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Memorie della

Microquasars

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Abstract. Microquasars are compact objects (stellar-mass black holes and neutron stars) that mimic, on a smaller scale, many of the phenomena seen in quasars. Their discovery provided new insights into the physics of relativistic jets observed elsewhere in the universe, and in particular, the accretion–jet coupling in black holes. Microquasars are opening new horizons for the understanding of ultraluminous X-ray sources observed in external galaxies, gamma-ray bursts of long duration, and the origin of stellar black holes and neutron stars. Microquasars are one of the best laboratories to probe General Relativity in the limit of the strongest gravitational fields, and as such, have become an area of topical interest for both high energy physics and astrophysics. Because during the "Dark Ages" of the universe accreting stellar black holes heated the intergalactic medium above 10.000 K these sources are becoming important for Cosmology.

Key words. Stars: binary – ISM: jets and outflows

1. Introduction

Microquasars are binary stellar systems where the remnant of a star that has collapsed to form a dark and compact object (such as a neutron star or a black hole) is gravitationally linked to a star that still produces light, and around which it makes a closed orbital movement. In this cosmic dance of a dead star with a living one, the first sucks matter from the second, producing radiation and very high energetic particles (Fig. 1). These binary star systems in our galaxy are known under the name of "microquasars" because they are miniature versions of the quasars ('quasi-stellar-radio-source'), that are the nuclei of distant galaxies harboring a super massive black hole, and are able to produce in a region as compact as the solar system, the luminosity of 100 galaxies like the Milky Way. Nowadays the study of microquasars is one of the main scientific motivations of the space observatories that probe the X-ray and γ-ray Universe.

Despite of the differences in the involved masses and in the time and length scales, the physical processes in microquasars are similar to those found in quasars. That is why the study of microquasars in our galaxy has enabled a better understanding of what happens in the distant quasars and AGN. Moreover, the study of microquasars may provide clues for the understanding of the class of gamma-ray bursts that are associated to the collapse of massive stars leading to the formation of stellar black holes, which are the most energetic explosions in our Universe after the Big-Bang.

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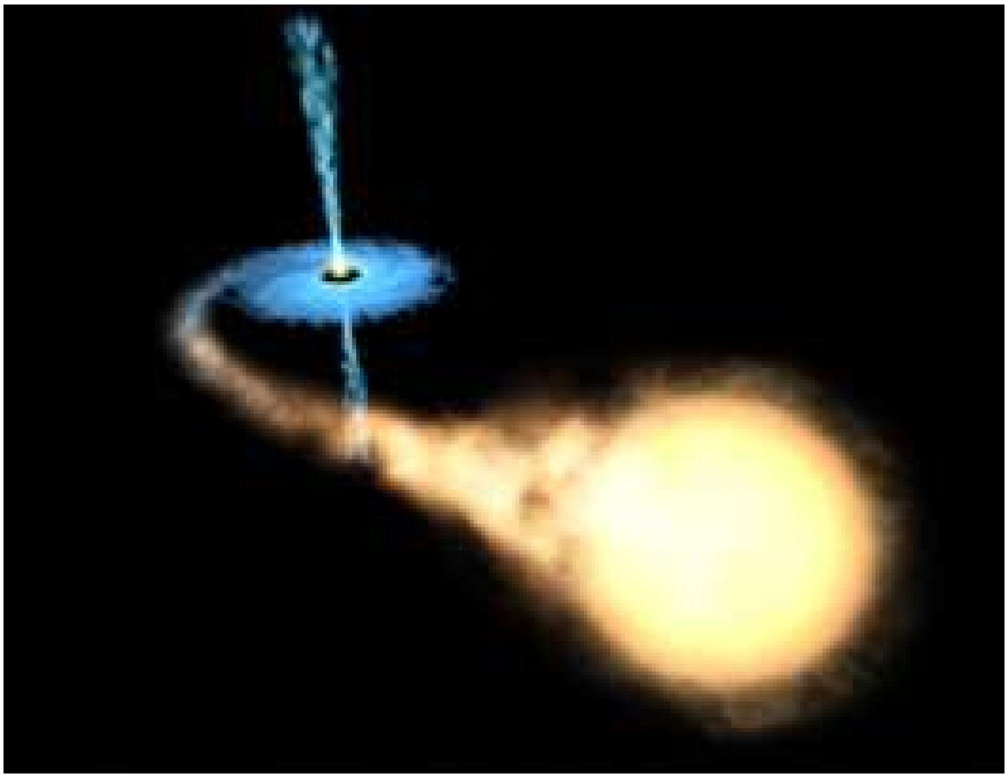

Fig. 1. In our galaxy there exist binary stellar systems where an ordinary star gravitates around a black hole that sucks the outer layers of the star's atmosphere. When falling out to the dense star, the matter warms and emits huge amounts of energy as X- and γ-rays. The accretion disk that emits this radiation also produces relativistic plasma jets all along the axis of rotation of the black hole. The physical mechanisms of accretion and ejection of matter are similar to those found in quasars, but in million times smaller scales. Those miniature versions of quasars are known under the name of 'microquasars' ($http://en.wikipedia.org/wiki/X-ray\_binary$).

2. Discovery of microquasars

During the second half of the 18th century, John Michell and Pierre-Simon Laplace first imagined compact and dark objects in the context of the classical concept of gravitation. In the 20th century in the context of Einstein's General Relativity theory of gravitation, those compact and dark objects were named black holes. They were then identified in the sky in the 1960s as X-ray binaries. Indeed, those compact objects, when associated to other stars, are activated by the accretion of very hot gas that emits X and γ-rays. In 2002, Riccardo Giacconi was awarded the Nobel Prize for the development of the X-ray Space Astronomy that led to the discovery of the first X-ray binaries (Giacconi et al. 1964). Later, Margon et al. (1979) found that a compact binary known as SS 433 was able to produce jets of matter. However, for a long time, people believed that SS 433 was a very rare object of the Milky Way and its relation with quasars was not clear since the jets of this object move only at 26% of the speed of light, whereas the jets of quasars can move at speeds close to the speed of light.

In the 1990s, after the launch of the Franco–Soviet satellite GRANAT, growing evidences of the relation between relativistic jets and X-ray binaries began to appear. The on-board telescope SIGMA was able to take X-ray and γ-ray images. It detected numerous black holes in the Milky Way. Moreover, thanks to the coded-mask-optics, it became possible for the first time to determine the position of γ-ray sources with arcmin precision. This is not a very high precision for astronomers who are used to dealing with other observing techniques. However, in high-energy astrophysics it represented a gain of at least one order of magnitude. It consequently made possible the systematic identification of compact γ-ray sources at radio, infrared and visible wavelengths.

With SIGMA/GRANAT it was possible to localize with an unprecedented precision the hard X-ray and γ-ray sources. In order to determine the nature of those X-ray binaries, a precision of a few tens of arc-seconds was needed. Sources that produce high energy photons should also produce high energy particles, that should then produce synchrotron radiation when accelerated by a magnetic field. Then, with Luis Felipe Rodríguez, we performed a systematic search of synchrotron emissions from X-ray binaries with the Very Large Array (VLA) of the National Radio Astronomy Observatory of the USA.

In 1992, using quasi-simultaneous observations from space with GRANAT and from the ground with the VLA, we determined the position of the radio counterpart of an X-ray source named 1E 1740.7-2942 with a precision of sub-arc-seconds. With GRANAT this object was identified as the most luminous persistent source of soft γ-rays in the Galactic center region. Moreover, its luminosity, variability and the X-ray spectrum were consistent with those of an accretion disk gravitating around a stellar mass black hole, like in Cygnus X-1. The most surprising finding with the VLA was the existence of well collimated two-sided jets that seem to arise from the compact radio counterpart of the X-ray source (Mirabel & Rodríguez 1992). These jets of magnetized plasma had the same morphology as the jets observed in quasars and radio galaxies. When we published those results, we employed the term microquasar to define this new X-ray source with relativistic jets in our Galaxy. This term appeared on the front page of the British journal Nature, which provoked multiple debates. Today the concept of microquasar is universally accepted and used widely in scientific publications.

Before the discovery of its radio counterpart, 1E 1740.7-2942 was suspected to be a prominent source of 511 keV electron-positron annihilation radiation observed from the centre of our Galaxy (Leventhal et al. 1989), and for that reason it was nicknamed as the "Great Annihilator". It is interesting that recently it was reported (Weidenspointner et al. 2008) that the distribution in the Galactic disk of the 511 keV emission, due to positron-electron annihilation, exhibit similar asymmetric distribution as that of the hard low mass X-ray binaries, where the compact objects are believed to be stellar black holes. This finding suggests that black hole binaries may be important sources of positrons that would annihilate with electrons in the interstellar medium. Therefore, positron-electron pairs may be produced by γ–γ photon interactions in the inner accretion disks, and microquasar jets would contain positrons as well as electrons. If this recent report is confirmed, 1E 1740.7-2942 would be the most prominent compact source of anti-matter in the Galactic Centre region.

3. Discovery of superluminal motions

If the proposed analogy (Mirabel & Rodríguez 1998) between microquasars and quasars was correct, it should be possible to observe superluminal apparent motions in Galactic sources. However, superluminal apparent motions had been observed only in the neighborhood of super-massive black holes in quasars. In 1E 1740.7-2942 we could not be able to discern motions, as in that persistent source of γ-rays the flow of particles is semi-continuous. The only possibility of knowing if superluminal apparent movements exist in microquasars was through the observation of a discreet and very intense ejection in an X-ray binary. This would allow us to follow the displacement in the firmament of discrete plasma clouds. Indeed, with the GRANAT satellite was discovered (Castro-Tirado et al. 1994) a new source of X-rays with such characteristics denominated GRS 1915+105. Then with Rodríguez we began with the VLA a systematic campaign of observations of that new object in the radio domain, and in collaboration with Pierre-Alain Duc (CNRS-France) and Sylvain Chaty (Paris University) we performed the follow-up of this source in the infrared with telescopes of the Southern European Observatory, and telescopes at Mauna Kea, Hawaii.

Since the beginning, GRS 1915+105 exhibited unusual properties. The observations in the optical and the infrared showed that this X-ray binary was very absorbed by the interstellar dust along the line of sight in the Milky Way, and that the infrared counterpart was varying rapidly as a function of time. Moreover, the radio counterpart seemed to change its position in the sky, so that at the beginning we did not know if those changes were due to radiation reflection or refraction in an inhomogeneous circumstellar medium ("Christmas tree effect"), or rather due to the movement at very high speeds of jets of matter. For two years we kept on watching this X-ray binary without exactly understanding its behavior. However, in March 1994, GRS 1915+105 produced a violent eruption of X and γ-rays, followed by a bipolar ejection of unusually bright plasma clouds, whose displacement in the sky could be followed during 2 months. From the amount of atomic hydrogen absorbed in the strong continuum radiation we could infer that the X-ray binary stands at about 40000 light years from the Earth. This enabled us to know that the movement in the sky of the ejected clouds implies apparent speeds higher than the speed of light.

The discovery of these superluminal apparent movements in the Milky Way was announced in Nature (Mirabel & Rodríguez 1994). This constituted a full confirmation of the hypothesis, that we had proposed two years before, on the analogy between microquasars and quasars. With Rodríguez we formulated and solved the system of equations that describe the observed phenomenon. The apparent asymmetries in the brightness and the displacement of the two plasma clouds could naturally be explained in terms of the relativistic aberration in the radiation of twin plasma clouds ejected in an antisymmetric way at 98% of the speed of light (Mirabel & Rodríguez 1999). The super-luminal motions observed in 1994 with the VLA (Mirabel & Rodríguez 1994) were a few years later re-observed with higher angular resolution using the MERLIN array (Fender et al. 1999).

Using the Very Large Telescope of the European Southern Observatory, it was possible to determine the orbital parameters of GRS 1915+105, concluding that it is a binary system constituted by a black hole of $\sim$14 solar masses accompanied by a star of 1 solar mass (Greiner et al. 2001). The latter has become a red giant from which the black hole sucks matter under the form of an accretion disk (see Fig. 1).

4. Disk–jet coupling in microquasars

The association of bipolar jets and accretion disks seems to be a universal phenomenon in quasars and microquasars. The predominant idea is that matter jets are driven by the enormous rotation energy of the compact object and accretion disk that surrounds it. Through magneto-hydrodynamic mechanisms, the rotation energy is evacuated through the poles by means of jets, as the rest can fall towards the gravitational attraction centre. In spite of the apparent universality of this relationship between accretion disks and bipolar, highly collimated, jets, the temporal sequence of the phenomena had never been observed in real time.

Since the scales of time of the phenomena around black holes are proportional to their mass, the accretion-ejection coupling in stellar-mass black holes can be observed in intervals of time that are millions of time smaller than in AGN and quasars. Because of the proximity, the frequency and the rapid variability of energetic eruptions, GRS 1915+105 became the most adequate object to study the connection between instabilities in the accretion disks and the genesis of bipolar jets.

After several attempts, finally in 1997 we could observe (Mirabel et al. 1998) on an interval of time shorter than an hour, a sudden fall in the luminosity in X and soft γ-rays, followed by the ejection of jets, first observed in the infrared, then at radio frequencies (see Fig. 2). The abrupt fall in X-ray luminosity could be interpreted as the silent disappearance of the warmer inner part of the accretion disk beyond the horizon of the black hole. A few minutes later, fresh matter coming from the companion star come to feed again the accretion disk, which must evacuate part of its kinetic energy under the form of bipolar jets. When moving away, the plasma clouds expand adiabatically, becoming more transparent to its own radiation, first in the infrared and then in radio frequency. The observed interval of time between the infrared and radio peaks is consistent with that predicted by van der Laan (1966) for extragalactic radio sources.

Based on the observations of GRS 1915+105 and other X-ray binaries, it was proposed (Fender et al. 2004) proposed a unified semiquantitative model for disk-jet coupling in black hole X-ray binary systems that relate different X-ray sates with radio states, including the compact, steady jets associated to low-hard X-ray states, that had been imaged (Dhawan et al. 2000) using the Very Long Baseline Array of the National Radio Astronomy Observatory.

After three years of multi-wavelength monitoring an analogous sequence of X-ray emission dips followed by the ejection of bright super-luminal knots in radio jets was reported (Marscher et al. 2002) in the active galactic nucleus of the galaxy 3C 120. The mean time between X-ray dips was of the order of years, as expected from scaling with the mass of the black hole.

5. Can we prove the existence of black holes?

Horizon is the basic concept that defines a black hole: a massive object that consequently produces a gravitational attraction in the surrounding environment, but that has no material border. In fact, an invisible border in the space-time, which is predicted by general relativity, surrounds it. This way, matter could go through this border without being rejected, and without losing a fraction of its kinetic energy in a thermonuclear explosion, as sometimes happen if the compact object is a neutron star instead of a black hole. In fact, as shown in Fig. 2, the interval of time between the sudden drop of the flux and the spike in the X-ray light curve that marks the onset of the jet signaled by the starting rise of the infrared synchrotron emission is of a few minutes, orders of magnitude larger than the dynamical time of the plasma in the inner accretion disk. Although the drop of the X-ray luminosity could be interpreted as dissipation of matter and energy, the most popular interpretation is that the hot gas that was producing the X-ray emission falls into the black hole, leaving the observable Universe.

So, have we proved with such observations the existence of black holes? Indeed, we do not find any evidence of material borders around the compact object that creates gravitational attraction. However, the fact that we do not find any evidence for the existence of a material surface does not imply that it does not exist. That means that it is not possible to prove the existence of black holes using the horizon definition. According to Saint Paul, *"faith is the substance of hope for: the evidence of the not seen"*. That is why for some physicists, black holes are just objects of faith. Perhaps the intellectual attraction of these objects comes from the desire of discovering the limits of the Universe. In this context, studying the physical phenomena near the horizon of a black hole is a way of approaching the ultimate frontiers of the observable Universe.

6. The rotation of black holes

For an external observer, black holes are the simplest objects in physics since they can be fully described by only three parameters: mass, rotation and charge. Although black holes could be born with net electrical charge, it is believed that because of interaction with environmental matter, astrophysical black holes rapidly become electrically neutral. The masses of black holes gravitating in binary systems can be estimated with Newtonian physics. However, the rotation is much more difficult to estimate despite it being probably the main driver in the production of relativistic jets.

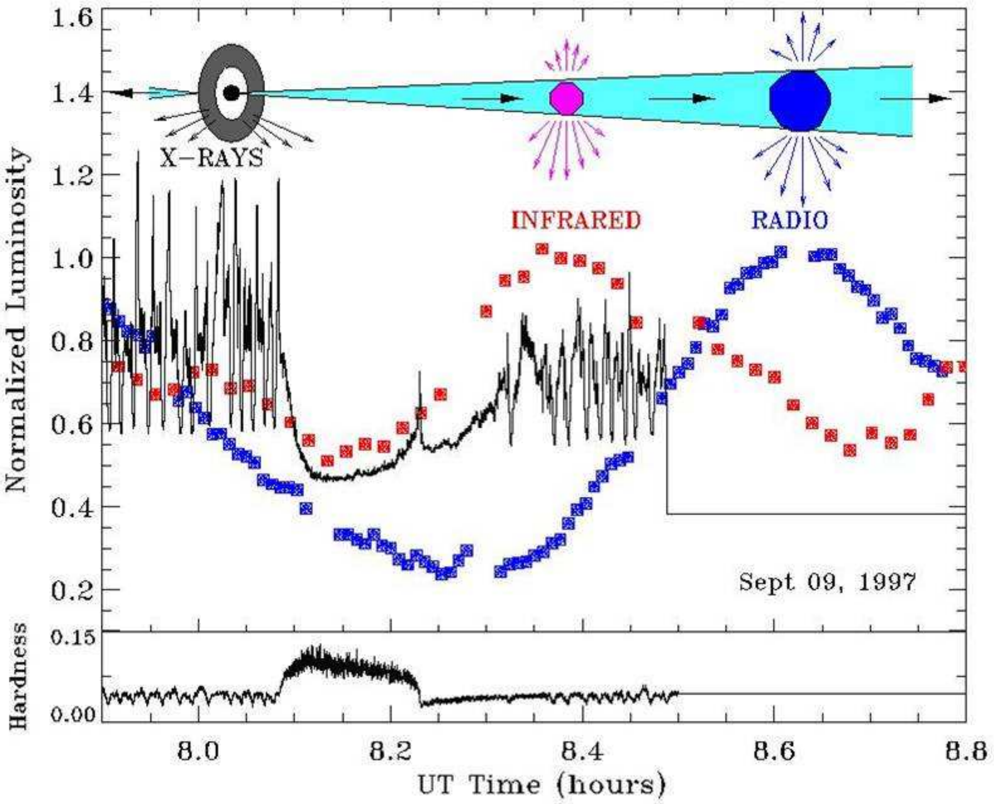

Fig. 2. Temporal sequence of accretion disk – jet coupling observed for first time in real time simultaneously in the X-rays, the infrared and radio wavelengths in the microquasar GRS 1915+105 (Mirabel et al. (1998), reproduced with permission ©ESO). The ejection of relativistic jets takes place after the evacuation and/or dissipation of matter and energy, at the time of the reconstruction of the inner side of the accretion disk, corona or base of the jet. A similar process has been observed years later in quasars (Marscher et al. 2002), but on time scales of years. As expected in the context of the analogy between quasars and microquasars (Mirabel & Rodríguez 1998), the time scale of physical processes in the surroundings of black holes is proportional to their masses.

There is now the possibility of measuring the rotation of black holes by at least three different methods: a) X-ray continuum fitting (Zhang et al. 1997; McClintock et al. 2006), b) asymmetry of the broad component of the Fe K_α line from the inner accretion disk (Tanak 2006), and c) quasi-periodic oscillations with a maximum fix frequency observed in the X-rays (Remillard & McClintock 2006). The main source of errors in the estimates of the angular momentum resides in the uncertanties of the methods employed.

The side of the accretion disk that is closer to the black hole is hotter and produces huge amounts of thermal X and γ radiations and is also affected by the strange configuration of space-time. Indeed, next to the black hole, space-time is curved by the black hole mass and dragged by its rotation. This produces vibrations that modulate the X-ray emission. Studies of those X-ray continuum and vibrations suggest that the microquasars that produce the most powerful jets are indeed those that are rotating fastest. It has been proposed that these pseudo-periodic oscillations in microquasars are, moreover, one of the best methods today to probe by means of observations general relativity theory in the limit of the strongest gravitational fields.

Analogous oscillations in the infrared range, may have been observed in the super massive black hole at the centre of the Milky Way. The quasi-periods of the oscillations (a few milliseconds for the microquasars X-ray emission and a few tens of minutes for the galactic centre black hole infrared emission) are proportionally related to the masses of the objects, as expected from the physical analogy between quasars and microquasars. Comparing the phenomenology observed in microquasars to that in black holes of all mass scales, several correlations among observables such as among the radiated fluxes in the low hard X-ray state, quasi-periodic oscillations, flickering frequencies, etc., are being found and used to derive the mass and angular momentum, which are the fundamental parameters that describe astrophysical black holes.

7. Extragalactic microquasars, microblazars and ultraluminous X-ray sources

Have microquasars been observed beyond the Milky Way galaxy? X-ray satellites are detecting far away from the centers of external galaxies large numbers of compact sources called 'ultraluminous X-ray sources', because their luminosities seem to be greater than the Eddington limit for a stellar-mass black hole (Fabbiano 2006). Although a few of these sources could be black holes of intermediate masses of hundreds to thousands solar masses, it is believed that the large majority are stellar-mass black hole binaries.

Since the discovery of quasars in 1963, it was known that some quasars could be extremely bright and produce high energetic emissions in a short time. These particular quasars are called blazars and it is thought that they are simply quasars whose jets point close to the Earth's direction. The Doppler effect produces thus an amplification of the signal and a shift into higher frequencies. With Rodríguez we imagined in 1999 the existence of microblazars, that is to say X-ray binaries where the emission is also in the Earth's direction (Mirabel & Rodríguez 1999). Microblazars may have been already observed but the fast variations caused by the contraction of the time scale in the relativistic jets, make their study very difficult. In fact, one worthwhile question is whether microblazars could have been already detected as "fast black hole X-ray novae" (Kasliwal et al. 2008). In fact, the so called "fast black hole X-ray novae" Swift J195509.6+261406 (which is the possible source of GRB 070610 (Kasliwal et al. 2008)), and V4541 Sgr (Orosz et al. 2001) are compact binaries that appeared as high energy sources with fast and intense variations of flux, as expected in microblazars (Mirabel & Rodríguez 1999).

Although some fast variable ultraluminous X-ray sources could be microblazars, the vast majority do not exhibit the intense, fast variations of flux expected in relativistic beaming. Therefore, it has been proposed (King et al. 2001) that the large majority are stellar black hole binaries where the X-ray radiation is –as the particle outflows– anisotropic, but not necessarily relativistically boosted. In fact, the jets in the Galactic microquasar SS 433, which are directed close to the plane of the sky, have kinetic luminosities of more than 10^{39} erg/sec, which are super-Eddington for a black hole of 10 solar masses.

An alternative model is that ultraluminous X-ray sources may be compact binaries with black holes of more than 30 solar masses that emit largely isotropically with no beaming into the line of sight, either geometrically or relativistically (Pakull et al. 2003). This conclusion is based on the formation, evolution and overall energetics of the ionized nebulae of several 100 pc diameter in which some ultraluminous X-ray sources are found embedded. The recent discoveries of high mass binaries with black holes of 15.7 solar masses in M 33

(Orosz et al. 2007) and 23-34 solar masses in IC 10 (Prestwich et al. 2007) support this idea. Apparently, black holes of several tens of solar masses could be formed in starburst galaxies of relative low metal content.

8. Very energetic γ-ray emission from compact binaries

Very energetic γ-rays with energies greater than 100 gigaelectron volts have recently been detected with ground based telescopes from four high mass compact binaries (Mirabel 2006). These have been interpreted by models proposed in the contexts represented in Fig. 1 of Mirabel (2006). In two of the four sources the γ radiation seems to be correlated with the orbital phase of the binary, and therefore may be consistent with the idea that the very high energy radiation is produced by the interaction of pulsar winds with the mass outflow from the massive companion star (Dubus 2006; Dhawan et al. 2006). The detection of TeV emission from the black hole binary Cygnus X-1 (Albert et al. 2007) and the TeV intraday variability in M 87 (Aharonian et al. 2006) provided support to the jet models (Romero 2008), which do not require relativistic Doppler boosting as in blazars and microblazars . It remains an open question whether the γ-ray binaries LS 5039 and LS I +61 303 could be microquasars where the γ radiation is produced by the interaction of the outflow from the massive donor star with jets (Romero 2008) or pulsar winds (Dubus 2006).

9. Microquasars and gamma-ray bursts

It is believed that gamma-ray bursts of long duration (t>1 sec) mark the birth of black holes by core collapse of massive stars. In this context, microquasars that contain black holes would be fossils of gamma-ray burst sources of long duration, and their study in the Milky Way and nearby galaxies can be used to gain observational inside into the physics of the much more distant sources of gamma-ray bursts. Questions of topical interest are: a) do all black hole progenitors explode as very energetic hypernovae of type Ib/c? ; b) what are the birth places and nature of the progenitors of stellar black holes?

The kinematics of microquasars provide clues to answer these questions. When a binary system of massive stars is still gravitationally linked after the explosion of one of its components, the mass centre of the system acquires an impulse, whatever matter ejection is, symmetric or asymmetric. Then according to the microquasar movement we can investigate the origin and the formation mechanism of the compact object. Knowing the distance, proper motion, and radial velocity of the centre of mass of the binary, the space velocity and past trajectory can be determined. Using multi-wavelength data obtained with a diversity of observational techniques, the kinematics of eight microquasars have so far been determined.

One interesting case is the black hole wandering in the Galactic halo, which is moving at high speed, like globular clusters (Mirabel et al. 2001) (Fig. 3). It remains an open question whether this particular halo black hole was kick out from the Galactic plane by a natal explosion, or is the fossil of a star that was formed more than 7 billions of years ago, before the spiral disk of stars, gas and dust of the Milky Way was formed. In this context, the study of these stellar fossils may represent the beginning of what could be called 'Galactic Archaeology'. Like archaeologists, studying these stellar fossils, astrophysicists can infer what was the history of the Galactic halo.

The microquasars LS 5039 (Ribó et al. 2002) and GRO J1655-40 (Mirabel et al. 2002) which contain compact objects with less that $\sim$7 solar masses were ejected from their birth place at high speeds, and therefore the formation of these compact objects with relative small masses must have been associated with energetic supernovae. On the contrary, the binaries Cygnus X-1 (Mirabel & Rodrigues 2003) and GRS 1915+105 (Dhawan et al. 2007) which contain black holes of at least 10 solar masses do not seem to have received a sudden impulse. Preliminary results on the

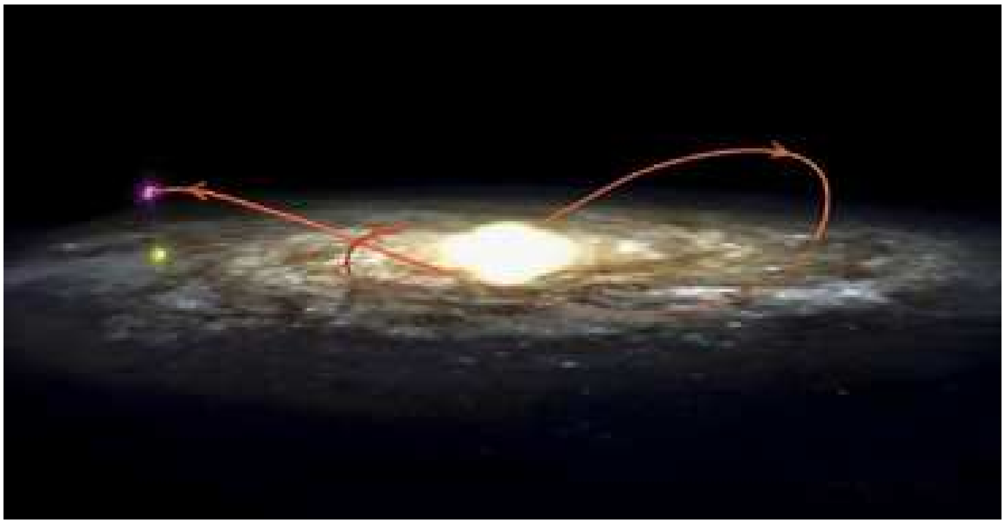

Fig. 3. A wandering black hole in the Galactic halo. The trajectory of the black hole for the last 230 million years is represented in red. The yellow dot represents the Sun (*http : //www.nrao.edu/pr/*2001*/blackhole/*).

kinematics of the X-ray binaries suggest that low mass black holes are formed by a delayed collapse of a neutron star with energetic supernovae, whereas stellar black holes with masses equal or greater than 10 solar masses are the result of the direct collapse of massive stars, namely, they are formed in the dark. This is consistent with the recent finding of gamma-ray bursts of long duration in the near universe without associated luminous supernovae (Della Valle et al. 2006).

There are indications that the mass of the resulting black hole may be a function of the metal content of the progenitor star. In fact, the black holes with 16 solar masses in M 33 (Orosz et al. 2007) and more than 23 solar masses in IC 10 (Prestwich et al. 2007), are in small galaxies of low metal content. This is consistent with the fact that the majority of the gamma-ray bursts of long duration take place in small starburst galaxies at high redshift, namely, in galactic hosts of low metal content (Le Floc'h et al. 2003). Since the power and redshift of gamma-ray bursts seem to be correlated this would imply a correlation between the mass of the collapsing stellar core and the power of the γ-ray jets.

Gamma-ray bursts of long duration are believed to be produced by ultra relativistic jets generated in a massive star nucleus when it catastrophically collapses to form a black hole. Gamma-ray bursts are highly collimated jets and it has been proposed (Mirabel & Rodrigues 2002) that there may be a unique universal mechanism to produce relativistic jets in the Universe, suggesting that the analogy between microquasars and quasars can be extended to the gamma-ray bursts sources.

10. New perspectives

With the launch of GAIA the distances and space velocities of compact binaries will be geatly improved, which will allow to determine the space velocities of microquasars with greater precision. Therefore, microquasars will be used to probe the models on the collapse of massive stars and the formation of black holes and neutron stars.

Theoretical models and several observations suggest that there should be a cosmic evolution of stellar mass black hole binaries (Mirabel 2010). The infered large population of microquasars hosted by the first galaxies formed at redshifts z¿6 would have played an important role during the epoch of reionization of the universe.

The research area on microquasars has become one of the most important areas in high energy astrophysics. In the last 14 years there have been seven international workshops on microquasars: 4 in Europe, 1 in America and 2 in Asia. They are being attended by 100–200 young scientists who, with their work on microquasars, are contributing to open new horizons in the common ground of high energy physics and modern astronomy.

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