SOURCES OF RELATIVISTIC JETS IN THE GALAXY

I. F. Mirabel

Centre d'Etudes de Saclay, CEA/DSM/DAPNIA/Sap

F-91191 Gif-sur-Yvette, France, and

Instituto de Astronomía y Física del Espacio

C.C. 67, Suc. 28. 1428, Buenos Aires, Argentina

mirabel@discovery.saclay.cea.fr

and

L. F. Rodríguez

Instituto de Astronomía, UNAM,

Apdo. Postal 70-264, 04510 México, D.F., México

luisfr@astrosmo.unam.mx

Shortened title: RELATIVISTIC JETS IN THE GALAXY

Send Proofs to: I. F. Mirabel (please contact by email first to check for address)

KEY WORDS: radio continuum stars, superluminal motion, X-rays binaries

ABSTRACT

Black holes of stellar mass and neutron stars in binary systems are first detected as hard X-ray sources using high-energy space telescopes. Relativistic jets in some of these compact sources are found by means of multiwavelength observations with ground-based telescopes. The X-ray emission probes the inner accretion disk and immediate surroundings of the compact object, whereas the synchrotron emission from the jets is observed in the radio and infrared bands, and in the future could be detected at even shorter wavelengths. Black-hole X-ray binaries with relativistic jets mimic, on a much smaller scale, many of the phenomena seen in quasars and are thus called microquasars. Because of their proximity, their study opens the way for a better understanding of the relativistic jets seen elsewhere in the Universe. From the observation of two-sided moving jets it is inferred that the ejecta in microquasars move with relativistic speeds similar to those believed to be present in quasars. The simultaneous multiwavelength approach to microquasars reveals in short timescales the close connection between instabilities in the accretion disk seen in the X-rays, and the ejection of relativistic clouds of plasma observed as synchrotron emission at longer wavelengths. Besides contributing to a deeper comprehension of accretion disks and jets, microquasars may serve in the future to determine the distances of jet sources using constraints from special relativity, and the spin of black holes using general relativity.

1. JETS IN ASTROPHYSICS

While the first evidence of jet-like features emanating from the nuclei of galaxies goes back to the discovery by Curtis (1918) of the optical jet from the elliptical galaxy M87 in the Virgo cluster, the finding that jets can also be produced in smaller scale by binary stellar systems is much more recent. The detection by Margon et al. (1979) of large, periodic Doppler drifts in the optical lines of SS433 resulted in the proposition of a kinematic model (Fabian & Rees 1979; Milgrom 1979) consisting of two precessing jets of collimated matter with velocity of 0.26c. High angular radio imaging as a function of time showed the presence of outflowing radio jets and fully confirmed the kinematic model (Spencer 1979; Gilmore & Seaquist 1980; Gilmore et al. 1981; Hjellming & Johnston 1981). The early history of SS433 has been reviewed by Margon (1984).

Since the detection of Sco X-1 at radio wavelengths (Ables 1969), some X-ray binaries had been known to be strong, time-variable non-thermal emitters. Ejection of synchrotron-emitting clouds was suspected from those days, but the actual confirmation of radio jets came only with the observations of SS433. At present, there are about 200 known galactic X-ray binaries (van Paradijs 1995), of which about 10 percent are radio-loud (Hjellming & Han 1995). Of these radio-emitting X ray binaries, 9 have shown evidence of relativistic jets of synchrotron emission, and this review focuses on this set of objects. After the definition of Bridle & Perley (1984) for extragalactic jets, we use the term “jets” to designate collimated ejecta that have opening angles $\leq 15°$.

In the last years it has become clear that collimated ejecta can be produced in several stellar environments when an accretion disk is present. Jets with terminal velocities in the order of a few hundred to a few thousand km s^{-1} are now known to emanate from objects as diverse as very young stars (Reipurth & Bertout 1997), nuclei of planetary nebulae (López 1997), and accreting white dwarfs that appear as supersoft X-ray sources (Motch 1998, Cowley et al. 1998). These types of stellar jets have, however, non-relativistic velocities ($\sim$100-10000 km s^{-1}) and their associated emission is dominantly thermal (i.e. free-free continuum emission in the radio as well as characteristic near-IR, optical and UV lines). Interestingly, in all known types of jet sources a disk is believed to be present. This review concentrates on synchrotron jets with velocities that can be considered relativistic ($v \geq 0.1c$), which are observed in X-ray binaries that contain a compact object, that is, a neutron star or a black hole. Our emphasis is on the radio characteristics of these sources. For detailed reviews of the X-ray properties of these sources we refer the reader to the reviews by Tanaka & Shibazaki (1996) and Zhang et al. (1997).

2. MICROQUASARS

At first glance it may seem paradoxical that relativistic jets were first discovered in the nuclei of galaxies and distant quasars and that for more than a decade SS433 was the only known object of its class in our Galaxy (Margon 1984). The reason for this is that disks around supermassive black holes emit strongly at optical and UV wavelengths. Indeed, the more massive the black hole, the cooler the surrounding accretion disk is. For a black hole accreting at the Eddington limit, the characteristic black body temperature at the last stable orbit in the surrounding accretion disk will be given approximately by $T \sim 2 \times 10^7 \ M^{-1/4}$ (Rees 1984), with T in K and the mass of the black hole, M, in solar masses. Then, while accretion disks in AGNs have strong emission in the optical and ultraviolet with distinct broad emission lines, black hole and neutron star binaries usually are identified for the first time by their X-ray emission. Among these sources, SS 433 is unusual given its broad optical emission lines and its brightness in the visible. Therefore, it is understandable that there was an impasse in the discovery of new stellar sources of relativistic jets until the recent developments in X-ray astronomy.

Observations in the two extremes of the electromagnetic spectrum, in the domain of the hard X-rays on one hand (Sunyaev et al. 1991; Paul et al. 1991), and in the domain of radio wavelengths on the other hand, revealed the existence of new stellar sources of relativistic jets known as *microquasars* (Mirabel et al. 1992; Mirabel & Rodríguez 1998). These are stellar-mass black holes in our Galaxy that mimic, on a smaller scale, many of the phenomena seen in quasars. The microquasars combine two relevant aspects of relativistic astrophysics: accreting black holes (of stellar origin) which are a prediction of general relativity and are identified by the production of hard X-rays and gamma-rays from surrounding accretion disks, and relativistic jets of particles that are understood in terms of special relativity and are observed by means of their synchrotron emission.

Multi-wavelength studies of the X-ray and gamma-ray sources in the galactic center region led in the year 1992 to the discovery of two microquasars: 1E1740.7-2942 and GRS 1758-258 (Mirabel et al. 1992; Rodríguez, Mirabel, & Martí 1992). The X-ray luminosity, the photon spectrum, and the time variability of these two sources are comparable to those of the black hole binary Cygnus X-1 (Churazov et al. 1994; Kuznetsov et al. 1997), and it is unlikely that they are extragalactic since no such persistent hard X-ray ultraluminous AGNs are observed (Mirabel et al. 1993). In Figure 1 we show the radio counterpart of 1E1740.7-2942. As in Cygnus X-1, the centimeter radio counterpart of 1E1740.7-2942 is a weak core source that exhibits flux variations of the order of $\sim 50\%$ which at epochs appear anticorrelated with the X-ray flux (Mirabel et al. 1992). At radio wavelengths these two X-ray persistent sources located near the galactic center have a striking morphological resemblance with distant radio galaxies; they consist of compact components at the center of two-sided jets that end in weak, extended lobes with no significant radio flux variations observed in the last 6 years (Rodríguez & Mirabel 1999b). 1E1740.7-2942 and GRS 1758-258 seem to be persistent sources of both X-rays and relativistic jets. Mirabel et al. (1993) have argued why it would be unlikely that the radio sources are radio galaxies accidentally superposed on the X-rays sources. For 1E1740.7-2942 no counterpart in the optical or near infrared wavelengths has been found so far, although there is a report of a marginal detection at $\lambda 3.8$ μm by Djorgovski et al. (1992). GRS 1758-258 has two possible faint candidate counterparts (Martí et al. 1998).

In these binaries of stellar-mass are found the three basic ingredients of quasars; a black hole, an accretion disk heated by viscous dissipation, and collimated jets of high energy particles. But in microquasars the black hole is only a few solar masses instead of several millon solar masses; the accretion disk has mean thermal temperatures of several millon degrees instead of several thousand degrees; and the particles ejected at relativistic speeds can travel up to distances of a few light years only, instead of several millon light years as in giant radio galaxies (Mirabel & Rodríguez (1998). Indeed, simple scaling laws govern the physics of flows around black holes, with length and time scales being proportional to the mass of the black holes (Sams et al. 1996; Rees 1998). The word *microquasar* was chosen to suggest that the analogy with quasars is more than morphological, and that there is an underlying unity in the physics of accreting black holes over an enormous range of scales, from stellar-mass black holes in binary systems, to supermassive black holes at the center of distant galaxies. Strictly speaking and not being for the historical circumstances described above, the acronym *quasar* ("quasi-stellar-radio-source") would have suited better the stellar mass versions rather than their super-massive analogs at the centers of galaxies.

3. SUPERLUMINAL SOURCES

Expansions at up to ten or more times the speed of light have been observed in quasars for more than 20 years (Pearson & Zensus 1987; Zensus 1997). At first these superluminal motions provoked concern because they appeared to violate relativity, but they were soon interpreted as illusions due to relativistic aberration (Rees, 1966). However, the ultimate physical interpretation had remained uncertain. In the extragalactic case the moving jets are observed as one-sided (because strong Doppler favoritism is required to render the approaching ejecta detectable) and it is not possible to know if superluminal motions represent the propagation of waves through a slowly moving jet, or if they reflect the actual bulk motion of the sources of radiation.

In the context of the microquasar analogy, one may ask if superluminal motions could be observed from sources known to be in our own Galaxy. Among the handful of black holes of stellar mass known so far, three transient X-ray sources have indeed been identified at radio waves as sporadic sources of superluminal jets. The first superluminal source to be discovered (Mirabel & Rodríguez 1994) was GRS 1915+105, a recurrent transient source of hard X-rays first found and studied with the satellite GRANAT (Castro-Tirado et al. 1994; Finogenov et al. 1994). The discovery of superluminal motions in GRS 1915+105 stimulated a search for similar relativistic ejecta in other transient hard X-ray sources. Soon after, the same phenomenon was observed by two different groups (Tingay et al. 1995; Hjellming & Rupen 1995) in GRO J1655-40, a hard X-ray nova found with the Compton Gamma Ray Observatory (Zhang et al. 1994). A third superluminal source may be XTE J1748-288 (Hjellming et al. 1998), a transient source with a hard X-ray spectrum recently found with XTE (Smith et al. 1998).

GRS 1915+105 is at ∼12 kpc from the Sun (Rodríguez et al. 1995; Chaty et al. 1996) on the opposite side of the galactic plane and cannot be studied in the optical. Given the large extinction by dust along the line of sight (Mirabel et al. 1994; Chaty et al. 1996), the precise nature of the binary has been elusive. Castro-Tirado et al. (1996) proposed that GRS 1915+105 is a low mass binary, while Mirabel et al. (1997) proposed that it is a long period binary with a companion star of transitional spectral type. From the nature of the line variability in the infrared, Eikenberry et al. (1998b) propose that the emission lines in GRS 1915+105 arise in an accretion disk rather than in the circumstellar disk of an Oe/Be companion (Mirabel et al. 1997). GRS 1915+105 has similarities in the X-rays and gamma-rays with GRO J1655-40 and other black hole binaries, and it is also likely to harbor a black hole (Greiner, Morgan, & Remillard 1996). The X-ray luminosity of GRS 1915+105 (reaching 2 10^6 solar luminosities) far exceeds the Eddington limit (above which the radiation pressure will catastrophically blow out the external layers of the source) for a 3 solar mass object, which is 10^5 solar luminosities. Furthermore, it shows the typical hard X-ray tail beyond 100 keV seen in black hole binaries (Cordier 1993; Finogenov et al. 1994; Grove et al. 1998). Finally, it is known that the absolute hard X-ray luminosities in black hole systems are systematically higher than in neutron star systems (Ballet et al. 1993; Barret, McClintock, & Grindlay 1996), another result that points to a black hole in GRS 1915+105.

GRO J1655-40 is at a distance of 3.2 kpc and the apparent transverse motions of its ejecta in the sky are the largest yet observed (Tingay et al 1995; Hjellming & Rupen 1995) until now from an object beyond the solar system. It has a bright optical counterpart and consists of a star of 1.7-3.3 solar masses orbiting around a collapsed object of 4-7 solar masses (Orosz & Bailyn 1997; Phillips et al. 1999). The compact object is certainly a black hole, since its mass is beyond the theoretical maximum mass limit of $\sim$ 3 solar masses for neutron stars (Kalogera & Baym 1996).

King (1998) proposes that the superluminal sources are black hole binaries with the secondary in the Hertzsprung-Russell gap, which provides super-Eddington accretion into the black hole. In the Galaxy there would have been $\geq 10^3$ systems of this class with a lifetime for the jet phase of $\leq 10^7$ years, which is the spin-down phase of the black hole.

3.1 *Superluminal motions in GRS 1915+105*

Figure 2 shows a pair of bright radio condensations emerging in opposite directions from the compact, variable core of GRS 1915+105. Before and after the remarkable ejection event shown in Figure 2, the source ejected other pairs of condensations but with flux densities one to two orders of magnitude weaker. One of these weaker pairs can be seen in the first four maps of Figure 2, as a fainter pair of condensations moving ahead of the bright ones at about the same proper motion and direction.

In Figure 3 we show the proper motions of the condensations detected from four ejection events in 1994. The angular displacements from the stationary core are consistent with ballistic (that is, unaccelerated) motions. The time separation between ejections suggests a quasi-periodicity at intervals in the range of 20-30 days. Although the clouds in each event appear to move ballistically, always in the same general region of the sky, their position angles suggest changes by $\sim 10^\circ$ in the direction of ejection in one month.

Figures 2 and 3 show two asymmetries: one in apparent transverse motions, another in brightness. The cloud that appears to move faster also appears brighter. It has been shown that both asymmetries, in proper motions and in brightness, are consistent with the hypothesis of an anti-parallel ejection of twin clouds moving at relativistic velocities (Mirabel and Rodríguez 1994), as discussed in section 4. At a distance of 12 kpc the proper motions measured with the VLA in 1994 of the approaching (17.6 ± 0.4 mas d^{-1}) and receding (9.0 ± 0.1 mas d^{-1}) condensations shown in Figure 2 imply apparent velocities on the plane of the sky of 1.25c and 0.65c, respectively. From the analysis of relativistic distorsion effects using the equations in the next section and the VLA data, it is inferred that the ejecta move with a speed of 0.92c at an angle $\theta = 70^\circ$ to the line of sight.

Within the errors of the measurements and a precession of $\leq 10^\circ$, relativistic ejections with a stable jet axis at scales of 500-5000 AU and larger were later observed from GRS 1915+105 over a time span of four years (Mirabel et al 1996a; Fender et al 1999; Dhawan, Mirabel and Rodríguez 1999). The VLBA images of GRS 1915+105 show that the jets are already collimated at milliarcsec scales (Dhawan, Mirabel and Rodríguez 1999), namely, at about 10 AU from the compact source (Figure 4). The core appears as a synchrotron jet of length

~100 AU before and during optically thin flares, and at those scales it already exhibits Doppler boosting. Discrete ejecta have appeared at about 500 AU. Both, the observations with MERLIN (Fender et al. 1999) and with the VLBA (Dhawan, Mirabel and Rodríguez 1999) in the years 1997 and 1998 have shown faster apparent superluminal motions at 1.3c-1.7c at scales of hundreds of AU, and intrinsic expansions of the expelled clouds mostly in the direction of their bulk motions. At present it is not clear if the faster motions measured with the higher resolution observations of MERLIN and VLBA in 1997 relative to the VLA observations in 1994 are due to intrinsic faster ejections, changes in the angle to the line of sight, or to resolution effects between the arrays as suggested by Fender et al. (1999).

A secular paralax of 5.8±1.5 mas yr^{-1} in the galactic plane, in rough agreement with the HI distance of 12 kpc (Rodríguez et al. 1995), has been measured with the VLBA (Dhawan, Mirabel and Rodríguez 1999).

3.2 *Superluminal motions in GRO J1655-40*

The relativistic ejections observed in the radio in GRO J1655–40 have striking similarities as well as differences with those in GRS 1915+105. Bright components moving apart with proper motions in the range of 40 to 65 mas d^{-1} were independently observed with the Southern Hemisphere VLBI Experiment array (Tingay et al. 1995), and the VLA and VLBA (Hjellming & Rupen 1995). In Figure 5 is shown a sequence of seven VLBA radio images of GRS J1655-40 from Hjellming & Rupen (1995). At a distance of 3.2 kpc the motions of the ejecta have been fit -using a kinematic model- with a velocity of 0.92c, and a jet axis inclined 85° to the line of sight at a position angle of 47°, about which the jets rotate every three days at an angle of 2°.

In contrast to what has been observed in the repeated ejections of GRS 1915+105, the flux ratios of the blobs on either side of GRO J1655–40 cannot be ascribed to relativistic Doppler boosting. In GRO J1655–40 the asymmetry in brightness appears to flip from side to side (Hjellming & Rupen 1995). Not only the jets appear to be intrinsically asymmetric, but also the sense of that asymmetry changes from event to event. Therefore, although similar intrinsic velocities greater than 0.9c are found in both superluminal sources, due to the asymmetries in GRO

J1655-40, the ultimate physical interpretation of the superluminal expansions in this source remains uncertain.

We point ou that in SS433 flux asymmetries between knots ejected simultaneously on both sides have also been observed (Fejes, 1986). This asymmetry could be due to intrinsic variations, so perhaps GRO J1655-40 is not unusual in this respect. However, VLBA multiwavelength monitoring of SS433 (Paragi et al. 1998) shows that it is always the receding part of the core-complex which is fainter compared to the approaching one, and that this effect cannot be explained simply by Doppler beaming. It is possible that free-free absorption and the different pathlengths through an absorbing medium could explain some of these asymmetries in SS433 and other jet sources. Furthermore, in SS433 more than 90% of the radio emission is in knots rather than in continuous jets, and the core complex disappears after large outbursts, as in GRS 1915+105 (Mirabel and Rodríguez 1994).

3.3 *Superluminal motions in XTE J1748-288*

Two major relativistic ejection sequences moving at least 20 mas/day were observed in June 1998 (Hjellming et al. 1998) from the hard X-ray transient XTE J1748-288 (Smith et al. 1998). Each sequence appeared to begin with a one-sided relativistic ejection. The ejecta are highly linearly polarized, and at a distance of 8 kpc, derived from the HI λ21cm absorption line, their motions would imply apparent speeds of 0.9c and 1.5c, and intrinsic velocities of more than 0.9c (Hjellming et al. 1998). This is the first galactic source of relativistic jets where it has been observed in real time that the jets collide with environmental material, being decelerated while brightening at the leading edge of the jet.

4. SPECIAL RELATIVITY EFFECTS

4.1 *Parameters of the Ejection*

The main characteristics of the superluminal ejections can be understood in terms of the simultaneous ejection of a pair of twin condensations moving at velocity β ($\beta = v/c$), with v being the velocity of the condensations and c the speed of light), with the axis of the flow making an angle θ ($0° \leq \theta \leq 90°$) with respect to the line of sight of a distant observer (Rees 1966; see Figure 6). The apparent proper motions in the sky of the approaching and receding condensations, μ_a and μ_r, are given by:

$$\mu_a = \frac{\beta\ sin\ \theta}{(1 - \beta\ cos\ \theta)} \frac{c}{D}, \tag{1}$$

$$\mu_r = \frac{\beta\ sin\ \theta}{(1 + \beta\ cos\ \theta)} \frac{c}{D}, \tag{2}$$

where D is the distance from the observer to the source. These two equations can be transformed to the equivalent pair of equations:

$$\beta\ cos\ \theta = \frac{\mu_a - \mu_r}{\mu_a + \mu_r}, \tag{3}$$

$$D = \frac{c\ tan\ \theta}{2} \frac{(\mu_a - \mu_r)}{\mu_a \mu_r}. \tag{4}$$

If only the proper motions are known, an interesting upper limit for the distance can be obtained from eqns. (3) and (4):

$$D \leq \frac{c}{\sqrt{\mu_a \mu_r}}. \tag{5}$$

In all equations we use cgs units and the proper motions are in radians s^{-1}. In the case of the bright ejection event of 1994 March 19 for GRS 1915+105, the proper motions measured were $\mu_a = 17.6 \pm 0.4$ mas day^{-1} and $\mu_r = 9.0 \pm 0.1$ mas day^{-1}. Using eqn. (5), we derive an upper limit for the distance, $D \leq 13.7$ kpc, confirming the galactic nature of the source.

The distance to GRS 1915+105 is found to be, from HI absorption studies, 12.5±1.5 kpc (Rodríguez et al. 1995; Chaty et al. 1996). Then, the proper motions of the approaching and receding condensations measured with the VLA in 1994 and 1995 imply apparent velocities on the plane of the sky of v_a = 1.25c and v_r = 0.65c for the approaching and receding components respectively. The ejecta move with a true speed of v = 0.92c at an angle $\theta = 70°$ with respect to the line of sight (Mirabel & Rodríguez 1994). The faster proper motions of 24 mas/day measured with MERLIN (Fender et al. 1999) and the VLBA (Dhawan et al. 1999) in 1997 would imply a true speed of 0.98c at an angle of 66° to the line of sight.

4.2 *A Relativistic Distance Determination*

We note that the detection of a known line from either of the condensations would allow a precise determination of the distance. The Doppler factors, namely, the ratios of observed to emitted frequency (ν_0) for the approaching and receding condensations are given by

$$\delta_a = \frac{\nu_a}{\nu_o} = \gamma^{-1}(1 - \beta\ cos\ \theta)^{-1}, \tag{6}$$

$$\delta_r = \frac{\nu_r}{\nu_o} = \gamma^{-1}(1 + \beta\ cos\ \theta)^{-1} \tag{7}$$

In these last two equations $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor. Since we know $\beta\ cos\ \theta$, a determination of either ν_a/ν_o or ν_r/ν_o will allow the determination of β and thus the determination of θ and of the distance from eqn. (4). In the case of cosmologically distant objects, the equations 1, 2, 4, and 5 are valid replacing the distance D by the angular size distance D_a (Peebles 1993), and the rest frequency ν_o by $\nu_o/(1+z)$, with z being the observed redshift of the central source. The angular size distance is given by $D_a = (c\ z/H_0)[1 - (1+q_0)z/2 + ...]$, where H_0 is Hubble's constant and q_0 is the dimensionless acceleration (or deceleration) parameter. Then, the observations of proper motions and frequency shifts in extragalactic relativistic ejecta pairs could potentially be used to test between different cosmological models.

4.3 *Doppler Boosting*

The ratios of observed to emitted flux density S_o, from a twin pair of optically-thin, isotropically emitting jets are:

$$\frac{S_a}{S_o} = \delta_a^{k-\alpha}, \tag{8}$$

$$\frac{S_r}{S_o} = \delta_r^{k-\alpha}, \tag{9}$$

where α is the spectral index of the emission ($S_\nu \propto \nu^\alpha$), and k is a parameter that accounts for the geometry of the ejecta, with k = 2 for a continuous jet and k =

3 for discrete condensations. Then, the ratio of observed flux densities (measured at equal separations from the core) will be given by

$$\frac{S_a}{S_r} = \left(\frac{1 + \beta\ cos\ \theta}{1 - \beta\ cos\ \theta}\right)^{k-\alpha}, \tag{10}$$

Since for the 1994 March 19 event $\beta\ cos\ \theta$ = 0.323 and α = - 0.8 the flux ratio in the case of discrete condensations would be 12, whereas for a continuous jet it would be 6. For a given angular separation it was found that the observed flux ratio between the approaching and receding condensations is 8 ± 1. Similar results were found using the MERLIN observations by Fender et al. (1999). Therefore, irrespective of the distance to the source, the flux ratios for equal angular separations from the core are consistent with the assumption of a twin ejection at relativistic velocities. Atoyan & Aharonian (1997) have considered the observable effects in the flux density ratio of asymmetries between the jet and counterjet. Bodo & Ghisellini (1995) have proposed that there could be a contribution of wave propagation in the pattern motions, but that most of the observed displacements are true bulk plasma velocities.

5. ACCRETION DISK INSTABILITIES AND JET FORMATION

Collimated jets seem to be systematically associated with the presence of an accretion disk around a star or a collapsed object. In the case of black holes, the characteristic dynamical times in the flow of matter are proportional to the black hole's mass, and the events with intervals of minutes in a microquasar could correspond to analogous phenomena with duration of thousands of years in a quasar of 10^9 $M_\odot$ (Sams et al. 1996; Rees, 1998). Therefore, the variations with minutes of duration observed in a microquasar in the radio, IR, optical, and X rays could sample phenomena that we have not been able to observe in quasars.

X-rays probe the inner accretion disk region, radio waves the synchrotron emission from the relativistic jets. The long term multiwavelength light curves of the superluminal sources show that the hard X-ray emission is a necessary but not sufficient condition for the formation of collimated jets of synchrotron radio emission. In GRS 1915+105 the relativistic ejection of pairs of plasma clouds have always been preceded by unusual activity in the hard X-rays (Harmon et al. 1997), more specifically, the onset of major ejection events seems to be simultaneous to the sudden drop from a luminous state in the hard X-rays (Foster et al. 1996; Mirabel et al. 1996a). However, not all unusual activity and sudden drops in the hard X-ray flux appear to be associated with radio emission from relativistic jets. In fact, in GRO J1655-40 there have been several hard X-ray outbursts without following radio flare/ejection events. A more detailed summary of the long term multifrequency studies of black hole binaries can be found in Zhang et al. (1997).

The episodes of large amplitude X-ray flux variations in time-scales of seconds and minutes, and in particular, the abrupt dips observed (Greiner et al. 1996; Belloni et al. 1997; Chen et al. 1997) in GRS 1915+105 are believed to be evidence for the presence of a black hole, as discussed below. These variations could be explained if the inner ($\leq$ 200 km) part of the accretion disk goes temporarily into an advection-dominated mode (Abramowicz et al. 1995; Narayan et al. 1997). In this mode, the time for the energy transfer from ions (that get most of the energy from viscosity) to electrons (that are responsible for the radiation) is larger than the time of infall to the compact object. Then, the bulk of the energy produced by viscous dissipation in the disk is not radiated (as it happens in standard disk models), but instead is stored in the gas as thermal energy. This gas, with large amounts of locked energy, is advected (transported) to the compact object. If the compact object is a black hole, the energy quietly disappears through the horizon. In constrast, if the compact object is a neutron star, the thermal energy in the superheated gas is released as radiation when it collides with the surface of the neutron star and heats it up. The cooling time of the neutron star photosphere is relatively long, and in this case a slow decay in the X-ray flux is observed. Thus, one would expect the luminosity of black hole binaries to vary over a much wider range than that of neutron star binaries (Barret et al. 1996). The idea of advection-dominated flow has also been proposed (Hameury et al. 1997) to explain the X-ray delay in an optical outburst (Orosz et al. 1997) of GRO J1655-40.

During large-amplitude variations in the X-ray flux of GRS 1915+105, remarkable flux variations on time-scales of minutes have also been reported at radio (Pooley & Fender 1997; Rodríguez & Mirabel 1997; Mirabel et al. 1998) and near-infrared wavelengths (Fender et al. 1997; Fender and Pooley, 1998; Eikenberry et al. 1998a; Mirabel et al. 1998). The rapid flares at radio and infrared waves are thought to come from expanding magnetized clouds of relativistic particles. This idea is supported by the observed time shift of the emission at radio waves as a function of wavelength and the finding of infrared synchrotron precursors to the follow-up radio flares (Mirabel et al. 1998). Sometimes the oscillations at radio waves appear as isolated events composed of twin flares with characteristic time shifts of 70±20 minutes (e.g. Pooley & Fender, 1997: Dhawan, Mirabel & Rodríguez, 1999). The time shift between the twin peaks seems to be independent of wavelength (Mirabel et al. 1998), and no Doppler boosting is observed. This suggests that these quasiperiodic flares may come from expanding clouds moving in opposite directions with non-relativistic bulk motions.

In Figure 7 are shown simultaneous light curves in the X-rays, infrared, and radio wavelengths, together with the X-ray photon index during a large amplitude oscillation. These light curves can be consistently interpreted to imply that the relativistic clouds of plasma emerge at the time of the dips and follow-up recovery of the X-ray flux. In adiabatically expanding clouds the maximum flux density at short wavelengths (i.e. the near infrared) should be observed very shortly after the ejection (10^{-3} sec), and it is only in the radio wavelengths that significant time delays occur (Mirabel et al. 1998). Figure 7 shows that the onset of the infrared flare occured ≥ 200 sec after the drop of the X-ray flux, during its recovery from the dip, probably at the time of the appearance of an X-ray spike (t = 13 min) which is associated to a sudden softening of the (13-60 keV)/2-13 keV) photon index due to the drop in the hard X-ray flux. Similar phenomena have been observed in this source by Eikenberry et al. (1998a). In the context of the unstable accretion disk model of Belloni et al. (1997), these observations suggest that the ejection of plasma clouds takes place during the subsequent replenishment of the inner accretion disk, well after the disappearance of the soft component at the sudden drop. The ejection of the clouds seems to be coincident with the soft X-ray peak at the dip. Furthermore, the slow rise of the infrared flux to maximum seen in Figure 7 indicates that the injection of relativistic particles is not instantaneous and that it could last up to tens of minutes.

Mirabel et al. (1998) have estimated that the minimum mass of the clouds that are ejected every few tens of minutes is $\sim 10^{19}$ g. On the other hand, the estimated total mass that is removed from the inner accretion disk in one cycle of a few tens of minutes is of the order of $\sim 10^{21}$ g (Belloni et al. 1997). Given the uncertainties in the estimation of these masses, it is still unclear what is the fraction of mass of the inner accretion disk that disappears through the horizon of the black hole. Anyway, it seems plausible that during accretion disk instabilities consisting on the sudden disappearance of its inner part, most of it is advected into the black hole, and only some fraction is propelled into synchrotron-emitting clouds of plasma.

Energy outbursts in the flat synchrotron spectrum over at least four decades of frequency have also been observed in Cygnus X-3 (Fender et al. 1996). The optical polarization observed in GRO J1655-40 (Scaltriti et al. 1997) could also be related to the presence of synchrotron emission at optical wavelengths. The study of GRS 1915+105 lead to the realization that besides the energy invested in the acceleration of the plasma clouds to their bulk motions, the oscillations of the type shown in Figure 7 require synchrotron luminosities of at least 10^{36} erg s^{-1}. This synchrotron luminosity is not negligible with respect to the thermal luminosity radiated in the X-rays. These results give support to the observation of synchrotron infrared jets reaching distances of a few thousand AU from GRS 1915+105 (Sams et al. 1996).

6. JET FORMATION

The processes by which the jets are accelerated and collimated are still not clearly understood, but it is believed that several of the concepts proposed for extragalactic jets can be extended to galactic jets.

Blandford & Znajek (1977) take advantage of the fact that, in principle, it is possible to extract energy and angular momentum from a rotating black hole (Penrose 1969), to produce electric and magnetic fields and possibly fast outflowing jets. A magnetized accretion disk around the Kerr black hole brakes it electromagnetically. However, Ghosh and Abramowicz (1997) and Livio et al. (1998) have called into question that the Blandford-Znajek process can provide the primary power in the jets.

A seminal idea that has been followed by many researchers in the field is that of the magnetohydrodynamical model of Blandford & Payne (1982). These authors proposed that the angular momentum of a magnetized accretion disk around the collapsed object is the responsible for the acceleration of the plasma. The magnetic field lines are taken to be frozen into the disk and the plasma is assumed to follow them like a “bead on a wire”, at least close to the disk. If the field line forms an angle with the plane of the disk smaller than 60°, the displacements of the plasma from its equilibrium position become unstable. This happens because along these field lines the component of the centrifugal force will be larger than the component of the gravitational force and the plasma will be accelerated outwards. Then, in its origin, the outflow motion has an important "equatorial" component, while on larger scales the jets are observed to have a motion that is dominantly "poloidal". In other words, after the acceleration a collimating mechanism is required to change the wide-angle centrifugal outflow into a collimated jet.

This collimation is proposed to be achieved as follows. Inside an inner region, the magnetic field energy density is larger than the kinetic energy density of the flow but at some distance from the disk (the Alfvén surface), this situation reverses and the flow stops corotating with the disk. This causes that a loop of toroidal (azimuthal) field is added to the flow for each rotation of the footpoint of the field line. The tension of this wound-up toroidal field that is formed external to the Alfvén surface produces a force directed toward the axis (the "hoop stress") that eventually collimates the flow into a jet. Most models for the production of jets in the astrophysical context use elements of MHD acceleration and collimation.

Recently, several groups (Spruit, Foglizzo, & Stehle 1997; Lucek & Bell 1997; Begelman 1998) have pointed out that the toroidal field traditionally held responsible for collimating jets in the MHD mechanism is unstable and cannot collimate the jets effectively. It has been proposed alternatively that the collimating agent is the poloidal component of the magnetic field.

Koide et al. (1998) have performed for the first time full general relativistic MHD numerical simulations of the formation of jets near a black hole. Their results suggest that the ejected jet has a two-layer structure with an inner, fast gas-pressure driven component and an outer, slow magnetically-driven component. The presence of the inner, fast gas-pressure driven component is a result of the strong pressure increase produced by shocks in the disk through fast advection flows inside the last stable orbit around a black hole. This feature is not seen in non-relativistic calculations.

Within the uncertainties of the small sample, the velocity of the jets seems to show a bimodal distribution, with some sources having $v_{jet} \simeq 0.3$c and others having $v_{jet} \geq 0.9$c. Two explanations have been offered in the literature. On one hand, Kudoh & Shibata (1995) suggest that the terminal velocity of the jet is of order of the Keplerian velocity at the footpoint of the jets, that is that the fastest jets probably come from the deepest gravitational wells (Livio, 1998). On the other hand, Meier et al. (1997) propose that the velocity of the jets is regulated by a magnetic "switch", with highly relativistic velocities achieved only above a critical value of the ratio of the Alfvén velocity to the escape velocity. The determination of the mass of the collapsed object in the jet sources would discriminate between these two models.

While it seems that a steady state MHD model can account for the formation of continuous relativistic jets, the events discussed by Mirabel et al. (1998), Belloni et al. (1998), and Fender & Pooley (1998) that seem to involve a connection between the disappearance of the inner accretion disk and the sudden ejection of condensations may require a different mechanism. Clearly, the time seems to be ripe for new theoretical advances on the models of formation of relativistic jets that take into account the observational features found in stellar jets.

Another characteristic that the jet models must account for is the production of relativistic particles that will produce the synchrotron emission that is observed in several sources. As in other astrophysical contexts, it is believed that the acceleration of electrons to relativistic speeds takes place in shocks (Blandford & Ostriker 1978). On the other hand, most of the X-ray binaries are "radio-quiet", implying that relativistic electrons and/or magnetic fields are not always present in sufficient amounts.

7. SYNCHROTRON EMISSION

The high brigthness temperature, rapid variability, and linear polarization observed in the radio emission from X-ray binaries indicates a synchrotron origin. The time evolution of the radio emission has been modeled in terms of conical jets or expanding clouds of magnetized plasma (Hjellming & Johnston 1988; Martí et al. 1992; Seaquist 1993).

In the simplest case of an adiabatically expanding spherical cloud in the optically-thin regime, the van der Laan (1966) model is used, where the flux density is given by $S_\nu \propto \nu^{(1-p)/2}\ r^{-2p}$, and the relativistic electrons have an energy distribution given by $N(E) = KE^{-p}$, with K being a constant that is related to the density of the relativistic electrons. In this equation r is the radius of the cloud. Assuming that the cloud expands linearly with time, the flux density is given by $S_\nu \propto \nu^{(1-p)/2}\ r^{-2p}$. Assuming a typical value of $p = 2.4$, one obtains $S_\nu \propto \nu^{-0.7}\ t^{-4.8}$. This simple model fits the flux decrease reasonably well for several of the radio-emitting X-ray binaries (Ball 1996). However, in some of the best studied jet sources (SS 443, Hjellming & Johnston 1988, Vermeulen et al 1993; GRS 1915+105, Rodríguez & Mirabel 1999a), much less steep decreases are observed. This situation can be accounted for by making modifications to the simple expanding model. One possibility is to attribute this shallower drop of flux density with time to constrained expansion (the source cannot expand in 3 dimensions but only in 1 or 2 dimensions). In fact, the GRS 1915+105 maps with milliarcsec resolution by Dhawan et al. (1999) show that the expansion of the clouds at hundreds of AU from the compact source is mostly in one direction. The flux density can be then approximately described as $S_\nu \propto \nu^{-0.7}\ t^{-(2/3)pn}$, where n is the number of dimensions where expansion is allowed. Both in SS 433 (Hjellming & Johnson 1988) and in GRS 1915+105 (Rodríguez & Mirabel 1999a), a break in the power law that describes the decrease in flux as a function of time is observed. Remarkably, in both sources the decrease close to the source can be described with $S_\nu \propto t^{-1.3}$, while after a distance of $\sim 2 \times 10^{17}$ cm, $S_\nu \propto t^{-2.6}$ is observed. Hjellming & Johnson (1988) have proposed that these power laws can be explained as a result of an initial slowed expansion followed by free expansion in two dimensions. This steepening of the decrease in flux density with angular separation could be related to the similar tendency observed in the jets of some radio galaxies, where the intensity I declines with angular distance ϕ as $I_\nu \propto \phi^{-x}$, with x = 1.2-1.6 in the inner regions and x ~4 in the outer regions of the jet (Bridle & Perley 1984).

It is also possible that continued injection of relativistic particles and/or magnetic field into the emitting plasma can produce shallower decreases with time of the flux density (Mirabel et al. 1998). The particle injection could result from in situ acceleration as the moving gas shocks and entrains ambient gas or could result from beams or winds from the central energy source. The optically thick rise occurs very rapidly and has yet to be observed in detail for a proper comparison with the theoretical expectations.

It is possible to estimate the parameters of the ejected condensations using the formulation of Pacholczyk (1970) for minimum energy, correcting for relativistic effects and integrating the radio luminosity over the observed range of frequencies. Rodríguez & Mirabel (1999a) estimate for the bright 1994 March 19 event in GRS 1915+105 a magnetic field of about 50 mGauss and an energy of about 4×10^{43} ergs in the relativistic electrons. Assuming that there is one (non-relativistic) proton per (relativistic) electron one gets a proton mass estimate in the order of 10^{23} g. To estimate the peak mechanical power during the ejection we need a value for the time over which the acceleration and ejection took place. Mirabel & Rodríguez (1994) conservatively estimate that the ejection event must have lasted ≤ 3 days, requiring a minimum power of $\sim 5 \times 10^{38}$ erg s^{-1}, a value comparable with the maximum observed steady photon luminosity of GRS 1915+105, which is $\sim 3 \times 10^{38}$ erg s^{-1} (Harmon et al. 1994).

The ejection events that preceded and followed the 1994 March 19 outburst are estimated to have masses in the order of 10^{21-22} g. Finally, if the repetitive events observed with periods of tens of minutes in GRS 1915+105 (Rodríguez & Mirabel 1997; Pooley & Fender 1997; Mirabel et al. 1998; Eikenberry et al. 1998a) are interpreted as mini-ejection episodes, the mass associated with them is of order 10^{19} g. We crudely estimate that, on the average, GRS 1915+105 injects energy in the order of 10^{23} g per year in the form of relativistic (0.92c0.98c), collimated outflows. This corresponds to an average mechanical energy of $L_{mech} \sim 10^3 L_\odot$. In contrast, SS 433 as a result of its more continuous jet flow, has $L_{mech} \sim 10^5 L_\odot$ (Margon 1984) despite having a lower flow velocity than GRS 1915+105. The GRS 1915+105 bursts are thus very energetic but more sporadic.

Recently, there has been evidence that during some events the synchrotron emission in GRS 1915+105 extends from the radio into at least the near-infrared (Mirabel et al. 1998; Fender & Pooley 1997). Then the synchrotron luminosity becomes significant, reaching values of 10^{36} erg s^{-1}.

As emphasized by Hjellming & Han (1995), relativistic plasmas are difficult to confine and synchrotron radiation sources in stellar environments will tend to be variable in time. Then, one of the behaviors most difficult to account for is the relative constancy of the radio flux in some sources, of which Cyg X-1 is the extreme example. The presence of a steady outflow that is too faint to be followed up in time as synchrotron-emitting ejecta could be consistent with the lack of large variability in this type of source.

8. POSSIBLE LABORATORIES FOR GENERAL RELATIVITY

The X-ray power of the superluminal sources exhibits a large variety of quasi-periodic oscillations (QPOs) of high frequency. Of particular interest is the class of fast oscillations with a maximum stable frequency of 67 Hz observed many times in GRS 1915+105, irrespective of the X-ray luminosity of the source (Morgan et al. 1997). A QPO with maximum fix frequency of 300 Hz has been observed in GRO J1655-40 (Remillard et al. 1998). These stable maximum frequencies are not seen at times of strong radio flares or jet injection. They are believed to be a function of the fundamental properties of the black holes, namely, their mass and spin.

One possible interpretation is that these frequencies correspond to the last stable circular orbit around the black hole. This frequency depends on the black hole's mass and spin, as well as on the rotation direction of the accretion disk, and offers the prospect of inferring the spin of black holes with masses independently determined. Since from optical observations the mass of the hole in GRO J1655-40 is known to be in the range of 4-7 solar masses, one can conclude that GRO J1655-40 contains a Kerr black hole rotating at $\geq 70\%$ of the maximum spin possible (Zhang et al. 1997).

Alternatively, the maximum QPO stable frequency could be related to general relativity disk seismology, more specifically, to the maximum radial epicyclic frequency (Nowak et al. 1997), which also depends on the spin of the black hole.

A third interpretation has been proposed in terms of the relativistic dragging of the inertial frame around the spinning black hole (Cui et al. 1998). By comparing the computed disk precession frequency with that of the QPO, the spin can be derived if the mass is known. The two sources of sporadic superluminal jets are found to be the black holes that spin at rates close to maximum limit. Obviously, theoretical work to distinguish between these three alternative interpretations will be important to estimate the spin of the black holes with known masses.

X-ray spectroscopy of the two superluminal sources obtained with the satellite ASCA (Ebisawa 1996; Ueda, 1998) has shown K_α H and He like iron absorption lines, whereas the observations with SAX have only shown emission features from the relativistic accretion disk around 7 keV, which have been interpreted as iron lines (Matt et al. 1998). One expects that with greater sensitivity these lines will show a profile reminiscent of that of the asymmetric iron lines observed in Seyfert galaxies (Tanaka et al. 1995). The accretion disks of GRS 1915+105 and GRO J1655-40 are viewed obliquely, and the blueshifted side of the lines should look much stronger due to the Doppler beaming effect. In addition, the center of the line should be redshifted as expected from general relativity effects on radiation escaping from the surroundings of a strongly gravitating object. In the future, perhaps these lines could be used as probes of general relativity effects in the innermost parts of the accretion flows into black holes.

General relativity theory in weak gravitational fields has been successfully tested by observing in the radio the expected decay in the orbit of a binary pulsar, an effect produced by gravitational radiation damping (Taylor & Weisberg 1982). Observations of binary pulsars have also been used to constrain the nature of gravity in the strong-field regime (Taylor et al. 1992). Although the interpretation of the maximum stable frequency of the X-ray power spectrum in the superluminal sources is still uncertain, these frequencies are known to originate close to the horizon of the black hole, and perhaps they could be used in the future to test the physics of accretion disks and black holes in the strong field limit.

9. OTHER SOURCES OF RELATIVISTIC JETS IN THE GALAXY

In X-ray binaries there is a general correlation between the X-ray properties and the jet properties. The time interval and flux amplitude of the variations in radio waves seems to correspond to the time and amplitude variations in the X-ray flux. More specifically, persistent X-ray sources are also persistent radio sources, and the transient X-ray sources produce at radio waves sporadic outburst/ejection events. Persistent sources of hard X-rays (e.g. 1E1740.7-2942, GRS 1758-258) are usually associated to faint, double-sided radio structures that have sizes of several arcmin (parsec scales). The radio core of these two persistent sources are weak ($\leq$ 1 mJy) and do not exhibit high amplitude variability. On the contrary, rapidly variable hard X-ray transients (e.g. GRS 1915+105, GRO J1655-40, XTE J1748-288) may exhibit variations in the X-rays and radio fluxes of several orders of magnitude in short intervals of time. Because these black-hole X-ray transients produce sporadic ejections of discrete, bright plasma clouds, the proper motions of the ejecta can be measured.

Conservation of angular momentum in accretion disks indicates that probably all hard X-ray sources that accrete at super-Eddington rates must produce relativistic jets. However, the observational study of these jets presents in practice several difficulties. Persistent hard X-ray sources like Cygnus X-1 are surrounded by faint non-thermal radio features extending several arcmin (Martí et al. 1996), and even in the cases where they are well aligned with the variable compact radio counterpart it is very difficult to prove conclusively that the faint and extended radio features are actually associated with the X-ray source. This was the case of Sco X-1, where possible large-scale radio "lobes" were found to be extragalactic sources symmetrically located in the plane of the sky with respect to Sco X-1 (Fomalont & Geldzahler 1991). On the other hand, in transient black hole binaries one may observe transient sub-arcsec jets, but unless the interferometric observations are conveniently scheduled, the evolution is too rapid and it may not be possible to follow up the proper motions of discrete clouds. This may have been the case in the radio observations of the X-ray sources Nova Oph 93 (Dela Valle, Mirabel, & Rodríguez 1994) and Nova Muscae (Ball et al. 1995), among others.

We list in Table 1 the 10 sources of relativistic jets in the Galaxy known so far. The first six are transients, whereas the next three are persistent X-ray sources. Proper motions of the relativistic ejecta have been determined with accuracy in GRS 1915+105, GRO J1655-40, XTE J1748-288, and SS 433. Besides these four sources, proper motions were also measured -but with less accuracy- for moving features in Cygnus X-3 (Schalinski et al. 1995, Martí et al. 1999), Circinus X-1 (Fender et al. 1998), and CI Cam (XTE J0421+560; Hjellming & Mioduszewski 1998; Mioduszewski et al. 1998). It is interesting that the ejecta from the black hole binaries GRS 1915+105, GRO J1655-40, and probably also XTE J1748-288 have velocities greater than 0.9c, while the ejecta from the four sources believed to be neutron star binaries have velocities $\leq$0.3c. From their models of magnetically driven jets, Kudoh & Shibata (1995) have proposed that jet velocities such as those listed in Table 1 are comparable to the Keplerian rotational velocities expected at the base of the jets, close to neutron stars and black holes, respectively. Livio (1998) has also stressed the similarity between the velocity of jets and the escape velocity of the gravitational well from where they were ejected. If this notion is confirmed, jet velocities could then be used to discriminate between neutron stars and black holes, with jet velocities close to the speed of light been produced only in black hole binaries.

Another possible source of relativistic jets in the Galaxy is, of course, Sgr A*, the presumed black hole of 2.5 million solar masses at the galactic center (Eckart & Genzel 1997). The radio source is always present at about the 1 Jy level and exhibits a flat spectrum with relative small variations, a behavior similar to that of the faint compact mJy radio sources associated with Cygnus X-1 (Martí et al. 1996) and GRS 1915+105 in its plateau state at times when no strong outburst/ejection events take place, a state that in the latter source can last from days to weeks (Pooley & Fender 1997). This type of radio emission could arise from a jet in a coupled jet-disk system (Falcke et al. 1993) or from electrons in an advection dominated flow (Narayan et al. 1998; Mahadevan 1998; Begelman and Blandford, 1999). Despite heavy interstellar scattering at radio wavelengths, recent VLBA observations at 7-mm may have resolved Sgr A* in an elongated radio source of 72 Schwarzschild radii suggesting the presence of a jet (Lo et al. 1998).

10. INTERACTION OF RELATIVISTIC JETS WITH THE ENVIRONMENT

If a compact source (black hole or neutron star) injects collimated relativistic jets into its cold environment, it is expected that some fraction of the injected power will be dissipated by shocks in the circumstellar gas and dust. The collision of relativistic ejecta with environmental material has been observed in real time in XTE J1748-288 (Hjellming et al. 1998), where the leading edge of the jet decelerates while strongly brightening. The interaction of the mildly relativistic jets from CI Cam (Hjellming & Mioduszewski, 1998) with an HII and dust shell nebula has been reported by García et al. (1998). Other signatures of the interaction of relativistic jets with the environment are the radio lobes of 1E 1740.7-2942 (Mirabel et al. 1992) and GRS 1758-258 (Rodríguez et al. 1992), the twisted arcmin jets of Circinus X-1 (Steward et al. 1993; Fender et al. 1998), and the two lateral extensions of tens of pc in the radio shell W50 that hosts at its center SS 433. The interaction of SS 433 with the nebula W50 has been studied in the X-rays (Brinkmann et al. 1996), infrared (Mirabel et al. 1996b), and radio wavelengths (Dubner et al. 1998 and references therein).

SS 433 is a high mass X-ray binary at a distance of $\sim$ 3 kpc near the centre of the radio shell W50 (Margon, 1984). The latter may be either the supernova remnant from the formation of the compact object (Velusamy & Kundu 1974), or a bubble evacuated by the energy outflow of SS 433 (Begelman et al. 1980). Besides the well known relativistic jets seen at sub-arcsec scales in the radio, large-scale jets become visible in the X-rays at distances $\sim$ 30 arcmin ($\sim$ 25 pc) from the compact source (Brinkmann et al. 1996). In the radio, the lobes reach distances of up to 1° ($\sim$50 pc). These large-scale X-ray jets and radio lobes are the result of the interaction of the mass outflow with the interstellar medium. From optical and X-ray emission lines it is found that the sub-arcsec relativistic jets have a kinetic energy of $\sim 10^{39}$ erg s^{-1} (Margon, 1984; Spencer, 1984), which is several orders of magnitude larger than the energy radiated in the X-rays and in the radio.

In Figure 8 is shown the λ20 cm map with 55 arcsec resolution by Dubner et al. (1998). It shows the connection between the subarcsec relativistic jets and the extended nebula over $\sim 10^5$ orders of magnitude in distance scales. Dubner et al. (1998) estimate that the kinetic energy transferred into the ambient medium is $\sim 2\ 10^{51}$ ergs, thus confirming that the relativistic jets from SS433 represent an important contribution to the overall energy budget of the surrounding nebula W50. Begelman et al. (1980) characterized W50 as a "beambag", interpreting the elongated shape and filled-in radio structure of W50 as evidence for continuing injection of magnetic field and high-energy particles from SS433.

Evidences for the interaction of jets with the environmental medium have also been searched in the two superluminal sources. In GRS 1915+105 Chaty, Rodríguez & Mirabel (1999) searched at millimeter, infrared, and X-rays for evidences of the physical association between the relativistic jets and two IRAS sources projected symmetrically on each side at $\sim$15 arcmin of angular distance from the compact source that at first glance could be lobes caused by the impact of the jets in interstellar molecular clouds (Rodríguez & Mirabel, 1999b). Besides the good alignment of the IRAS sources with the subarcsec jets and the presence of an intriguing non-thermal jet-like source in the SE IRAS source (Rodríguez & Mirabel, 1999b), no conclusive physical evidence for association with GRS 1915+105 has been found, with the IRAS sources most probably being normal HII regions. On the other hand, Hunstead et al. (1998) find regions of extended low-surface-brightness emission aligned with the radio jets of GRO J1655-40, but their real association with the high energy source have not been confirmed. The jets in GRS 1915+105 and GRO J1655-40 are faster than those in SS 433, but much more sporadic, and this probably accounts for the lack of obvious lobes associated with them.

It has been proposed that the interaction of relativistic jets with the environment may induce high energy radiation. Positrons released impulsively from the compact source could annihilate locally in the hot plasma producing a broad 511 keV spectral feature (Sunyaev et al. 1991; Ramaty et al. 1992). Alternatively, a fraction of the positrons could stream up to the interstellar gaseous environment, slowing down and annihilating in such cold medium, thus emitting 511 keV narrow line emission, inducing radio lobe synchrotron emission and bremsstrahlung gamma-ray continuum emission (Laurent & Paul 1994).

11. MICROBLAZARS AND GAMMA-RAY BURSTS

It is interesting that in all three sources where θ (the angle between the line of sight and the axis of ejection) has been determined, a large value is found (that is, the axis of ejection is close to the plane of the sky). These values are $\theta \simeq 79^\circ$ (SS 433; Margon 1984), $\theta \simeq 66^\circ - 70^\circ$ (GRS 1915+105; Mirabel & Rodríguez 1994; Fender et al. 1999), $\theta \simeq 85^\circ$ (GRO J1655-40; Hjellming & Rupen 1995), and $\theta \geq 70^\circ$ for the remaining sources. This result is not inconsistent with the statistical expectation since the probability of finding a source with a given θ is proportional to $sin\ \theta$. We then expect to find as many objects in the $60^\circ \leq \theta \leq 90^\circ$ range as in the $0^\circ \leq \theta \leq 60^\circ$ range. However, this argument suggests that we should eventually detect objects with a small θ. For objects with $\theta \leq 10^\circ$ we expect the timescales to be shortened by 2γ and the flux densities to be boosted by $8\gamma^3$ with respect to the values in the rest frame of the condensation. For instance, for motions with v = 0.98c ($\gamma = 5$), the timescale will shorten by a factor of ∼10 and the flux densities will be boosted by a factor of $\sim 10^3$. Then, for a galactic source with relativistic jets and small θ we expect fast and intense variations in the observed flux. These microblazars may be quite hard to detect in practice, both because of the low probability of small θ values and because of the fast decline in the flux.

Gamma-ray bursts are at cosmological distances and ultra-relativistic bulk motion and beaming appear as essential ingredients to solve the enormous energy requirements. Beaming reduces the energy release by the beaming factor f $= \Delta\Omega/4\pi$, where $\Delta\Omega$ is the solid angle of the beamed emission. Additionally, the photon energies can be boosted to higher values. Extreme collimated flows from collapsars with bulk Lorentz factors > 100 have been proposed as sources of γ-ray bursts (e.g. Dar 1998; Mészáros & Rees 1997; Fargion, 1998). Because the jets are highly directional, the properties of the bursts will depend on the viewing angle relative to the rotation axis. In this context, the study of less extreme collimated flows in our own Galaxy may provide clues for a better understanding of the super-relativistic jets associated to the more distant γ-ray bursters. Of particular interest are the afterglow phenomena recently observed in microquasars that may result from internal shocks in the jets or from the impact of these jets in the environmental interstellar matter. However, γ-ray bursters are different to the microquasars found so far in our own Galaxy. The former do not repeat and seem to be related to catastrophic events, and have much larger super-Eddington luminosities. Therefore, the scaling laws in terms of the black hole mass that are valid in the analogy between microquasars and quasars do not apply in the case of γ-ray bursters.

12. CONCLUSIONS AND PERSPECTIVES

The study of relativistic jets from X-ray binaries in our own galaxy sets on a firmer basis the relativistic ejections seen elsewhere in the Universe. The analogy between quasars and microquasars lead to the discovery of superluminal sources in our own galaxy, where it is possible to follow the motions of the two-sided ejecta. This permits to overcome the ambiguities that had dominated the physical interpretation of one-sided moving jets in quasars, and conclude that the ejecta consist mainly of matter moving with relativistic bulk motions, rather than waves propagating through a slowly moving jet. The Lorentz factors of the bulk motions in the jets from microquasars seem to be similar to those believed to be common in quasars. From the study of the two-sided moving jets in one microquasar, an upper limit for the distance to the source was derived, using constraints from special relativity.

Because of the relative short timescales of the phenomena associated with the flows of matter around stellar mass black holes, one can sample phenomena that we have not been able to observe in quasars. Of particular importance is to understand the connection between accretion flow instabilities observed in the X-rays, with the ejection of relativistic clouds of plasma observed in the radio, infrared, and possibly in the optical. The detection of synchrotron infrared flares implies that the ejecta in microquasars contain very energetic particules with Lorentz factors of at least 10^3.

The discovery of microquasars opens several new perspectives that could prove to be particularly productive:

1. They provide a new method to determine distances using special relativity constraints. If the proper motions of the two-sided ejecta and the Doppler factor of a spectral line from one ejecta are measured, the distance to the source can be derived. With the rapid advance of technological capabilities in astronomy, this relativistic method to determine distances may be applied first to black hole jet sources in galactic binaries, and in the decades to come to quasars.

2. Microquasars are nearby laboratories that can be used to gain a general understanding of the mechanism of ejection of relativistic jets. The multiwavelength observations of GRS 1915+105 during large-amplitude oscillations suggest that the clouds are ejected during the replenishment of the

inner accretion disk that follows its sudden dissappearance beyond the last stable orbit around the black hole. In the context of these new data, the time seems to be ripe for new theoretical advances on the models of formation of relativistic jets.

3. High sensitivity X-ray spectroscopy of jet sources with future X-ray space observatories may clarify the phenomena in accretion disks that are associated to the formation of jets.

4. More microquasars will be discovered in the future. Among them, microblazars should appear as sources with fast and large amplitude variations in the observed flux. Depending on the beaming angle and bulk Lorentz factor they will be observed up to very high photon energies.

5. The spin of stellar mass black holes could be derived from the observed maximum stable frequency of the QPOs observed in the X-rays, provided the mass has been independently determined. However, theoretical work is needed to distinguish between the alternative interpretations that in the context of general relativity have been proposed for the maximum stable frequency of QPOs.

6. Finally, microquasars could be test grounds for general relativity theory in the strong field limit. General relativity theory in weak gravitational fields has been successfully tested by observing in the radio wavelengths the expected decay in the orbit of a binary pulsar, an effect produced by gravitational radiation damping. We expect that phenomena observed in microquasars could be used in the future to investigate the physics of strong field relativistic gravity near the horizon of black holes.

ACKNOWLEDGEMENTS

We are most grateful to Vivek Dhawan for permission to include in this review unpublished results from our VLBA observations, and to Sylvain Chaty and Josep Martí for help in producing Figure 7. We thank Ralph Spencer, Jacques Paul, Josep Martí, and Alan Harmon for comments on the original manuscript. We are also greateful to Philippe Durouchoux for the organization of the workshop on *Relativistic Jet Sources in the Galaxy* held in Paris on December 12-13, 1998, from which we have benefitted. During this work, LFR received partial support from CONACyT, México and DGAPA, UNAM.

Figure Captions

Figure 1. Contour map of the 6-cm emission from the radio counterpart of 1E1740.7-2942, as observed with the Very Large Array (Mirabel et al. 1992; Rodríguez & Mirabel 1999c). The error circle of the ROSAT position (Heindl, Prince, & Grunsfeld 1995), that includes the core source, is also shown. At a distance of 8 kpc the length of the jet structure would be ~5 pc. The half power contour of the beam is shown in the top left corner. Contours are -4, 4, 5, 6, 8, 10, 12, 15, and 20 times 28 μJy beam^{-1}.

Figure 2. Pair of radio condensations moving away from the hard X-ray source GRS 1915+105 (Mirabel and Rodríguez, 1994). These uniform-weight VLA maps were made at λ3.5-cm for the 1994 epochs on the right side of each map. The position of the stationary core is indicated with a small cross. The maps have been rotated 60° clockwise for easier display. The cloud to the left appears to move away from the stationary core at 125% the speed of light. Contours are 1, 2, 4, 8, 16, 32, 64, 128, 256 and 512 times 0.2 mJy/beam for all epochs except for March 27 where the contour levels are in units of 0.6 mJy/beam. The half power beam width of the observations, 0.2 arc sec, is shown in the top right corner.

Figure 3. Angular displacements as a function of time for four ejection events observed in 1994 in GRS 1915+105 (Rodríguez & Mirabel 1999a). Top: Angular displacements as a function of time for four approaching condensations corresponding to ejections that took place on (from left to right) 1994 January 29 (triangles), February 19 (squares), March 19 (circles), and April 21 (crosses). Bottom: Angular displacements as a function of time for three receding condensations corresponding to ejections that took place on (from left to right) 1994 February 19 (squares), March 19 (circles), and April 21 (crosses). The clouds of the 1994 January 29 ejection were relatively weak and the receding component could not be detected unambiguously. The dashed lines are the least squares fit to the angular displacements of the 1994 March 19 event, the brighter and better studied. Note that the motions appear to be ballistic (that is, unaccelerated).

Figure 4. Contour map of the 2-cm emission from the core of GRS 1915+105, as observed on April 11, 1997 with the Very Long Baseline Array at milliarcsecond angular resolution (Dhawan, Mirabel and Rodríguez 1999). The angular resolution corresponds to about 10 AU at GRS 1915+105. The half power contour of the

beam is shown in the bottom left corner. Contours are -1, 1, 2, 4, 8, 16, 32, 64, and 96 times 0.26 mJy beam^{-1}. The position angle of this ejection at milliarcsec scale, is the same as that seen at the arcsec scales three years before.

Figure 5. A sequence of seven VLBA images of GRO J1655–40 at 1.6 GHz, each rotated anticlockwise by 43°, and each having an angular resolution of 3.0×0.4 arcsec (Hjellming & Rupen 1995). Each image is labeled with the date of the observations. The solid lines between images identify motions of 54 mas day^{-1} (left) and 45.5 mas day^{-1} (right). The vertical line marks the position of the central source, assumed to be the brightest point on each image.

Figure 6. Geometry of the two-sided ejection. The emission is symmetric, but when the emitting clouds move at relativistic speeds the approaching component of the pair appears to move faster and to be brighter than the receding component.

Figure 7. Radio, infrared, and X-ray light curves for GRS 1915+105 at the time of quasi-periodic oscillations on 1997 September 9 (Mirabel et al. 1998). The infrared flare starts during the recovery from the X-ray dip, when a sharp, isolated X-ray spike is observed. These observations show the connection between the rapid disappearance and follow-up replenishment of the inner accretion disk seen in the X-rays (Belloni et al. 1997), and the ejection of relativistic plasma clouds observed as synchrotron emission at infrared wavelengths first and later at radio wavelengths. A scheme of the relative positions where the different emissions originate is shown in the top part of the figure. The hardness ratio (13-60 keV)/(2-13 keV) is shown at the bottom of the figure.

Figure 8. Very Large Array continuum mosaic of W50 at 1.5 GHz (Dubner et al. 1998). The radio counterpart of SS433 is the bright unresolved source at the center of the image. The lateral E-W extension of the nebula over $\sim1^\circ$ ($\sim$50 pc) is caused by the injection of the relativistic jets from SS433. The greyscale varies from 1 to 25 mJy beam^{-1}. The angular resolution is 56×54 arcsec.

Literature Cited

Ables, JG. 1969, *Proc. Astron. Soc. Australia* 1: 237-40

Abramowicz, MA, Chen, X, Kato, S, Lasota, JP, Reguev, O. 1995, *Ap. J.* 438: L37-40

Atoyan, AM, Aharonian, FA. 1997, *Ap. J.* 490: L149-52

Ball, L, Kesteven, MJ, Campbell-Wilson, D, Turtle, AJ, Hjellming, RM. 1995, *MNRAS* 273: 722-30

Ball, L. 1996, in *Radio Emission from the Stars and the Sun, ASP Conf. Ser.* 93: 219-27

Ballet, J. et al. 1994, *AIP Conference Proceedings* 308: 131-34

Barret, D, McClintock, JE, Grindlay, JE. 1996, *Ap. J.* 473: 963-73

Begelman, MC. 1998, *Ap. J.* 493: 291-300

Begelman, MC, Blandford, RD. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Begelman, MC, Hatchett, SP, McKee, CF, Sarazin, CL, Arons, J. 1980, *Ap. J.* 238: 722-30

Belloni, T, Méndez, M, King, AR, van der Klis, M, van Paradijs, J. 1997, *Ap. J.* 479: L145-48

Blandford, RD, Ostriker, JP. 1978, *Ap. J.* 221: L29-32

Blandford, RD, Payne, DG. 1982, *MNRAS* 199: 883-94

Blandford, RD, Znajek, RL. 1977, *MNRAS* 179: 433-40

Bodo, G, Ghisellini, G. 1995, *Ap. J.* 441: L69-71

Bridle, AH, Perley, RA. 1984, *Annu. Rev. Astr. Astrophys.* 22: 319-58

Brinkmann, W, Aschenbach, B, Kawai, N. 1996, *Astron. Astrophys.* 312: 306-16

Castro-Tirado, AJ, Brandt, S, Lund, N, Lapshov, I, Sunyaev, RA, et al. 1994, *Ap. J. Suppl.* 92: 469-72

Castro-Tirado, AJ, Geballe, TR, Lund, N. 1996, *Ap. J.* 461: L99-102

Chaty, S, Mirabel, IF, Duc, PA, Wink, JE, Rodríguez, LF. 1996, *Astron. Astrophys.* 310: 825-30

Chaty, S, Mirabel, IF, Rodríguez, LF. 1999, in preparation

Chen, X, Swank, JH, Taam, RE. 1997, *Ap. J.* 477: L41-44

Churazov, E, Gilfanov, M, Sunyaev, R, Khavenson, N, Novikov, B, et al. 1994, *Ap. J. Suppl.* 92: 381-85

Cordier, B, Paul, J, Ballet, J, Goldwurm, A, Bouchet, L, et al, 1993, *Astron. Astrophys.* 275, L1-4

Cowley, AP, Schmidthe, PC, Crampton, D, Hutchings, JB. 1998, *Ap. J.* 504: 854-65

Cui, W, Zhang, SN, Chen, W. 1998, *Ap. J.* 492: L53-56

Curtis, HD. 1918, *Publ. Lick Obs.* 13: 9-42

Dar, A. 1998, *Ap. J.* 500: L93-96

Dela Valle, M, Mirabel, IF, Rodríguez, LF. 1994, *Astron. Astrophys.* 290: 803-06

Dhawan, V, Mirabel, IF, Rodríguez, LF. 1999, in preparation

Djorgovski, S, Thompson, D, Mazzarella, J, Klemola, A, Neugebauer, G. 1992, *IAU Circular 5596*

Dubner, GM, Holdaway, M. Goss, WM, Mirabel, IF. 1998, *Astron. J.* 116: 1842-55

Ebisawa, K. 1996, in *X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas*, ed. F. Makino & K. Mitsuda, Tokyo: University Academy Press, 427-31

Eckart, A, Genzel, R. 1997, *MNRAS* 284: 576-98

Eikenberry, SS, Matthews, K, Morgan, EH, Remillard, RA, Nelson, RW. 1998a, *Ap. J.* 494: L61-64

Eikenberry, SS, Matthews, K, Murphy, TW, Nelson, RW, Morgan, EH, Remillard, RA, Muno, M. 1998b, *Ap. J.* 506: L31-34

Fabian, AC, Rees, MJ. 1979, *MNRAS* 187: 13p-16p

Falcke, H, Mannheim, K, Biermann, PL. 1993, *Astron. Astrophys.* 278: L1-4

Fargion, D. 1998, astro-ph/9808005

Fejes, I. 1986, *Astron. Astrophys.* 168: 69-71

Fender, RP, Bell Burnell, SJ, Williams, PM, Webster, AS. 1996, *MNRAS* 283: 798-804

Fender, RP, Garrington, ST, McKay, DJ, Muxlow, TWB, Pooley, GG, Spencer, RE, Stirling, AM, Waltman, EB. 1999, *MNRAS* in press

Fender, RP, Pooley, GG. 1998, *MNRAS* 300: 573-76

Fender, RP, Pooley, GG, Brocksopp, C, Newell, SJ. 1997, *MNRAS* 290: L65-69

Fender, RP, Spencer, R, Tzioumis, T, Wu, K. et al. 1998, *Ap. J.* 506: L121-125

Finogenov, A. et al. 1994, *Ap. J.* 424: 940-42

Fomalont, EB, Geldzahler, BJ. 1991, *Ap. J.* 383: 289-94

Foster, RS, Waltman, EB, Tavani, M, Harmon, BA, Zhang, SN, et al. 1996, *Ap. J.* 467: L81-84

García, MR et al. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.*

Paris, December 12-13, 1998

Ghosh, P, Abramowicz, MA. 1997, *American Astron. Soc.* 191, 66

Gilmore, WS., Seaquist, ER. 1980, *Astron. J.* 85: 1486-95

Gilmore, WS., Seaquist, ER, Stocke, JT, Crane, PC. 1981, *Astron. J.* 86: 864-70

Greiner, J, Morgan, EH, Remillard, RA. 1996, *Ap. J.* 473: L107-10

Grove, JE, Johnson, WN, Kroeger, RA, McNaron-Brown, K, Skibo, JG, et al. 1998, *Ap. J.* 500: 899-908

Hameury, JM, Lasota, JP, McClintock, JE, Narayan, R. 1997, *Ap. J.* 489: 234-43

Harmon, BA, Deal, KJ, Paciesas, WS, Zhang, SN, Gerard, E, Rodríguez, LF, Mirabel, IF. 1997, *Ap. J.* 477: L85-90

Harmon, BA, Zhang, SN, Wilson, CA, Rubin, BC, Fishman, GJ, et al. 1994, in *AIP Conference Proceedings No. 304* eds. Fichtel, CE, Gehrels, N, Norris, JP. (AIP: New York), 210-19

Heindl, WA, Prince, TA, Grunsfeld, JM. 1995, *Ap. J.* 430: 829-33

Hjellming, RM, Han, X. 1995, in *X-Ray Binaries (Cambridge University Press: Cambridge)*, p. 308

Hjellming, RM, Johnston, KJ. 1981, *Ap. J.* 246: L141-45

Hjellming, RM, Johnston, KJ. 1988, *Ap. J.* 328: 600-09

Hjellming, RM, Mioduszewski, AM. 1998, *IAU Circular 6872*

Hjellming, RM, Rupen, MP. 1995, *Nature* 375: 464-67

Hjellming, RM, Rupen, MP, Mioduszewski, AM, et al. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Hunstead, RW, Wu, K, Campbell-Wilson, D. 1998, in preparation

Kalogera, V, Baym, G. 1996, *Ap. J.* 470: L61-64

King, A. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Koide, S., Shibata, K., Kudoh, T. 1998, *Ap. J.* 495: L63-66

Kudoh, T. & Shibata, K. 1995, *Ap. J.* 452: L41-44

Kuznetsov, S, Gilfanov, M, Churazov, E, Sunyaev, R, Korel, I, et al. 1997, *MNRAS* 292: 651-56

Laurent, P, Paul, J. 1994, *Ap. J. Suppl.* 92: 375-79

Livio, M. 1998 in *Accretion Flows and Related Phenomena* IAU Colloquium 163, eds. Wickramasinghe, D, Ferrario, L, Bicknell, G. in press

Livio, M., Ogilvie, GI, Pringle, JE. 1998, *Ap. J.* in press

Lo, KY, Shen, ZQ, Zhao, JH, Ho, PTP. 1998, *Ap. J.* 508, L61-64

López, JA. 1997, *Planetary Nebulae*, IAU Symposium No. 180 pp. 197-203, eds. H.J. Habing & H.J.G.L.M. Lamers, Kluwer.

Lucek, SG, Bell, AR. 1997, *MNRAS* 290, 327-33

Mahadevan, R. 1998, *Nature* 394: 651-53

Margon, BA, Stone, RPS, Klemola, A, Ford, HC, Katz, JI, et al. 1979, *Ap. J.* 230: L41-45

Margon, BA. 1984, *Annu. Rev. Astr. Astrophys.* 22: 507-36

Martí, J, et al. 1999, in preparation

Martí, J, Mereghetti S, Chaty, S, Mirabel, IF, Goldoni, P, et al. 1998, *Astron. Astrophys.* 338: L95-99

Martí, J, Paredes, JM, Estalella, R. 1992, *Astron. Astrophys.* 258: 309-15

Martí, J, Rodríguez, LF, Mirabel, IF, Paredes, JM. 1996, *Astron. Astrophys.* 306: 449-54

Matt, G. et al. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Meier, DL, Edgington, S, Godon, P, Payne, DG, Lind, KR. 1997, *Nature* 388: 350-52

Mészáros, P, Rees, MJ. 1997, *Ap. J.* 482: L29-32

Milgrom, M. 1979, *Astron. Astrophys.* 79: L3-6

Mioduszewski, AM. et al. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Mirabel, IF, Bandyopadhyay, R, Charles, PA, Shahbaz, T, Rodríguez, LF. 1997, *Ap. J.* 477: L45-48

Mirabel, IF, Claret, A, Cesarsky, CJ, Cesarsky, DA, Boulade, O. 1996b, *Astron. Astrophys.* 315: L113-16

Mirabel, IF, Dhawan, V, Chaty, S, Rodríguez, LF, Robinson, C, Swank, J, Geballe, T. 1998, *Astron. Astrophys.* 330: L9-12

Mirabel, IF, Duc, P-A, Rodríguez, LF. et al. 1994, *Astron. Astrophys.* 282: L17-20

Mirabel, IF, Rodríguez, LF. 1994, *Nature* 371: 46-48

Mirabel, IF, Rodríguez, LF. 1998, *Nature* 392: 673-76

Mirabel, IF, Rodríguez, LF, Chaty, S, Sauvage, M, Gerard, E, et al. 1996a, *Ap. J.* 472: L111-14

Mirabel, IF, Rodríguez, LF, Cordier, B, Paul, J, Lebrun, F. 1992, *Nature* 358:

215-17

Mirabel, IF, Rodríguez, LF, Cordier, B, Paul, J, Lebrun, F. 1993, in *Sub-arcsecond Radio Astronomy*, eds. RJ Davis & RS Booth, Cambridge University Press, 47-49

Morgan, EH, Remillard, RA, Greiner, J. 1997, *Ap. J.* 482: 993-1010

Motch, C. 1998, *Astron. Astrophys.* 338: L13-16

Narayan, R, García, MR, McClintock, JE. 1997, *Ap. J.* 478: L79-82

Narayan, R, Mahadevan, R, Grindlay, JE, Popham, RG, Gammie, C. 1998, *Ap. J.* 492: 554-68

Nowak, MA, Wagoner, RV, Begelman, MC, Lehr, DE. 1997, *Ap. J.* 477: L91-94

Orosz, JA, Bailyn, CD. 1997, *Ap. J.* 477: 876-96

Orosz, JA, Remillard, RA, Bailyn, CD, McClintock, JE. 1997, *Ap. J.* 478: L83-86

Pacholczyk, AG. 1970, *Radio Astrophysics*, Freeman, San Francisco

Paragi, Z, Vermeulen, RC, Fejes, I, Schilizzi, RT, Spencer, RE, Stirling, AM. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Paul, J. et al. 1991, in *Advances in Space Research*, 11: 8289-302

Pearson, TJ, Zensus, JA. 1987, in *Superluminal Radio Sources, Cambridge University Press*, eds. Zensus, J. A. & Pearson, T. J., p. 1

Peebles, PJE. 1993, *Principles of Physical Cosmology*, Princeton University Press, Princeton

Penrose, R. 1969, *Nuovo Cimento* 1, 252-76

Phillips, SN, Shahbaz, T, Podsiadlowski, Ph. 1999, *MNRAS*, in press

Pooley, GG, Fender, RP. 1997, *MNRAS* 292: 925-33

Ramaty, R, Leventhal, M, Chan, KW, Lingenfelter, RE. 1992, *Ap. J.* 392: L63-67

Rees, MJ. 1966, *Nature* 211: 468-70

Rees, MJ. 1982, *The Galactic Center* AIP: New York, pp 166-76

Rees, MJ. 1984, *Annu. Rev. Astr. Astrophys.* 22, 471-506

Rees, MJ. 1998, in *Black Holes and Relativistic Stars*, ed. Wald, RM, University of Chicago, 79-101

Reipurth, B., Bertout, C. 1997, *Herbig-Haro Flows and the Birth of Stars,* IAU Symposium No. 182 (Kluwer)

Remillard, RA, Morgan, EH, McClintock, JE, Bailyn, CD, Orosz, JA, et al. 1998, in *Proc. 18th Texas Symposium on Relativistic Astrophysics* eds. Olinto, A, Frieman, J, Schramm, D. (Singapore: World Scientific), in press

Rodríguez, L. F., Gerard, E. Mirabel, I. F., Gómez, Y., Velázquez, A., 1995, *Ap. J. Suppl.* 101: 173-79

Rodríguez, LF, Mirabel, IF. 1997, *Ap. J.* 474, L123-25

Rodríguez, LF, Mirabel, IF. 1999a, *Ap. J.* in press

Rodríguez, LF, Mirabel, IF. 1999b, *Astron. Astrophys.* 340: L47-50

Rodríguez, LF, Mirabel, IF. 1999c, in preparation

Rodríguez, LF, Mirabel, IF, Martí, J. 1992 *Ap. J.* 401: L15-18

Sams, BJ, Eckart, A, Sunyaev, R. 1996 *Nature* 382: 47-49

Scaltriti, F, Bodo, G, Ghisellini, G, Gliozzi, M, Trussoni, E. 1997, *Astron. Astrophys.* 327: L29-31

Schalinski, CJ, Johnston, KJ, Witzel, A, Spencer, RE, Fiedler, R, et al. 1995, *Ap. J.* 447: 752-59

Seaquist, ER. 1993, *Reports on Progress in Physics* 56: 1145-208

Smith, DA, Levine, A, Wood, A. 1998, *IAU Circular 6932*

Spencer, RE, 1979, *Nature* 282: 483-84

Spencer, RE, 1984, *MNRAS*, 209: 869-79

Spruit, H. C., Foglizzo, T., Stehle, R. 1997, *MNRAS* 288: 333-42

Stewart, RT, Caswell, JL, Haynes, RF, Nelson, GJ. 1993, *MNRAS* 261: 593-98

Sunyaev, R, Churazov, E, Gilfanov, M, et al. 1991, *Ap. J.* 383: L49-53

Tanaka, Y, Nandra, K, Fabian, AC, Inoue, H, Otani, C. et al. 1995, *Nature* 375: 659-61

Tanaka, Y, Shibazaki, N. 1996, *Annu. Rev. Astr. Astrophys.* 34: 607-44

Taylor, JH, Weisberg, JM. 1982, *Ap. J.* 253: 908-20

Taylor, JH, Wolszczan, A, Damour, T, Weisberg, JM. 1992, *Nature* 355: 132-36

Tingay, SJ, Jauncey, DL, Preston, RA, Reynolds, JE, Meier, DL, et al. 1995, *Nature* 374: 141-43

van der Laan, H. 1966, *Nature* 211: 1131-33

van Paradijs, J. 1995, in *X-Ray Binaries* (Cambridge University Press: Cambridge), p. 536

Velusamy, T, Kundu, MR. 1974, *Astron. Astrophys.* 32: 375-90

Vermeulen, RC, Schilizzi, RT, Spencer, RE, Romney, JD, Fejes, I. 1993, *Astron. Astrophys.* 270: 177-88

Ueda, Y. et al. 1998, in *Workshop on Relativistic Jet Sources in the Galaxy.* Paris, December 12-13, 1998

Zensus, JA. 1997, *Annu. Rev. Astr. Astrophys.* 35: 607-36

Zhang, SN, Mirabel, IF, Harmon, BA, Kroeger, RA, Rodríguez, LF, et al. 1997, *Proceedings of the Fourth Compton Symposium* ed. CD Dermer, MS Strickman, JD Kurfess, (AIP: New York), 141-62

Zhang, SN, Wilson, CA, Harmon, BA, Fishman, GJ, & Wilson, RB. 1994, *IAU Circular 6046*

Table 1 Sources of Relativistic Jets in the Galaxy[(1)]

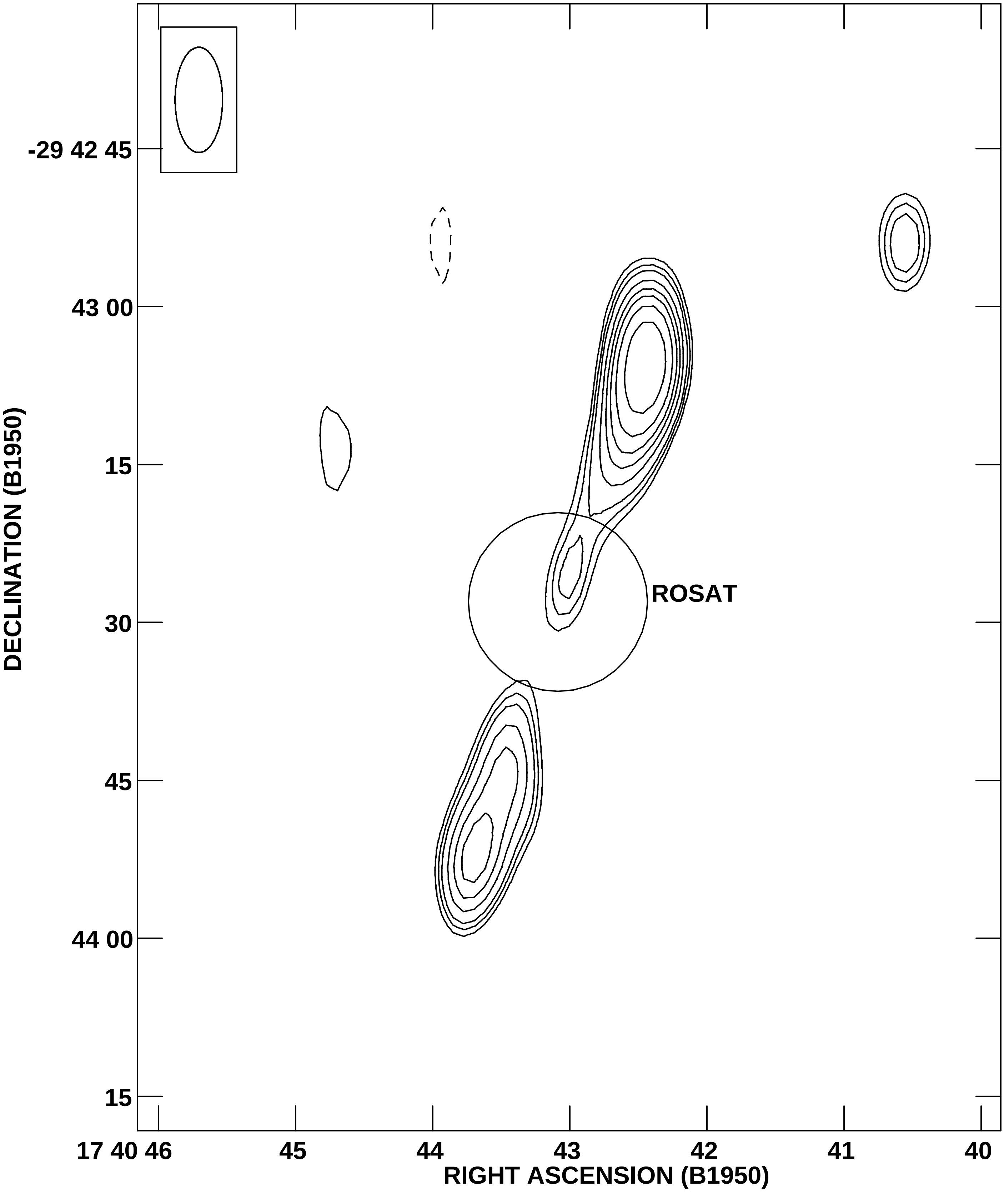
Source	Compact object	V_{app} [(2)]	V_{int} [(3)]	Θ [(4)]	References
GRS 1915+105	black hole	1.2c-1.7c	0.92c-0.98c	66°-70°	MR94; F+99; DMR99
GRO J1655-40	black hole	1.1c	0.92c	72°-85°	T+95; HR95; OB97
XTE J1748-288	black hole	0.9c-1.5c	>0.9c		H+98
SS 433	neutron star ?	0.26c	0.26c	79°	M84; S84
Cygnus X-3	neutron star ?	∼0.3c	∼0.3c	>70°	S+93; M+99
CI Cam	neutron star ?	∼0.15c	∼0.15c	>70°	M+98; G+98
Circinus X-1	neutron star	≥0.1c	≥0.1c	>70°	S+93; F+98
1E1740.7-2942	black hole				M+92; RM99c
GRS 1758-258	black hole				R+94
Sgr A*	black hole				L+98

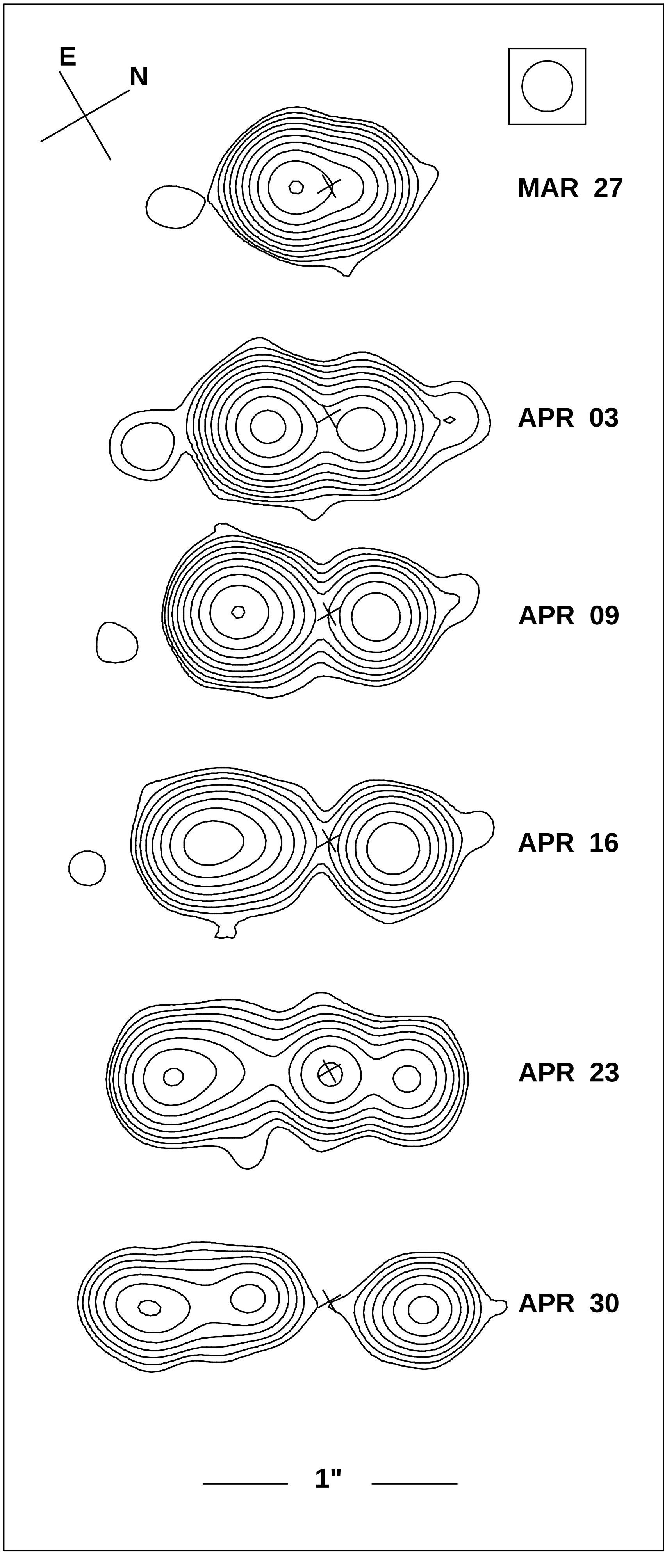
(1) Sources reported as of December 1998.

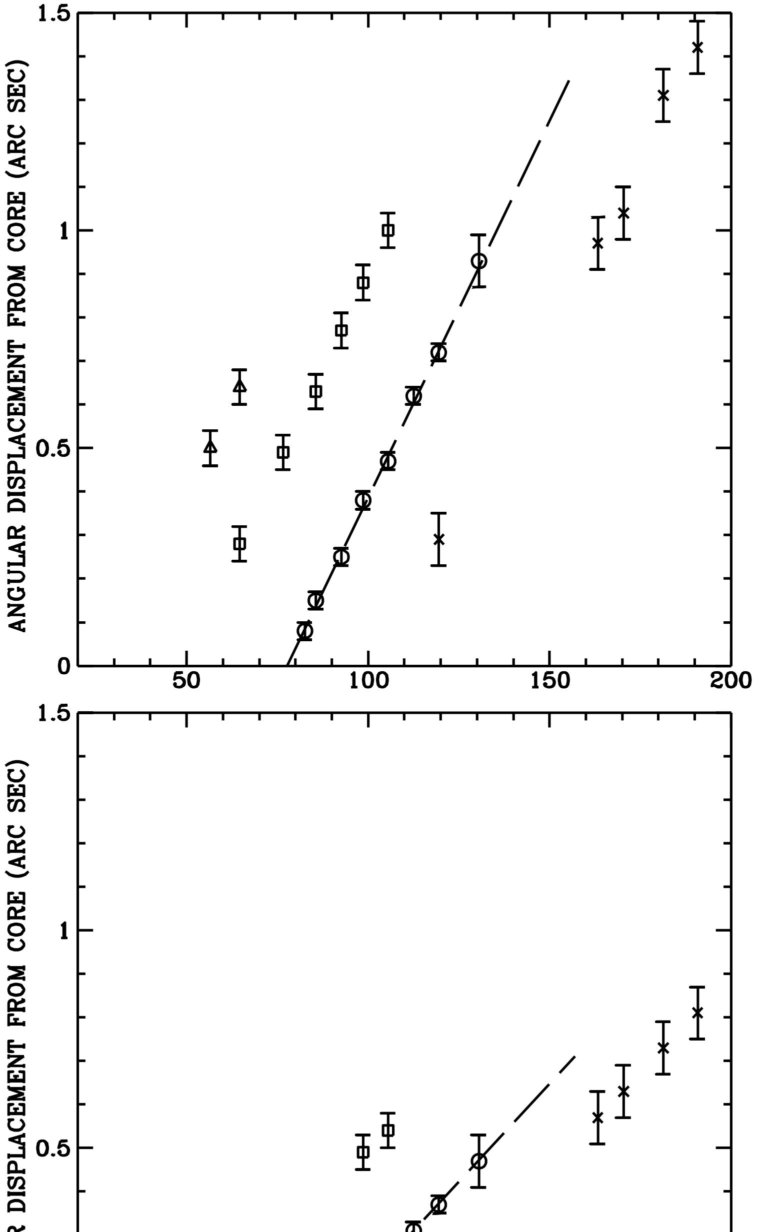
(2) V_{app} is the apparent speed of the highest velocity component of the ejecta.

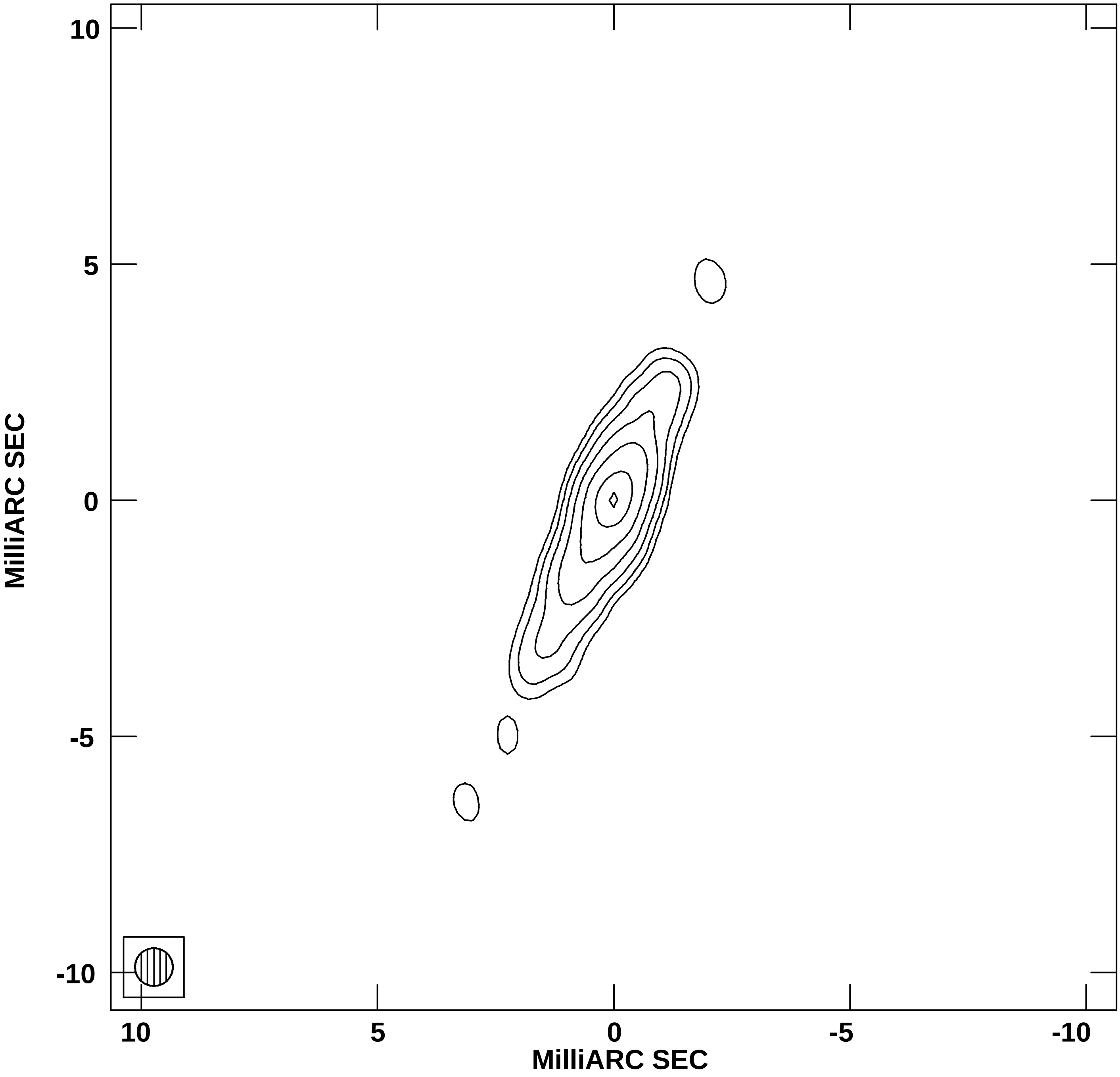
(3) V_{int} is the intrinsic velocity of the ejecta.

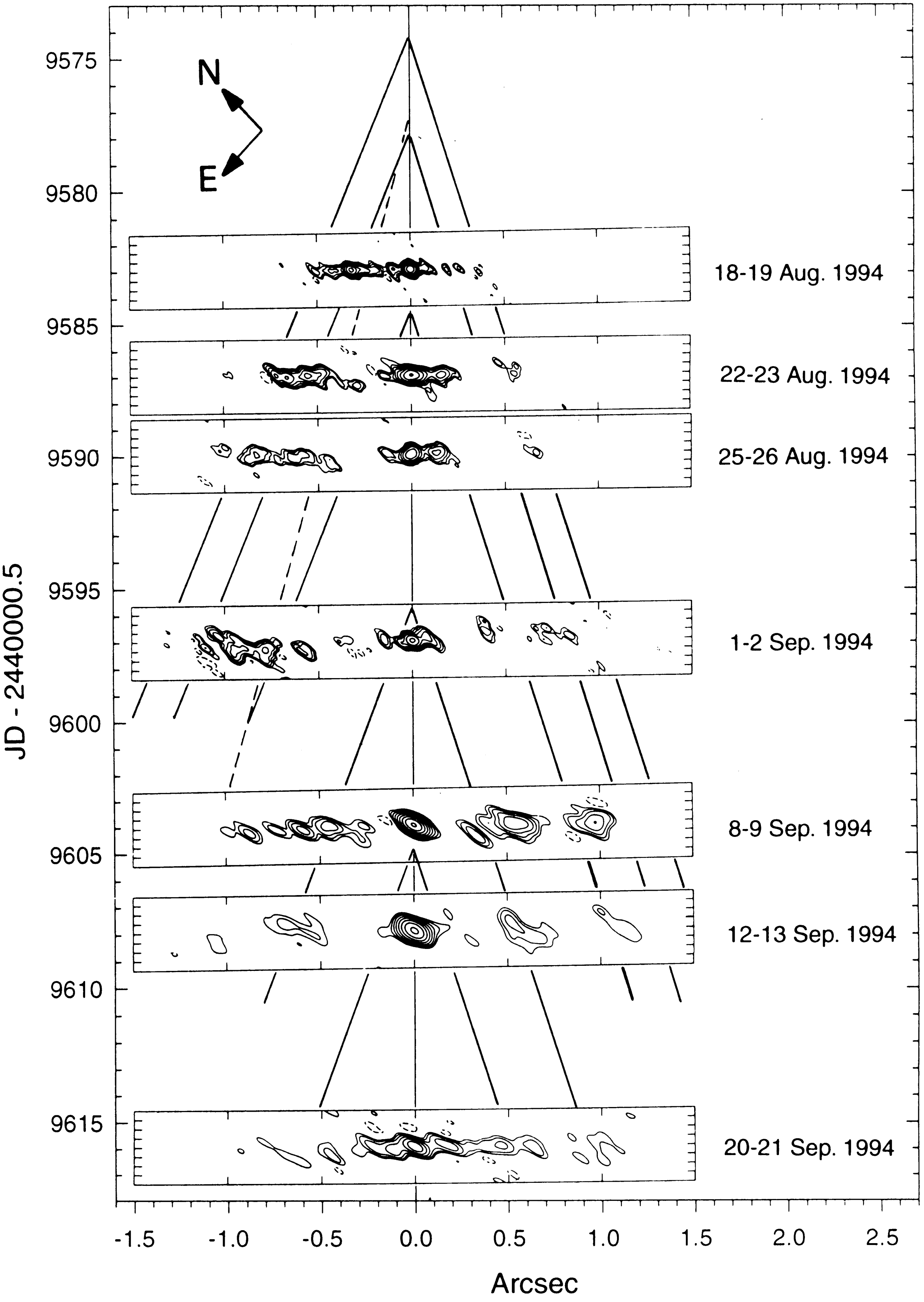
(4) Θ is the angle between the direction of motion of the ejecta with the line of sight.


-29 42 45
43 00
15
30
45
44 00
15
DECLINATION (B1950)
ROSAT
17 40 46
45
44
43
42
41
40
RIGHT ASCENSION (B1950)

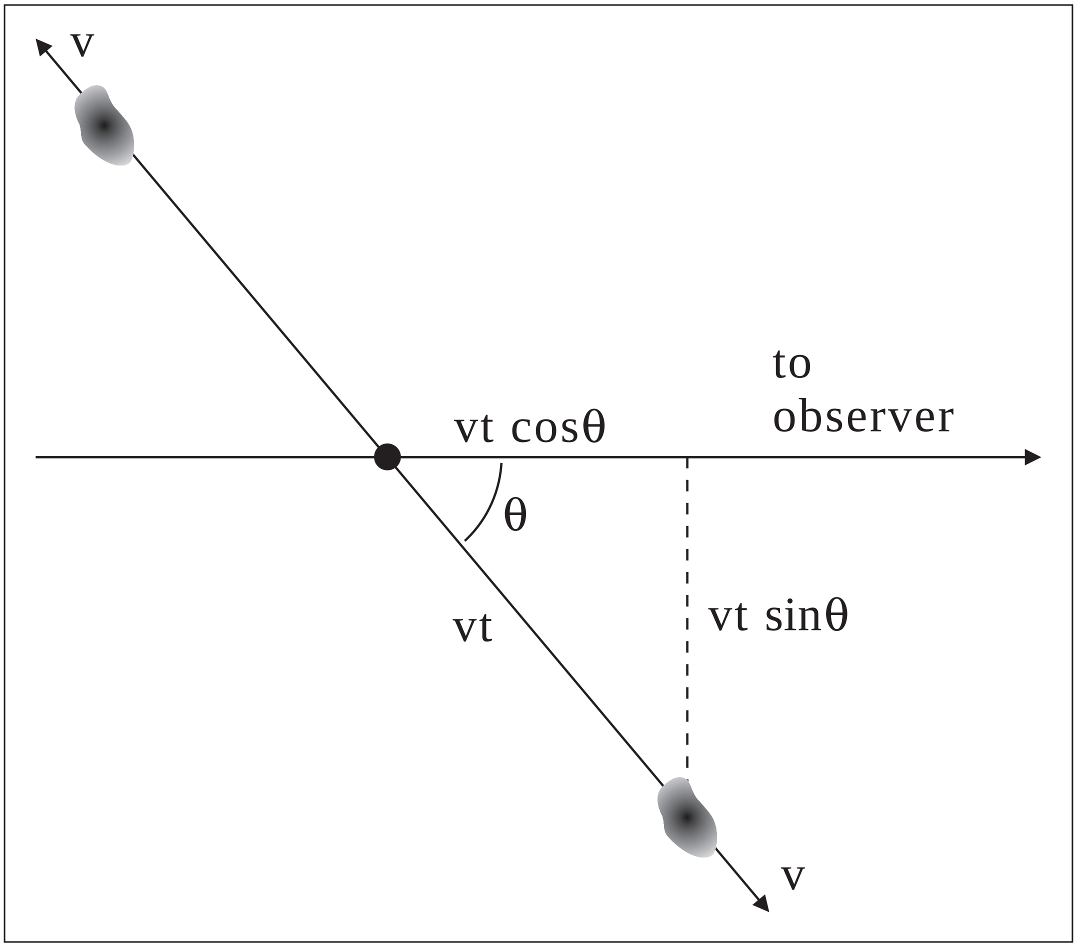

E
N
MAR 27
APR 03
APR 09
APR 16
APR 23
APR 30
1"

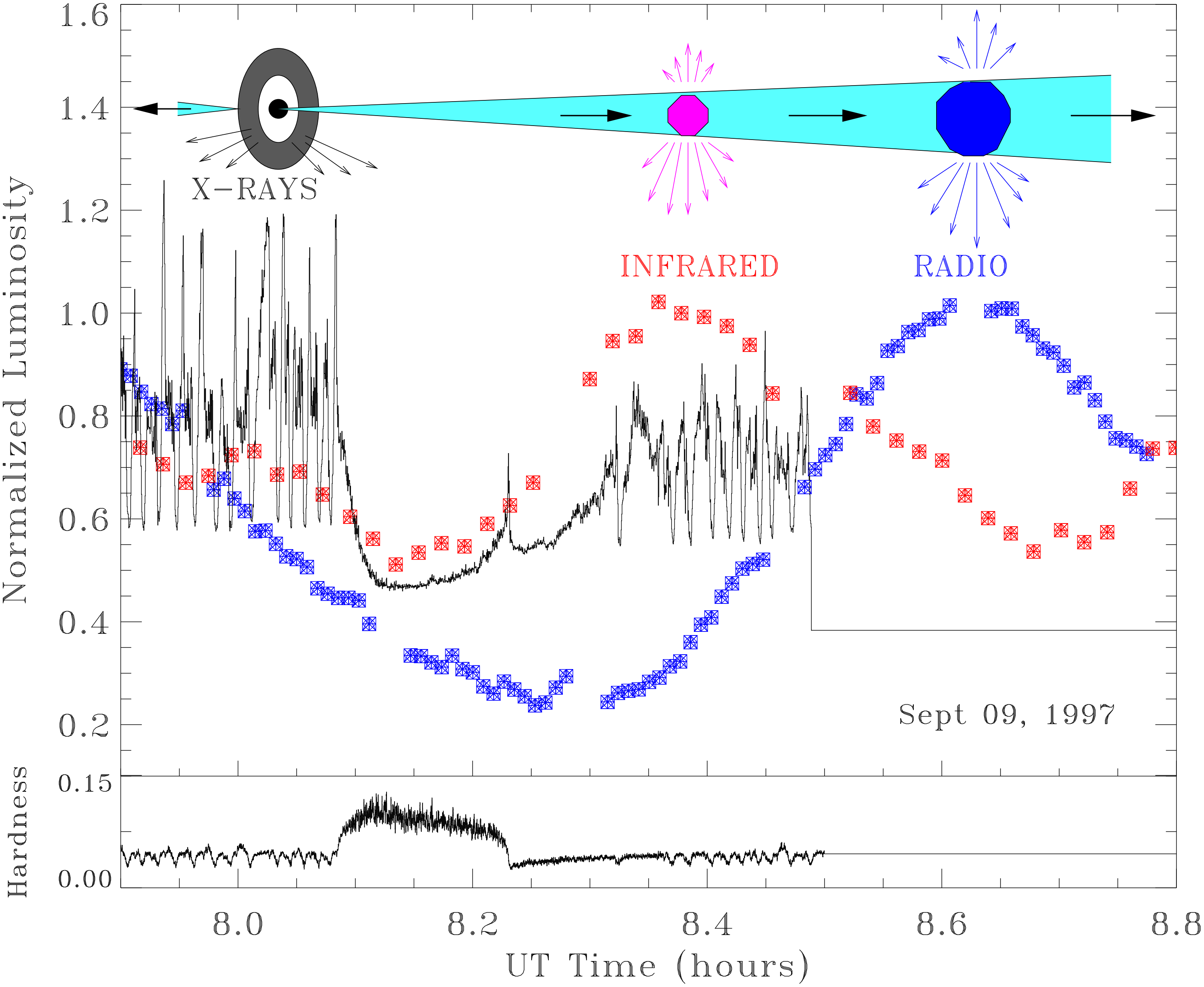

ANGULAR DISPLACEMENT FROM CORE (ARC SEC)
1.5
1
0.5
0
50
100
150
200
ANGULAR DISPLACEMENT FROM CORE (ARC SEC)
1.5
1
0.5
0
50
100
150
200
TIME (DAYS SINCE 1994 JAN 01 AT 0 HOURS UT)

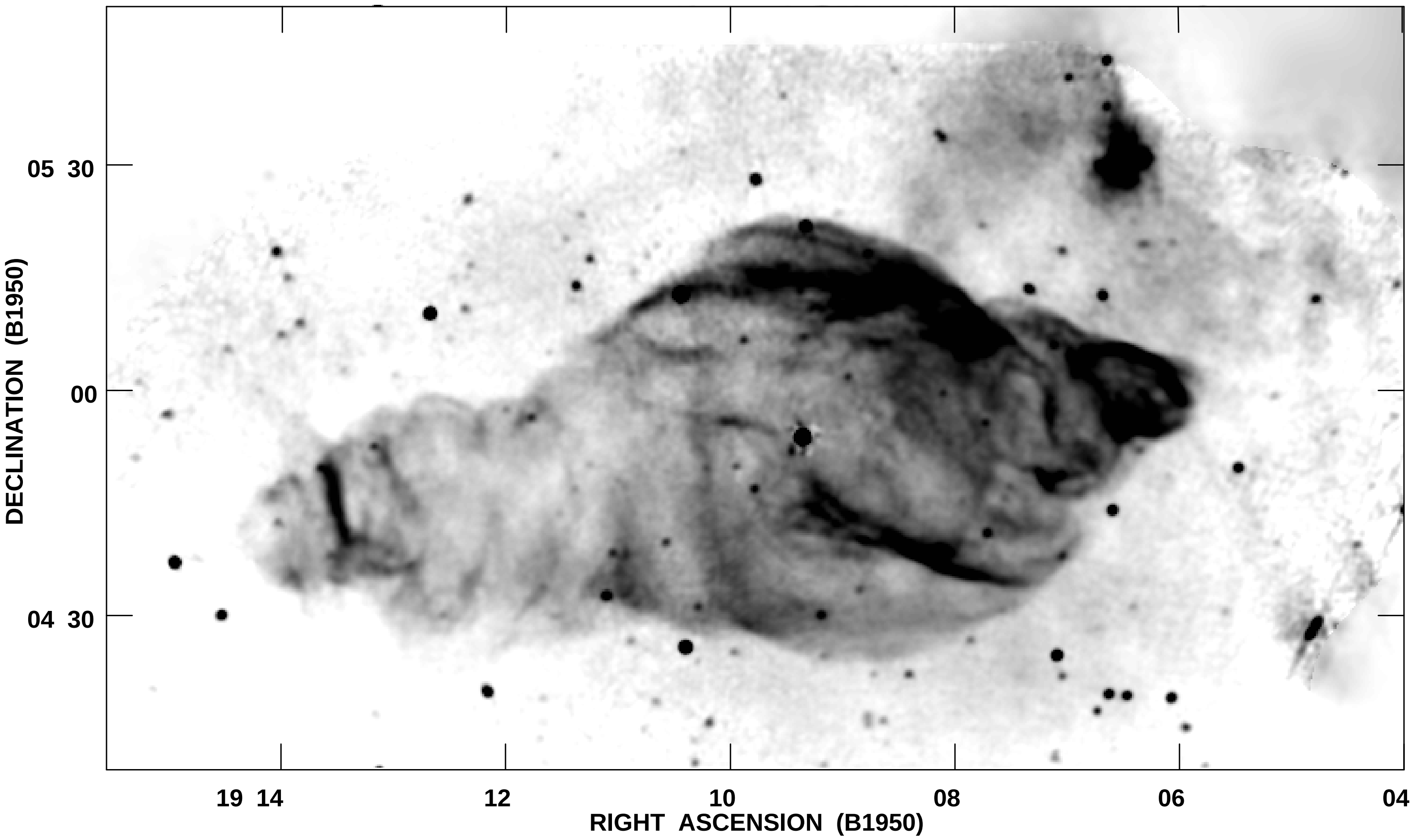

10
5
0
-5
-10
MilliARC SEC
10
5
0
-5
-10
MilliARC SEC



N
E
9575
9580
9585
9590
9595
9600
9605
9610
9615
JD - 2440000.5
18-19 Aug. 1994
22-23 Aug. 1994
25-26 Aug. 1994
1-2 Sep. 1994
8-9 Sep. 1994
12-13 Sep. 1994
20-21 Sep. 1994
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
Arcsec


v
to
observer
vt cosθ
θ
vt sinθ
vt
v


X−RAYS
INFRARED
RADIO
Sept 09, 1997
Normalized Luminosity
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Hardness
0.15
0.00
8.0
8.2
8.4
8.6
8.8
UT Time (hours)


05 30
00
04 30
DECLINATION (B1950)
19 14
12
10
08
06
04
RIGHT ASCENSION (B1950)