas excess; 4) DIRBE observations and upper limits; 5) Visible background; 6) Background from *Voyager*; 7) Interstellar photo-ionization cross section (use the right hand scale for this); 8) Soft X-ray background; and 9) Hard X-ray and γ-ray background. This figure differs from the figure in Henry (1999) in several respects. Only one FIRAS spectrum is shown

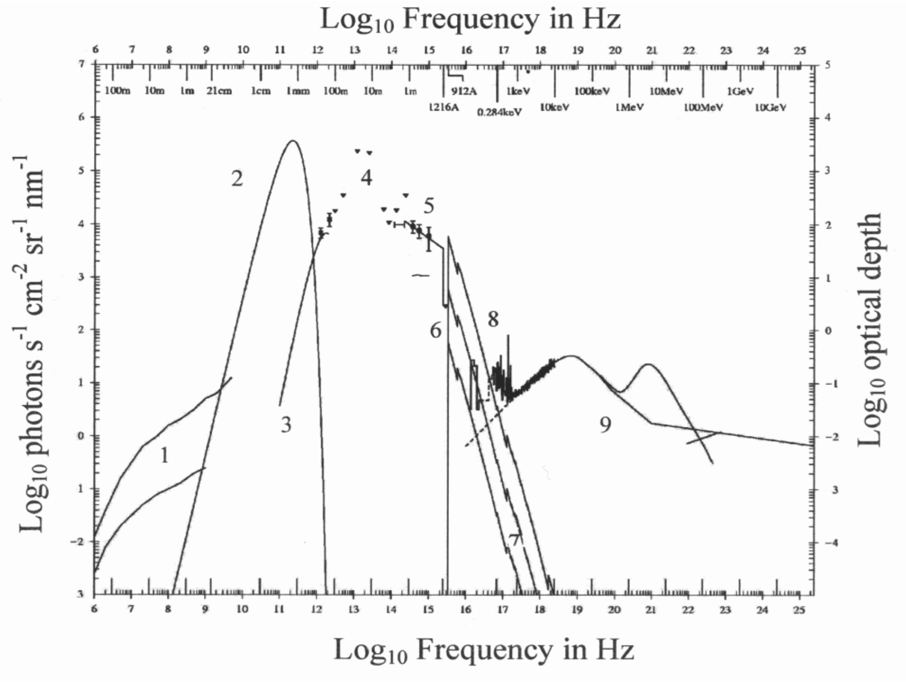

Fig. 16 The Grand Unified Photon Spectrum of the Diffuse Extragalactic Background Radiation updated by Henry (2002).

(instead of observed and $\pm 1\sigma$). Instead of actual observations of the soft X-ray background, what is shown here is a simulation of what might be expected from David Burrows' CUBIC experiment (Burrows 1996). And finally, in addition to the new γ-ray background, he showed the earlier spectrum that was reported by Fichtel, Simpson & Thompson (1978). The short straight line near 10^{22} Hz is the estimate of a galactic component that was provided by the latter authors. The large MeV bump proved to be an artifact (Sreekumar et al. 1998); for a detailed independent description of the *Comptel* data analysis that led to this important advance, see Weidenspointner (1999).

7 ASTROPARTICLES: MULTIFREQUENCY WITNESSES OF THE HISTORY OF THE UNIVERSE

In the last few decades, cosmic-ray physics and high energy astrophysics strongly developed thanks to ground– and space–based experiments. They originated the new branch of physics named *Astroparticle Physics*. Higher and higher capabilities in reproducing extreme conditions in which the nature demonstrates, and better and better sensitivities of the detectors used have been the key of such a development. Figure 17 shows schematically the connections between ground–based experiments, such as accelerators (LEP, LHC) and the history of the Universe (Denegri 2006).

However, in spite of the enormous jumps in our knowledge of the physics of our Universe, many *old* problems are still open and many *new* problems are arising with the new data. They foment the most exciting race in which humans are pursuing *mother nature* in order to unveil its deepest secrets.

The subject of High Energy Astrophysics is generally approached through the study of cosmic rays. The reason for this is historical in nature. Since the discovery of this extraterrestrial radiation by Victor Hess (1912) the scientific research involved in trying to discover its nature has been enormous and as a result many separate research fields have been developed. Before particle accelerators came into operation the high energy cosmic rays were the laboratory tools for investigations of elementary particle production,

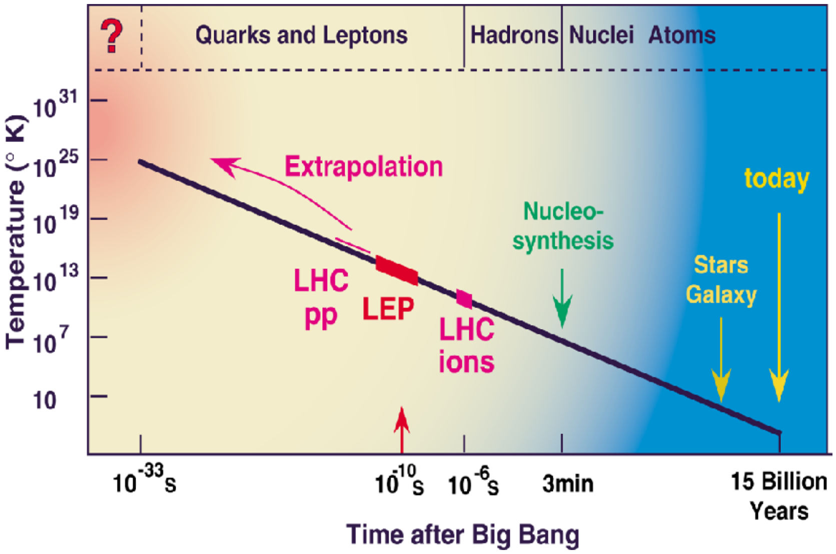

Fig. 17 Connecting LEP, LHC and the Universe: towards the origin (Denegri 2006).

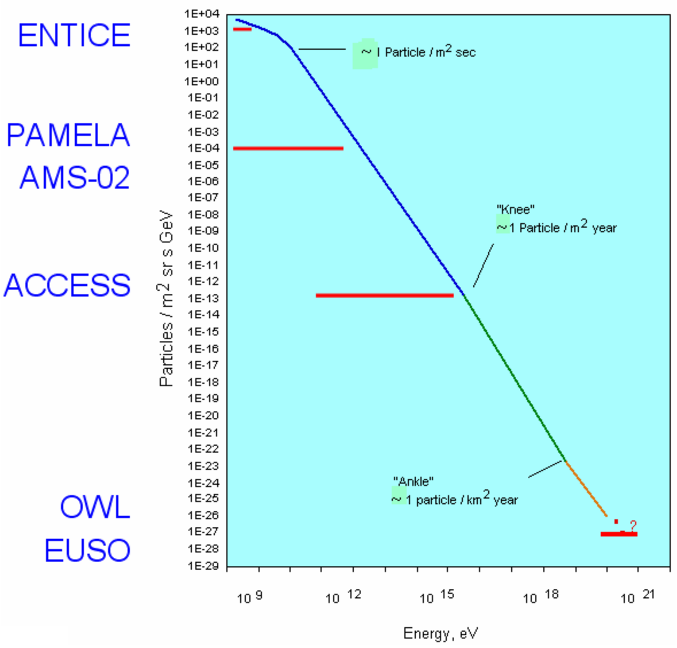

Fig. 18 The number of cosmic rays versus their energy. At energies below ≈ 10^{14} eV, cosmic rays, which are mainly protons, are detected by space experiments. At energies above ≈ 10^{14} eV information comes from arrays of ground based detectors. Several cosmic ray space experiments are marked with red lines (Streitmatter 2005).

and to date they are still the only source of particles with energies greater than 10^{12} eV. The research into the composition of the radiation led to developing the study of the astrophysical environment using the information in the charge, mass, and energy spectra; this field is also known as Particle Astrophysics.

Of great importance was the discovery of high energy photons near the top of the Earth's atmosphere which originated the development of new astronomical fields such as the X-ray or γ-ray astronomy. But many of these high energy photons have their origin in interactions of the high energy charged particles with cosmic matter, light, or magnetic fields. The particle astrophysics and the astronomical research field have found in this fact a bond to join their efforts in trying to understand the high energy processes which occur in astrophysical systems.

The modern picture of cosmic rays is that of a steady rain of particles moving at speeds close to that of light. The particles are primarily nuclei with atomic weights less than 56, as well as a few nuclei of heavier elements, some electrons and positrons, a few γ-rays and neutrinos.

The energy spectrum extends over 12 orders of magnitude ($\sim 10^{8} - 10^{20}$ eV) and the particle flux rapidly decreases with increasing energy, as shown in Figure 18. Several cosmic ray space experiments, briefly discussed by Giovannelli (2007), are marked with red lines, roughly indicating the range of energy and fluxes (Streitmatter 2005).

Although cosmic rays were discovered a century ago it is puzzling that after so many years the problem of their 'origin' is still an open problem, in spite of the great progress made in any adjacent field of Physics and Astrophysics.

Obviously the main problem is that the bulk of cosmic rays are charged. Therefore we detect at Earth a nearly isotropic flux which does not point back to any particular direction in the Galaxy. Another problem is that the spectrum of cosmic rays is apparently simple and nearly featureless. In fact, if we look at Figure 18, we can hardly distinguish their spectrum from a single power law distribution. Such an extended simple power law distribution spanning over about twelve orders of magnitude of energy is one of the more astonishing example of the fractal symmetry in Nature. There are arguments supporting the diffusive shock acceleration (DSA) model introduced by Fermi (1949, 1954), which can give a very natural explanation of the simplicity of the cosmic ray spectrum.

The bulk of the cosmic ray particles in the vicinity of Earth have energies around $10^{8} - 10^{9}$ eV, but many particles with much greater energies are also seen. Above 10^{9} eV the number of particles drops steadily with increasing energy all the way to 10^{20} eV. We know very little about cosmic rays with energies greater than 10^{19} eV because few of them arrive daily on the Earth. There is, nevertheless, great interest in such particles because they have energies vastly greater than can be generated by particle accelerators in Earth's laboratories. They are witness of acceleration processes occurring nearby the most active cosmic sources in the universe. Such energetic cosmic rays have so much momentum that they are practically un–deflected as they pass through the Solar System toward the Earth. In contrast, cosmic rays with energies less that 10^{8} eV are strongly influenced by the solar magnetic field and by the ever changing solar wind of ions that stream out from it. Then few particles with such energies reach the Earth.

The chemical composition of the cosmic rays with energies up to 10^{12} eV has been well determined using data from space experiments. New generation space experiments can extend this range up to $\approx 10^{15}$ eV. In general the abundances of the different nuclei follow closely the measured values in the solar system. The over-abundance of the light elements lighter than iron, experimentally found, is the result of spallation collisions during the propagation through the interstellar medium.

For the highest energies (roughly above $\approx 4 \times 10^{14}$ eV) the data are derived from studies of Extensive Air Shower (EAS) and owed to the disagreements in interpreting the experimental data by the different experiments it cannot be concluded whether the composition is similar to that at lower energies or whether there is a deficit of heavy nuclei relative to protons (e.g., Müller 1993). A good general review on the composition of cosmic rays was written by Erlykin (1995).

In their propagation through space the charged cosmic rays are influenced by the magnetic fields in the Galaxy, and for the lowest energy particles also in the solar system. The result is that the distribution of arrival directions as the radiation enters the Earth's atmosphere is nearly isotropic. It is not possible to identify the sources of the cosmic rays by detecting them. However, in the high energy interactions produced at the source, electrically neutral particles such as photons, neutrons, and neutrinos are also produced and their trajectories are not deviated, being directed from their point of origin to the observer. Owing to their short lifetime neutrons cannot survive the path length to the Earth (decay length $\sim$ 9 pc at 1 PeV) and neutrinos do not interact efficiently in the atmosphere.

It is in this context that the Gamma Ray Astronomy has demonstrated itself to be a powerful tool. The observations made to date have detected γ-rays from many astronomical objects such as neutron stars, interstellar clouds, the center of our Galaxy and the nuclei of active galaxies (AGNs). One might expect very important implications for high energy astrophysics from the observations at energies greater than 10^{11} eV of extragalactic sources (e.g., Hillas & Johnson 1990). The fluxes of γ-rays at these energies are attenuated because of their interactions with the cosmic radio, microwave, infrared and optical radiation fields. Measurements of the flux attenuation can then provide important information on the distribution of such fields. For instance, the threshold energy for pair production in reactions of photons with the 2.7 K background radiation is reached at 10^{14} eV and the absorption length is of the order of $\sim$ 7 kpc. For the infrared background the maximum absorption is reached at energies greater than 10^{12} eV.

The qualitative problem of the origin of cosmic rays is practically solved, whilst the quantitative problem in determining the fraction of them coming from the different possible sources is still open. A qualitative picture on the origin of cosmic rays is shown in Figure 19 (Ptuskin 2005).

7.1 Understanding the Message of Cosmic Rays

Figure 20 shows the energy spectrum of cosmic rays, roughly starting at 10^{11} eV (Nagano & Watson 2000 and the references therein). In order to emphasize the variations in the spectrum, poorly seen in Figure 18, the flux reported in Figure 20 is multiplied by E^3. This operation, obviously, compresses the spectrum, reducing the decades in the y-axis, rendering the features of the whole spectrum much more readable.

A simple inspection of the Figure 20 points out the evidence of a break in the spectrum around 10^{15}–10^{16} eV. This break is also called the *knee*. The *knee* has been found at the end of the 1950s initially as the steepening in the EAS size spectrum (Kulikov & Khristiansen 1958). Since then more than 49 years have passed but its origin is still a challenge for the cosmic ray physics. The steepening appears when the intensity of the showers falls down to a value of $\sim$ (4–5) $\times 10^{-11}$ cm^{-2} s^{-1} sr^{-1}. This intensity delivers one shower above the *knee* per an area of $\sim 25\,\mathrm{m}^2$ in one hour. Owing to this low intensity the *knee* has not yet been studied by direct measurements in space, but by indirect methods which use atmospheric cascades.

Summarizing, the cosmic ray spectrum for protons is at GeV energies close to $E^{-2.75}$, and for He and higher elements close to $E^{-2.65}$ below the *knee* at $\approx 5 \times 10^{15}$ eV, where the spectrum turns down to $\sim E^{-3.1}$, to flatten out again near $10^{18.5}$ eV, called the *ankle* (e.g., Lawrence, Reid & Watson 1991; Nagano et al. 1992; Zatsepin 1995).

The origin of the *knee* can be clarified by the detailed study of the primary spectrum, mass composition and arrival directions of cosmic rays. Reviews of Erlykin (1993, 1995, 1997), Müller (1993), and Hillas (1999) discussed in details such topics. In particular, Erlykin (1995) discussed in a very clear way the mass composition and the origin of cosmic rays. Indeed, the origin of them, independent of all the discussions and models, is focussed around four main possible reasons, namely: i) sources of cosmic rays; ii) acceleration mechanisms; iii) propagation through the ISM; iv) interaction characteristics.

In most models based on one of these four items the mass composition varies with the energy in different ways. Then he discussed the mass composition below 10^5 GeV, near the *knee* (10^5–10^8 GeV), and above 10^8 GeV. He concluded that most of the results indicated that the genesis of cosmic rays is much more complicated than was thought in the past. The most likely tendency for cosmic rays is to grow heavier with the rising energies up to the *knee* region and then become lighter beyond the *knee*. Several reviews have been published about the chemical composition around the *knee* (Alessandro 2001), about ultra high energy (UHE) cosmic rays (Blasi 2001), and about the propagation and clustering of cosmic rays (Stanev 2001).

A possible interpretation of the *knee* is that it represents the energy at which cosmic rays can escape more freely from the Galaxy or it may indicate a transition between two different acceleration mechanisms. In the first case one might expect an anisotropy effect in the distribution of arrival directions above this energy if the cosmic rays were originated within the Galaxy.

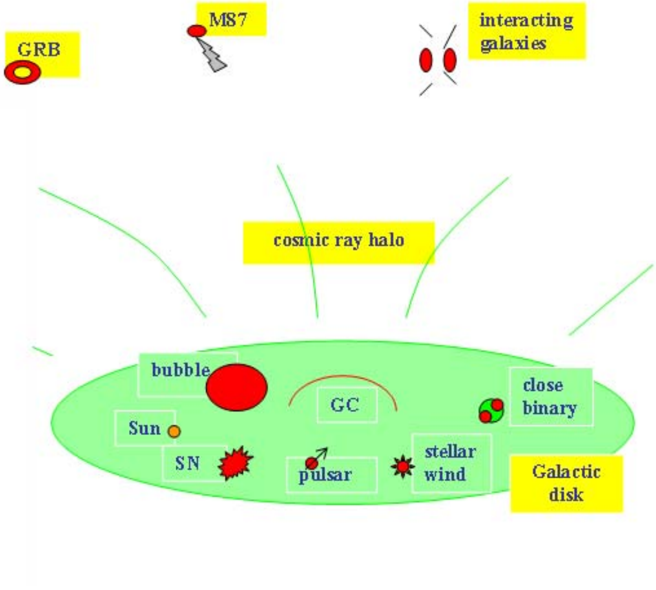

Fig. 19 The possible sources of cosmic rays (Ptuskin 2005).

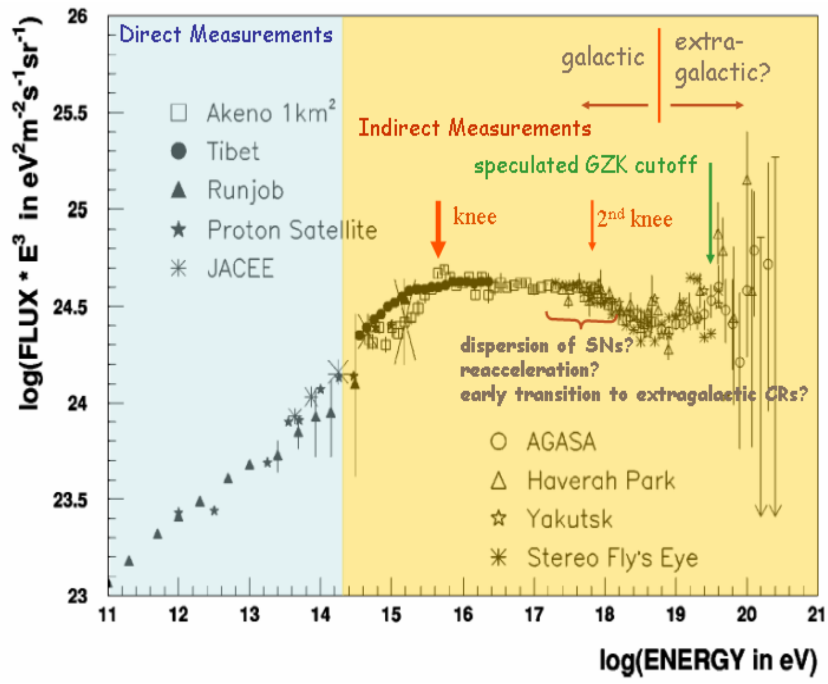

Fig. 20 The all particle spectrum of cosmic rays obtained by several experiments cited in the figure. Energies less or greater than 4×10^{14} eV divide the two ranges in which direct and indirect measurements of CR spectrum are possible. The *knee*, the *ankle* and the *Greisen–Zatsepin–Kuzmin cutoff*, and a $2^{\rm nd}$ *knee* are clearly shown (after Nagano & Watson 2000).

A 2^{nd} *knee* is present at about 10^{18} eV. Its origin is not yet completely clear: it could be due to dispersion of SNs, or reacceleration of particles or early transition to extragalactic cosmic rays (Nagano & Watson 2000).

A summary, still valid, on the status of the search for the origin of the highest energy cosmic rays has been published by Biermann (1999). He mentioned several competing proposals, such as the supersymmetric particles, Gamma Ray Bursts also giving rise to energetic protons, interacting high energy neutrinos and cosmological defects, and then he discussed on the possibility of the propagation of these particles, assuming that they are charged. The distribution of arrival directions of the highest energy particles on the sky ought to reflect the source distribution as well as the propagation history. He remarked that the present status can be summarized as inconclusive. However, he concluded as follows: *If we can identify the origin of the events at the highest energies, beyond* 5×10^{19} eV*, the Greisen–Zatsepin–Kuzmin cutoff owed to the microwave background, near to* 10^{21} eV $= 1$ EeV*, and if we can establish the nature of their propagation through the universe to us, then we will obtain a tool to do physics at* EeV *energies.*

8 PROSPECTIVES

8.1 The High Energy Sky

The high energy sky before the sixties was simply empty. Only optical, a few UV and radio measurements were available. A first important jump in our knowledge of the X-ray sky was provided by the Uhuru satellite, whose 4th catalog reports 125 sources (Forman et al. 1978). Increasing the sensitivity, HEAO-1 satellite provided a catalog containing about 800 sources (Wood et al. 1984). The history of the γ-ray sky was similar: from the COS B satellite, whose catalog reports 25 sources (Swanenburg et al. 1981) to EGRET experiment on board CGRO whose catalog reports 124 sources (Hartman et al. 1999). The VHE sky, which was empty about 20 years ago, is now populated by many galactic and extragalactic sources for a total of more than 40 sources (Dubus 2007). So that, the numbers of γ-ray sources is raising like in the past X-ray sources did because of increasing sensitivities and sizes of VHE experiments. Figure 21 shows the number of high energy sources versus time: X-ray and γ-ray sources are represented with blue dots and pink rhombuses, respectively Santangelo (2006).

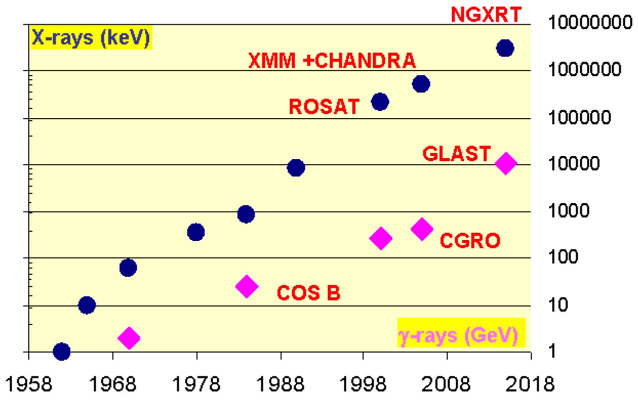

Fig. 21 The history of the population of X-ray (blue dots) and γ-ray sources (pink rhombuses). Several recent and future satellites are marked (Santangelo 2006).

Also in this case, multifrequency approach is fundamental in order to search for the associations of the unidentified γ-ray sources with known sources which appear in other energy ranges.

Many attempts for searching cosmic counterpart of the unidentified EGRET sources in the Milky Way have been performed (e.g. Grenier 2003; Harding et al. 2004; Romero et al. 2004; Gonthier et al. 2005; Grenier, Kaufman-Bernadó & Romero 2005). For instance, Mattox, Hartman & Reimer (2001) searched for the association of the unidentified EGRET sources with radio sources. They found 46 associations with a high probability of being correct, 37 associations with a ‘plausible identification’ and 15 more plausible identifications, which were not suggested previously at all.

Important results are those of the association of several clusters of galaxies with EGRET sources (Colafrancesco 2002). All the clusters probably associated with the EGRET sources have a strong radio emission. The cluster radio emission suggests that the relativistic particles which are diffusing in the intracluster medium might be also responsible for their γ-ray emission. Spatial associations of clusters with unidentified EGRET sources, a correlation between the radio flux at 1.4 GHz of the cluster’s brightest source and the γ-ray flux, F(> 100 MeV), of the associated EGRET source, and a further correlation between the X-ray luminosity of galaxy clusters and the γ-ray luminosity of the associated γ-ray source under the hypothesis that the EGRET sources have the same redshift of clusters render this association virtually certain. Further investigations are necessary for closing this problem.

8.2 Gamma-ray Astronomy as Probe for Cosmic-rays

A particular attention is necessary at the highest energies where the cosmic ray spectrum extends to 10^{20} eV (see Figure 20). Yet the origins of such spectacularly high energy particles remains obscure. Particle energies of this magnitude imply that near their acceleration sites a range of elementary particle physics phenomena is present which is beyond the ability of present day particle accelerators to explore. VHE γ-ray astronomy may catch a glimpse of such phenomena. As discussed by Stanev (2007), the features of high energy cosmic rays detected with air shower observations, as well as the discussion about the sources and astrophysical acceleration, pointed at the same problem, which seems to worry many of us - where is the end of the galactic cosmic ray spectrum?

It is becoming increasingly clear that the energy régime covered by VHE γ-ray astronomy will be able to address a number of significant scientific questions, which include: i) What parameters determine the cut-off energy for pulsed γ-rays from pulsars? ii) What is the role of shell-type supernovae in the production of cosmic rays? iii) At what energies do AGN blazar spectra cut-off? iv) Are gamma blazar spectral cut-offs intrinsic to the source or due to intergalactic absorption? v) Is the dominant particle species in AGN jets leptonic or hadronic? vi) Can intergalactic absorption of the VHE emission of AGN’s be a tool to calibrate the epoch of galaxy formation, the Hubble parameter, and the distance to γ-ray bursts? vii) Are there sources of γ-rays which are ‘loud’ at VHEs, but ‘quiet’ at other wavelengths?

9 CONCLUSIONS

As discussed by Giovannelli & Sabau-Graziati (1996) the ‘new’ branch of science: the so-called *Multifrequency Astrophysics* can develop from two different points of view, converging toward a better knowledge of the Universe: i) *Experimental Multifrequency Astrophysics*; ii) *Theoretical Multifrequency Astrophysics*.

Far from the completeness in this paper we have discussed about the importance of the multifrequency observations and their interpretation by means of several examples which on the other hand have bounded the topics of this workshop. We can briefly summarize as follows:

i) Experimental Multifrequency Astrophysics

- By means of simultaneous observations with different experiments and/or facilities in different energy ranges was possible to have the total energy distribution of the T Tauri star RU Lupi from X-ray to IR energy ranges;
- By using data bases and/or literature it was possible to find simultaneous observations in different energy regions obtained by chance. In this way, very probably, the rotational velocity of RU Lupi has been indirectly obtained;
- By means of coordinated observations:
  - it was possible to predict the forthcoming fourth X-ray outburst of the X-ray pulsar A 0535+26. This event occurred just at the time predicted, so that the association of the early–type star HDE 245770 (Flavia’ star) — which to coincide with X-ray outburst had an optical outburst — as the optical counterpart of A0535+26 was rendered possible;

  - it was possible to determine the spin period history of A 0535+26, different kinds of X-ray outbursts triggered by accreting matter from the optical companion in different states of activity, and to generalize the results to the whole class of X-ray pulsars in eccentric orbits around giant Be companions;
  - by means of optical spectroscopy it was possible to support the possible presence of a temporary accretion disc around the neutron star at the periastron passage. This possibility had suggested and discussed many years before by Giovanelli & Ziółkowski (1990), and experimentally proved during an X-ray outburst by Finger, Wilson & Harmon (1996) by means of spin–up behaviour of the X-ray pulsar.
- By means of simultaneous and coordinated multifrequency observations it has been possible a better understanding of jets from different kinds of cosmic sources, both galactic and extragalactic. This allowed to draw a strong analogy between quasars and microquasars, with undoubtedly advantages in studying the physics of the latter for extending the results to the former. The emitted spectra of jets are strongly dependent on the angle formed by the beam axis and the line of sight, and obviously by the Lorentz factor of the particles. So, observations of jet sources at different frequencies can provide new inputs for the comprehension of such extremely efficient carriers of energy, like for the cosmological GRBs.
- Multifrequency observations, not necessarily simultaneous, have produced results useful:
  - to constrain some parameters for modelling GRBs. More than 100 claimed association of GRBs with the host galaxies at high redshift, at the moment, favors the extragalactic origin of GRBs. However, such an origin has not yet definitively demonstrated, at least for most of them. Many observational features remain still unclear in the model of cosmological GRBs. Observations of γ-ray flashes and the correspondent afterglows in different energy ranges put serious bounds to the models for GRBs, and fomented heated arguments among theoreticians, not yet completely solved. Critical experimental evidences are needed: spectra of prompt optical afterglows; study of hard γ-ray afterglows; search for orphans optical afterglows in all sky monitoring. Cosmological GRBs may come from collapse of massive rotating star followed by the formation of a Kerr black hole surrounded by a massive magnetized disc, and rapid accretion leading to a GRB; or from sources described by exotic models;
  - to search for the associations of unknown γ-ray sources with objects manifesting themselves in other energy regions.
- Multifrequency observations and/or theoretical evaluations of some limits in the DEBRA, spread over 29 decades in energy, allowed the construction of the GUPS for the whole extragalactic cosmic background. This GUPS is continuously updated thanks to results coming from many experiments in different energy ranges.

ii) Theoretical Multifrequency Astrophysics

- Studying physical processes manifesting their effects in a wide range of the electromagnetic spectrum, theoretical spectra have been derived. They have been used to successfully fit multifrequency experimental data of GRS 1915+105 and LS 5039.

iii) What about the future?

- A particular attention is necessary at the highest energies where the cosmic ray spectrum extends to 10^{20} eV (see Figure 20). Yet the origins of such spectacularly high energy particles remains obscure.
- The important problem for the next generation experiments is a deep investigation of cosmic sources with experiments designed for higher and higher energies with sensitivities, spectral and spatial resolutions better and better. However this is in contrast with the sizes and costs of missions. Then, a compromise is mandatory.
- In spite of the many ground– and space–based experiments providing an impressive quantity of excellent data in different energy regions, many open problems still exist. We believe that only drastically changing the philosophy of the experiments, it will be possible to solve faster most of the present open problems. For instance, in the case of space–based experiments, small satellites — dedicated to specific missions and problems, and having the possibility of scheduling very long time

observations — must be supported because of their relative faster preparation, easier management and lower costs with respect to medium and large satellites.

We strongly believe that in the next decades passive-physics experiments space– and ground–based will be the most suitable probes in sounding the physics of the Universe. Probably the active physics experiments have already reached the maximum dimensions compatible with a reasonable cost/benefit ratio, with the obvious exception of the neutrino-astronomy experiments.

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