MULTIWAVELENGTH STUDIES OF RADIO-JET X-RAY BINARIES

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Academic dissertation

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Helsinki, 1999
Out of misery comes joy, clear and sweet.
I feel that I am learning.

— Sylvia Plath
Abstract

Radio-jet X-ray binaries are X-ray binaries known to undergo episodic ejections of radio-emitting plasma clouds. GRS 1915+105 and GRO J1655−40, two of the sources presented here, have been observed to expel matter at apparent superluminal velocities. Optical radial velocity measurements have shown GRO J1655−40 to harbor a stellar mass black hole, and there is compelling evidence from X-ray observations that the compact object in GRS 1915+105 is also a black hole. The third source, GX 339−4, has been included in this work on the basis that it is a strong black hole candidate, and may have undergone a jet ejection episode.

GRS 1915+105, GRO J1655−40 and GX 339−4 have been monitored in the hard X-rays with the Burst and Transient Source Experiment on the Compton Gamma-Ray Observatory and in the soft X-rays with the All-Sky Monitor on the Rossi X-Ray Timing Explorer since their respective launches. In addition, ground-based radio telescopes have observed and occasionally extensively monitored all three sources. The Molonglo Observatory Synthesis Telescope monitored GRS 1915+105 for a period of about three months in 1996, GRO J1655−40 for about three months in 1994 during a period of ejection episodes and then again for a week in 1996, and monitored GX 339−4 intermittently from April 1994 to February 1997. GRO J1655−40 was also observed at six frequencies with the Australia Telescope Compact Array during the 1994 ejection events.

Long-term monitoring has shown all three sources to be highly variable and has not revealed a consistent relationship between the radio and X-ray emission. The GRS 1915+105 hard X-ray light curve shows extended outbursts lasting up to ~ 450 days. The soft X-ray light curve shows periods of flaring and chaotic activity interspersed with “lulls”. Two double-peaked radio flares were observed, the second (recorded with the Green Bank Interferometer whose variable source monitoring program includes X-ray binaries) associated with a series of ejection events, and with lulls in the soft X-ray light curves. No high resolution imaging was conducted at the time of the first double-peaked flare, so there is no firm evidence that an ejection did occur. However, based on similarities in the soft X-rays and radio behavior, we proposed that an ejection may indeed have occurred in conjunction with the first double-peaked radio flare. For GRO J1655−40, the hard X-ray light curve shows clearly defined multiple outbursts, most of which are associated with jet ejection episodes and major radio flares. The radio emission during the ejections was found to be significantly linearly polarized, indicating ordered magnetic fields in the radio emitting ejecta. An outburst occurred simultaneously in the radio and the soft and hard X-rays in GX 339−4 lasting for about 100 days.

This doctoral thesis discusses radio and X-ray observations of GRS 1915+105, GRO J1655−40 and GX 339−4, highlighting the differences and similarities in the behavior especially during jet ejection episodes. Certain features in the radio and X-ray data are singled out as possible signatures of jet ejections, the origin of which is still an enigma.
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I dedicate this thesis to them.
Original publications


Abbreviations used in the text

ASM All-Sky Monitor (RXTE)
ATCA Australia Telescope Compact Array
BATSE Burst and Transient Source Experiment (CGRO)
CGRO Compton Gamma-Ray Observatory
GBI Green Bank Interferometer
HartRAO Haartebeesthoek Radio Astronomy Observatory
MERLIN Multi Element Radio Linked Interferometry Network
MOST Molonglo Observatory Synthesis Telescope
PCA Proportional Counter Array (RXTE)
RXTE Rossi X-Ray Timing Explorer
SHEVE Southern Hemisphere VLBI Experiment
SIGMA Satellite d’Imagerie Gamma avec Masque Aléatoire
VLA Very Large Array
VLBA Very Long Baseline Array
VLBI Very Long Baseline Interferometry
WATCH Wide Angle Telescope for Cosmic Hard X-rays

MJD Modified Julian Date (JD−240,000.5)

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Chapter 1

Introduction

X-ray binaries, which are composed of a compact primary, either a neutron star or black hole, and a mass-losing secondary, have been observed extensively at all wavelengths since the discovery of Sco X–1, which was the first non-solar X-ray point source to be discovered (Giacconi et al. 1962) and the first object to be classified as an X-ray binary (Gursky et al. 1966). Sco X–1 was also the first X-ray binary to be identified as a source of radio emission (Ables 1969).

Black holes in X-ray binaries have been studied ever since improvements in the X-ray error box of Cyg X–1 (Tananbaum et al. 1971; Rappaport, Zaumen & Dossey 1971) led to the discovery of a variable radio source (Hjellming & Wade 1971; Braes & Miley 1971). This in turn permitted optical spectroscopic observations of the blue supergiant HD 226868 located at the radio source position, which revealed an orbital period of 5.6 days and a corresponding mass function which implied a mass greater than 3 M⊙ for the unseen object — i.e. higher than the theoretical upper limit for a neutron star (Webster & Murdin 1972; Bolton 1972).

X-ray binaries can be loosely divided into two categories, depending on the nature of the non-degenerate secondary. Systems with giant or supergiant companions are referred to as High Mass X-Ray Binaries, while those containing a main sequence secondary are known as Low Mass X-Ray Binaries. Accretion processes are deemed to be the main source of power in X-ray binaries. The form the accretion takes depends on the spectral type of the companion. O or B stars generate a stellar wind which is captured by the compact object. If the companion is later than spectral type A, and fills its Roche lobe, accretion will occur via mass transfer through the inner Lagrangian point L1. In the absence of a strong magnetic field, the mass flow possesses sufficient angular momentum to form an accretion disk around the compact primary.

Some X-ray binaries are persistent sources of X-ray emission, while others are detectable only during transient outbursts. On the whole, the X-ray emission from the persistent sources is defined as 'hard' X-ray emission, which is characterized in X-ray spectra by a featureless power law continuum that can extend into the MeV range (e.g. McConnell et al. 1994). In sources that undergo transient outbursts, the X-ray luminosity in the soft X-ray range (≤ 10 keV) can often increase by a factor of $10^3 - 10^4$ (e.g. Tanaka & Lewin 1995). These outbursts are signatures of episodic accretion processes that are reflected in Eddington or even super-Eddington X-ray luminosities. A handful of sources is known to exhibit both long periods of persistent hard X-ray emission interspersed with short-lived energetic soft X-ray outbursts.
A number of X-ray binaries has been found to exhibit radio jets, or the episodic ejection of radio-emitting plasma clouds (also called ejecta, plasmoids, plasmons, blobs). SS 433 was the first X-ray binary from which jets were observed (Spencer 1979) and subsequent mapping with the Very Large Array (Hjellming & Johnston 1981a) showed the ejecta to have velocities of $\sim 0.26c$. Since then, about a dozen X-ray binaries, either with a neutron star or a black hole primary, have exhibited jets in one form or another, i.e. either the continuous or episodic ejection of radio-emitting material.

In some of the radio-jet X-ray binaries the apparent ejection velocities of the plasmoids are superluminal, i.e. faster than the speed of light. This, and the general consensus that the compact object residing in these systems is a black hole, have earned these systems their nickname, “microquasars”, due to their similarity to quasars. The central engines of quasars themselves are not very well understood. One of the main obstacles in understanding quasars is that the timescale on which events, such as the ejection of matter, take place can be of the order of thousands of years for a $\sim 10^9 M_\odot$ quasar. In the microquasars these timescales are reduced to more practical timescales of minutes. The two confirmed Galactic superluminal sources are GRS 1915+105 and GRO J1655−40.

This doctoral thesis describes observations undertaken at several radio frequencies as well as soft (generally $\sim 2 \to 12$ keV) and hard ($> 20$ keV) X-rays of GRS 1915+105 (Papers I, II, IV, and V) and GRO J1655−40 (Papers III, VI, and VII). While GX 339–4 (Papers II & III) is not an established jet source, it has been included in this work on the basis that it is a strong black hole candidate X-ray binary, and a possible ejection may have taken place. Long-term radio and X-ray light curves are discussed, in addition to temporal variations in the radio spectra. Emphasis is placed on the behavior during jet ejection events, in view of identifying patterns that are signatures of the ejection of matter from these sources. Both data reduced as well as analyzed by the author of this thesis and data obtained from the literature are presented.
Chapter 2

Theoretical overview

2.1 Outflows and apparent superluminal motion

In 1963, Maarten Schmidt identified the radio source 3C 273 with a star-like, quasi-stellar object (Schmidt 1963). The optical spectrum revealed that this object had spectral lines redshifted by $z = 0.158$. The redshift was interpreted by Hubble's law, which implied huge distances to 3C 273. Shortly afterwards, Rees & Simon (1968) postulated that the only way to accommodate for rapid radio fluctuations in these sources was by introducing relativistic expansion. Then in 1971, Very Long Baseline Interferometry (VLBI) observations of 3C 279 (across a California–Australia baseline) revealed an expanding radio component (Moffet et al. 1972). Relativistic outflows have been observed from extragalactic sources ever since. However, due to their large distances and the supermassive black holes they are believed to harbor, the timescales on which phenomena can be observed are of the order of thousands of years for a black hole mass of $10^9 M_\odot$; even for a black hole mass of $10^6 M_\odot$, the timescales are on the order of years (Shakura & Sunyaev 1976). The radio-jet X-ray binaries, with their stellar mass black hole primaries and distances of the order of kiloparsecs exhibit phenomena similar to the quasars, but on timescales of, in some cases, minutes. In this section, some of the basic principles of relativistic outflows are reviewed.

Special relativity must be invoked to explain the superluminal motion of the plasmoids seen in the Galactic radio-jet binaries. Fig. 2.1 illustrates the apparent superluminal motion of a plasmoid ejected from a stationary core at an angle $\theta$ to the line of sight. After time $t$, the plasmoids having a true velocity $v$ have travelled a distance $vt$ from the core. This translates to a projected distance of $vt \sin\theta$ to an external observer. The apparent velocity, $v_a$, of the approaching plasmoid is $v_a = vt \sin\theta / t \left(1 - \frac{v}{c} \cos\theta\right)$, which can be larger than $c$. The receding component will have a corresponding velocity $v_r = vt \sin\theta / t \left(1 + \frac{v}{c} \cos\theta\right)$.
Figure 2.1: The geometry of the apparent velocity of the plasmoids (basis for the diagram courtesy of R. Fender).

The proper motions of the plasmoids are:

\[
\begin{align*}
\mu_a &= \frac{u \sin \theta}{(1 - (v/c) \cos \theta) D} \\
\mu_r &= \frac{u \sin \theta}{(1 + (v/c) \cos \theta) D},
\end{align*}
\]  

(2.1)

where \( D \) is the distance to the source (e.g. Mirabel & Rodríguez 1999). In addition, if one can measure the wavelength of the spectral lines in either the approaching or the receding jet \( \lambda_{asr} \) with respect to the rest wavelength, \( \lambda_{rest} \), one gets

\[
\frac{\lambda_{asr}}{\lambda_{rest}} = \frac{1 \mp (v/c) \cos \theta}{[1 - (v/c)^2]^{1/2}},
\]

(2.2)

By solving the three equations the unknowns, \( v, \theta \) and \( D \), can be found. Doppler boosting is an effect that plays a role in the ejections of radio-emitting clouds. For an object moving at relativistic speeds, the emitted radiation is focused in the direction of motion — resulting in the approaching component appearing brighter than the sometimes undetectable receding component, which explains why extragalactic jet sources are often observed to be one-sided. If one can overcome the observational difficulty of detecting strongly Doppler broadened lines from plasmoids that are both moving and expanding relativistically, this may prove to be an invaluable method for measuring distances to either Galactic radio-jet X-ray binaries and/or quasars (e.g. Hjellming & Johnston 1981a; Mirabel & Rodríguez 1994; Mirabel & Rodríguez 1999).

The question of how magnetized plasma drawn from a companion star can be expelled from a black hole binary system in a highly collimated fashion has been posed since the discovery of extragalactic radio jets. One theory proposed by Blandford and Payne (1982) involves hydro-magnetic acceleration in the accretion disk. In other words, the energy and angular momentum
are removed magnetically from the disk via field lines that leave the disk surface and extend to large distances. The toroidal component of the magnetic field becomes important at large distances from the disk, and can collimate the plasma into a pair of anti-parallel jets perpendicular to the disk. Closer to the disk the outflow may be driven by gas pressure in a hot magnetic corona. Thus, magnetic stresses can extract angular momentum from a thin accretion disk and enable matter to be accreted. The outcome of this model is that most of the power is concentrated within a central core while the angular momentum and magnetic flux is carried near the jet walls.

Another model proposed by Blandford and Znajek (1977) invokes the electromagnetic extraction of energy from a rotating black hole. An electric potential difference will be induced if a rotating black hole is threaded by magnetic field lines supported by external currents flowing in an equatorial disk. With a large enough field strength an electron-positron pair cascade will be produced, and a force-free magnetosphere will be established. Energy and angular momentum can thus be extracted and relativistic electrons can be accelerated out to large distances. With paraboloidal field lines, the energy will be beamed in anti-parallel directions.

2.2 Emission mechanisms & regions

The emission from radio-jet X-ray binaries covers the entire electromagnetic spectrum. For the purpose of this thesis we will discuss three main areas: radio, and soft and hard X-ray emission. The inner accretion disk is believed to be the site for the production of X-rays; soft X-ray emission is attributed to the hot inner portions of the accretion disk while hard X-rays are thought to arise from the inverse Compton scattering of soft X-ray photons in a hot plasma cloud, or corona, surrounding the central compact object (e.g. Shapiro, Lightman & Eardley 1976). X-rays also reflect any occurring accretion processes. The plasma clouds that constitute the jets emit in the radio via the synchrotron mechanism. Occasionally, the core of these systems, regarded to be an extended plasma cloud surrounding the central source, can also be observed at radio wavelengths. Some of the principal emission regions are portrayed in Fig. 2.2.

Much of the emission observed from X-ray binaries is attributed to accretion processes. Accretion is the conversion of gravitational potential energy into radiation. The luminosity which results from the accretion onto a compact object of mass $M$ is then the rate at which the gravitational energy is released:

$$ L = \frac{G\dot{M}}{R}, $$

(2.3)

where $\dot{M}$ is the accretion rate, $R$ the radius of the object and $G$ the gravitational constant. If the accretion rate, and thus the luminosity, becomes large enough, radiation pressure can set in and diminish the accretion of matter onto the compact object. The maximal accretion rate is achieved when the inward force and outward force are in equilibrium. This equilibrium condition gives us the Eddington luminosity which can be expressed as

$$ L_E = \frac{4\pi GMm_p c}{\sigma_T} \approx 1.3 \times 10^{38}(M/M_\odot) \text{ erg s}^{-1}, $$

(2.4)

where $\sigma_T$ is the Thomson cross-section, $m_p$ the proton mass and $c$ the velocity of light (e.g.
Figure 2.2: The principal emission regions in radio-jet X-ray binaries.

Frank, King & Raine 1992).

Whether the emission from astrophysical sources is thermal or nonthermal depends on the initial velocity distribution of the electrons. For a gas in local thermodynamic equilibrium (LTE), the velocity distribution of the electrons is Maxwellian, and the resulting emission spectrum of such a gas is said to be thermal. For a gas not able to acquire LTE, the electrons may have other types of velocity distributions, for example a power law distribution. In this case, the emission spectrum is said to be nonthermal. Examples of thermal and nonthermal spectra are shown in Fig. 2.3. Below we review some of the main mechanisms that give rise to the observed emission from radio-jet X-ray binaries. Basic equations for bremsstrahlung, blackbody radiation, and synchrotron emission are quoted, without deriving them. The polarization properties of synchrotron emission are also presented.

2.2.1 Bremsstrahlung

Free-free emission, or bremsstrahlung, arises when a charge is accelerated in the Coulomb field of another charge. In astrophysical contexts this is taken to be the scattering of an electron in the field of an ion, though other forms of scattering such as electron-electron may be considered elsewhere. As ions are more massive than electrons, it is taken that the electrons are the radiating charges in the field of the ions, since the relative accelerations are inversely proportional to the masses. The following derivations are taken from Longair (1981).

Thermal bremsstrahlung was invoked to explain certain characteristics in the radio spectra of GRO J1655-40 (Hannikainen et al. 1999a; Hannikainen et al. 1999b). For a Maxwellian distribution of electron velocities,

\[ P(v) \, dv = Av^2 \exp\left(-\frac{1}{2}m_e v^2/kT\right) \, dv, \] 

(2.5)

the emissivity of a plasma at temperature \( T \) and of electron density \( N_e \) at a frequency \( \omega \) (where
\( \omega = 2\pi v \) will be

\[
I(\omega) = (\text{constant}) \frac{Z^2 e^6}{m_e^2} \left( \frac{m_e}{kT} \right)^{1/2} g(\omega, T)N_eN_i, \quad (2.6)
\]

where \( g(\omega, T) \) is a correction factor known as the Gaunt factor.

The expected spectrum from thermal free-free emission is characterized by a high energy exponential cutoff, \( \exp(-\hbar \omega / kT) \), and is relatively flat in the low frequency regime, except for when self-absorption effects become important at low frequencies when \( \hbar \nu \ll kT \) — in this case, the spectrum will then correspond to the Rayleigh-Jeans approximation to Planck’s law, \( I_\nu = 2kT / \nu^2 \), for a plasma radiating as a blackbody at temperature \( T \).

Nonthermal free-free emission arises when the velocity distribution of the electrons is non-Maxwellian. An approximation to the emission spectrum is found by integrating over all energies that contribute at frequency \( \omega \) for an electron energy distribution \( N(E)dE \) (Longair 1981), resulting in an emissivity

\[
I(\omega) \propto \omega^{-(6-1)/2}. \quad (2.7)
\]

The spectrum is flat up to a frequency at which an electron of energy \( E \) loses all of its energy, \( E \sim \frac{1}{2} m_e c^2 \), in a single collision.
2.2.2 Inverse Compton scattering

Inverse Compton scattering occurs when ultra-relativistic electrons lose energy in collisions with photons, which consequently are scattered to much higher energies. This may be the case when soft X-ray photons originating in the inner accretion disk are subsequently upscattered after collisions with particles in a hot plasma cloud, or corona, surrounding the central source and inner accretion disk. Emission in the hard X-ray energy range suggests the presence of such a corona, and dips in the hard X-ray light curve could indicate that the corona has been disrupted by the ejection of matter from the system (e.g. Harmon et al. 1997; Hannikainen et al. 1999c; Hannikainen et al. 1999d).

2.2.3 Blackbody radiation

Blackbody radiation, reflected in soft X-ray emission, is attributed to the inner regions of accretion disks. A 'black' surface does not reflect or scatter radiation incident upon it, but absorbs and re-emits it. Such a surface is known as a blackbody and is an ideal radiator. Any optically thick Maxwellian distribution of electrons will show a blackbody spectrum. The intensity at a frequency $\nu$ of a blackbody at temperature $T$ is

$$B_\nu(T) = \frac{2h\nu^3}{c^2 \exp(h\nu/kT) - 1},$$

(2.8)

where $h$ is Planck’s constant and $k$ is Boltzmann’s constant (e.g. Lang 1980). At low energies, i.e. when $h\nu \ll kT$, the intensity is defined by the Rayleigh-Jeans approximation to Planck’s law.

2.2.4 Synchrotron radiation

Synchrotron emission arises when relativistic electrons are accelerated in a magnetized plasma. As the plasma expands the emission becomes optically thin and the spectral peak will move from the high frequency to the low frequency region. The optically thick emission is characterized by a low frequency downturn caused by synchrotron self-absorption. The basic synchrotron model has provided good fits to the observed radio flux density curves and spectra of many black hole candidates.

For a power law energy distribution of relativistic electrons

$$N(E)dE = \kappa E^{-\alpha}dE,$$

(2.9)

where $\alpha$ represents the energy spectral index and $\kappa$ is a constant describing the density of the electrons, the flux density from a synchrotron source may be expressed as (Longair 1981)

$$S_\nu = 1.35 \times 10^{-22} a(p) \frac{VKB^{(p+1)/2}}{R^2} \left( \frac{6.26 \times 10^{18}}{\nu} \right)^{(p-1)/2},$$

(2.10)

where $V$ is the volume of the source, $B$ is the strength of the magnetic field in Gauss, $R$ is the distance and $a(p)$ is a constant. The resulting synchrotron spectrum will have a spectral index $\alpha = -(p-1)/2$; in other words, $S_\nu \propto \nu^\alpha$. 

8
If the synchrotron energy density in the emitting volume is very large, self-absorption effects become important at frequencies below $\nu_c$, when the brightness temperature equals the kinetic temperature of the radiating electrons, and the spectrum will be of the form (Longair 1981)

$$S_\nu \propto \frac{\Theta^2 \nu^{5/2}}{B^{1/2}},$$

(2.11)

where $\Theta$ is the angular size of the source. Note that in this case $S_\nu$ does not depend on the original spectrum of the emitting particles.

Synchrotron spectra for optically thin emission look like some of the examples portrayed in Fig. 2.3, e.g. Virgo A or Cas A. Spectra which describe emission from an optically thick medium will appear to be ‘flat’, or “inverted”, on a plot of log intensity vs. log frequency. With two observing frequencies two-point spectral indices can be derived from spectra of the form $S_\nu \sim \nu^\alpha$. The more negative $\alpha$ is the steeper the spectrum. Thus, an $\alpha$ of about zero describes a flat spectrum, while a positive value of $\alpha$ will indicate an inverted spectrum. Initially, when a plasma cloud is formed at the source, the spectrum will be flat or inverted, denoting the presence of an optically thick self-absorbed component. The subsequent steepening of the spectrum indicates that a plasm has been ejected and is expanding with time, emitting via the synchrotron mechanism.

**Synchrotron bubble**

In the synchrotron bubble model, first developed by van der Laan (1966), and subsequently elaborated on by Hjellming & Johnston (1988) and Ball & Vlasis (1993), a homogeneous spherical bubble composed of relativistic electrons and magnetic field expands adiabatically exhibiting synchrotron emission. As the bubble expands, the emission becomes optically thin at progressively lower frequencies, i.e. the frequency at which the flux density is a maximum decreases with time as does the maximum flux density.

Following the arguments presented in Ball & Vlasis (1993), in the optically thick rising phase the flux density varies as

$$S(\nu, t) \approx S_0(t/t_0)^3(\nu/\nu_0)^{5/2}$$

(2.12)

where $\nu_0$ is a reference frequency and $S_0$ is the flux density at time $t_0$ when the sphere was ejected. In most cases, though, $t_0$ is taken to be a free parameter. The frequency spectrum will exhibit the features of a synchrotron self-absorbed source with a power law index of $5/2$.

During the optically thin decay phase we have

$$S(\nu, t) \approx \frac{2}{3} S_0 \tau_0(t/t_0)^{-2p}(\nu/\nu_0)^{-(p-1)/2}$$

(2.13)

where $\tau_0$ is the optical depth as a function of $\nu_0$ and $r_0$, and $r_0$ is the size of the source at time $t_0$. The spectrum will show the characteristics of pure optically thin synchrotron emission of power law index $-(p-1)/2$, or $\alpha$.

**Polarization**

As mentioned above, an important feature of synchrotron radiation is that it is polarized. Thus, detecting polarized radio emission establishes the synchrotron origin of the radiation.
Polarized radio emission has been observed from GRS 1915+105 (Fender et al. 1999a) and GRO J1655−40 (Hannikainen et al. 1999a; Hannikainen et al. 1999b), in both cases during major radio outbursts in conjunction with jet ejection episodes. Below we shall briefly discuss certain aspects of polarization.

**Stokes parameters** Stokes parameters are widely used to describe polarization. They can be derived using the major and minor axes $E_a$ and $E_b$ and the position angle $\psi$ describing the polarization ellipse (Fig. 2.4). In 1892, Poincaré showed that there is a one-to-one relation between polarization states and points on a sphere described by radius $S_0$, longitude $2\psi$ and latitude $2\chi$ (left-hand side of Fig. 2.5; Rohlfs 1990). The right-hand side of Fig. 2.5 depicts this circle, where the equator represents linear polarization, and the north and south poles correspond to right-circular and left-circular polarization respectively.

The Stokes parameters will then be the cartesian coordinates of the points on the sphere, with the following definitions (e.g. Rohlfs 1990):

\[
\begin{align*}
S_0 &= I = E_a^2 + E_b^2 \\
S_1 &= Q = S_0 \cos 2\chi \cos 2\psi \\
S_2 &= U = S_0 \cos 2\chi \sin 2\psi \\
S_3 &= V = S_0 \sin 2\chi .
\end{align*}
\]

(2.14)

Only three of the parameters are independent, as

\[
\begin{align*}
S_0^2 &= S_1^2 + S_2^2 + S_3^2 \\
I^2 &\geq Q^2 + U^2 + V^2 .
\end{align*}
\]

(2.15)

The Stokes I parameter represents the total energy flux density, and so the degree of polarization is determined by the expression

\[
\Pi = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} .
\]

(2.16)
Figure 2.5: **Left.** Definition of the Stokes parameters. **Right.** Poincaré sphere. (Both taken from Robrhs 1990)

The angle $\chi$ which defines the position of the major axis of the polarization ellipse is given by $\tan 2\chi = U/Q$ and the ellipticity, characterized by the angle $\beta$ is given by $\sin 2\beta = V/I$.

For a uniform magnetic field, the degree of linear polarization in the optically thin and thick cases respectively is (Pacholczyk 1970):

\[
\Pi_{\text{thin}} = \frac{p+1}{p+3}, \\
\Pi_{\text{thick}} = \frac{3}{6p+13},
\]

where $p$ is the energy spectral index. For a spectral index of $-0.5$, the degree of linear polarization in the optically thin case will be about 0.7. The actual observed integrated polarization is often much less than this, which is attributed to a disordering of the magnetic field.

**Faraday rotation and intrinsic polarization angle** A plane polarized wave can be decomposed into two circularly polarized components of opposite hand. These two components have different phase velocities when propagating through a magnetized plasma. After travelling some distance their relative phase has altered and the plane of polarization of the linearly polarized wave will be effectively rotated by an amount

\[
\Delta \chi = 8.1 \times 10^5 \lambda^2 \int N_e B_|| dr \, \text{rad},
\]

where $\lambda$ is the wavelength in meters, $N_e$ the electron density in $\text{cm}^{-3}$, $B_||$ the longitudinal component of the magnetic field, and $dr$ is an element of length along the line of sight in parsecs (Scheffler & Elsasser 1988). The rate of change of the direction of polarization with $\lambda^2$
is constant, and is called the “rotation measure” which is given by

\[
RM = \frac{\delta \Delta \chi}{\delta \lambda^2} = 8.1 \times 10^5 \int N_e B_\parallel dr \text{ rad m}^{-2}.
\] (2.19)

The rotation measure is positive if the magnetic field is directed towards the observer. Combining equations 2.18 and 2.19 gives

\[
\Delta \chi = \lambda^2 \text{ RM}.
\] (2.20)

The intrinsic polarization angle at the source is thus obtained by extrapolating a straight line to zero wavelength on a plot of measured position angles of the polarization at various frequencies vs. \(\lambda^2\).
Chapter 3

Telescopes

Several telescopes and instruments were used to gather the data presented in this thesis and are referred to in the original papers. Below is a brief overview of the principal instruments involved.

3.1 Radio telescopes

**Molonglo Observatory Synthesis Telescope** The MOST is located near Canberra, Australia, and is operated by the Astrophysics Department of the University of Sydney. The MOST operates on the principle of earth-rotation aperture synthesis at a frequency of 843 MHz, with a bandwidth of 3 MHz. It is a 1.6 km East-West array, consisting of two cylindrical paraboloids of dimension $778 \text{m} \times 12 \text{m}$, separated by a gap of 15 m. The total length is 1571 m and the physical aperture is \( \sim 18050 \text{ m}^2 \). The basic field of view is $23' \times 23' \csc \delta$ with a resolution of $43'' \times 43'' \csc \delta$. A full synthesis requires a 12 hour observation. The declination range for full hour angle coverage is $-30^\circ < \delta > -90^\circ$. Details of the instrument can be found in Mills (1981) and Robertson (1991).

**Australia Telescope Compact Array** The ATCA is an earth-rotation aperture interferometer consisting of six 22-meter antennae. Five of the six antennae lie along a three kilometer east-west railway track, and the sixth lies three kilometers away on a 75m track. This permits a number of different configurations and a maximum baseline of 6 km. At the time of the observations presented in this thesis, the ATCA operated at frequencies ranging from $1.2 - 10.2 \text{ GHz}$, with a $104 \text{ MHz}$ bandwidth in two linear polarizations. The primary beam (full width half power) is $33' in the lowest frequency band and 5' in the higher frequency band. Details of the ATCA can be found in Frater, Brooks & Whiteoak (1992).

**Haarbeesthoek Radio Astronomy Observatory** The HartRAO is a 26 m single dish radio telescope situated in Gauteng in South Africa, which operates at seven frequencies between $1.7 \text{ GHz}$ and $12 \text{ GHz}$.

**The Ryle Telescope** The Ryle Telescope, situated near Cambridge, England, consists of eight elements, with four elements mounted on a 1.2 km rail track and the other four fixed at 1.2 km intervals. The baselines thus available are between 18 m and 4.8 km in a variety of configurations. The telescope operates at 5 and 15 GHz, with a bandwidth of 350 MHz.
The Green Bank Interferometer  The GBI is operated by the National Radio Astronomy Observatory in West Virginia, USA. It includes three 26 m telescopes, providing a baseline of 2.4 km. The GBI operates at 2.25 and 8.3 GHz.

3.2 X-ray satellites

Due to the high opacity of the Earth's atmosphere to X-rays, X-ray detectors are flown on satellites.

Rossi X-Ray Timing Explorer  The RXTE, a Goddard Space Flight Center mission, is an X-ray satellite which was launched in December 1995. RXTE carries three instruments, the Proportional Counter Array, the High Energy X-Ray Timing Experiment and the All-Sky Monitor (ASM). The ASM, which is the most relevant to this thesis, consists of three wide-angle shadow cameras, with Xenon-filled position-sensitive proportional counters (Levine et al. 1996). The principal function of the ASM is to monitor Galactic and extragalactic X-ray sources in the 2–12 keV energy range over long periods of time. ASM data is publicly available and can be downloaded off the World Wide Web.

Compton Gamma-Ray Observatory  The CGRO was launched in April 1991. It carries four instruments, one of which is the Burst and Transient Source Experiment (BATSE), designed to detect gamma-ray bursts, in the 20–1000 keV energy range (Fishman et al. 1985). BATSE is composed of eight identical Large Area Detectors, each one occupying one side of an octahedron. BATSE, like ASM, has also been used to monitor Galactic X-ray sources, and the light curves can be downloaded from the World Wide Web.
Chapter 4

Observations and results

GRS 1915+105, GRO J1655−40 and GX 339−4 are all strong black hole candidates. Optical radial velocity measurements of the visible companion provide the most direct method of determining the mass, in other words the nature, of the invisible compact object in X-ray binaries. If the mass thus derived is firmly above the theoretical upper limit for neutron stars (≈ 3 M⊙; Tanaka & Lewin 1995 and references therein), then it is assumed that the system contains a black hole. This method proved to be successful in the case of Cyg X−1. However, for many X-ray binaries attempts to derive the mass through direct optical spectroscopic observations are thwarted by factors such as high extinction towards the source, or emission from the accretion disk dominating the optical spectrum. A way around these obstacles is to use the X-ray properties of Cyg X−1 as canonical signatures for identifying black hole candidates. These include (Tanaka & Lewin 1995 and Liang 1998 and references therein):

- a hard X-ray spectrum (power law with an exponential cutoff above ≈ hundred keV)
- an ultrasoft component
- anticorrelated soft and hard X-ray state transitions
- persistent gamma-ray tail above 1 MeV
- low-frequency quasi-periodic oscillations
- persistent radio emission and radio flaring correlated with X-ray transitions.

Although some neutron stars have also exhibited one or more of the above properties, none has exhibited a majority of them — hence, if an X-ray binary has exhibited most of the above properties, it is taken to be a black hole candidate (Liang 1998).

In this chapter, the general properties of GRS 1915+105, GRO J1655−40 and GX 339−4 will be described, in addition to introducing the long-term radio and X-ray light curves. The end products of the MOST radio observations discussed in this thesis are images at the various observing frequencies. The MOST light curves are obtained by applying a fitting routine to the known positions of the sources in the reduced images, and hence extracting the flux densities. The only occasion when further analysis of the images themselves was necessary towards the work of thesis was in determining whether there was evidence of any prominent extended emission associated with GX 339−4 (Hannikainen et al. 1998). For the other telescopes, e.g. the Ryle Telescope or ATCA, the light curves are Stokes-I amplitudes measured by the telescopes.

The X-ray and radio emission is both highly complex and variable — not only do the three sources themselves exhibit different behavior, but the X-ray/radio relationship also differs for
the same source at different epochs. The purpose here is to highlight various aspects of the activity in the three energy ranges for the three sources, and see how they associate with ejection events. In addition, certain characteristics of the radio spectra of GRS1915+105 and GROJ1655−40 will also be discussed.

4.1 GRS 1915+105

GRS1915+105 was the first Galactic source observed to exhibit superluminal motion. It was originally detected as a hard X-ray source with the Wide Angle Telescope for Cosmic Hard X-rays (WATCH) all-sky monitor on the GRANAT satellite in 1992 (Castro-Tirado, Brandt & Lund 1992) with a flux of 0.35 Crab in the 6–15 keV range. Its position was refined by the SIGMA (Satellite d’Imagerie Gamma avec Masque Aléatoire) telescope on GRANAT (Finoguenov et al. 1994), which permitted follow-up observations at all wavelengths. Subsequent monitoring with BATSE on CGRO showed it to be the most luminous hard X-ray source in the Galaxy (Paciesas et al. 1996), with $L_{30–100 \text{ keV}} \sim 3 \times 10^{38} \text{ erg s}^{-1}$ (at a distance of 12.5 kpc). Based on the hard X-ray tail observed in the X-ray spectrum at energies $\geq 150 \text{ keV}$ (Harmon et al. 1994; Finoguenov et al. 1994) and integrated X-ray luminosities $L_X \geq 4 \times 10^{38} \text{ erg s}^{-1}$, the primary has been classified as a black hole candidate. Mirabel et al. (1993a; 1994) discovered a time-variable radio counterpart with the Very Large Array (VLA); observations on 1992 Dec 11 (MJD 48967) showed the 20 cm peak flux to be $2.5 \pm 0.1 \text{ mJy}$, while on 1993 Mar 10 (MJD 49056) it had risen to $5.0 \pm 0.1 \text{ mJy}$. High optical absorption ($\geq 33$ magnitudes) towards GRS1915+105 has prevented the identification of the non-degenerate companion; however, an infrared counterpart was identified with a K magnitude of 14.3 (Mirabel et al. 1993b). In 1994 Jan–Apr, remarkable observations with the VLA by Mirabel & Rodríguez (1994) revealed the multiple ejection of pairs of radio-emitting plasma clouds at apparent superluminal velocities. Fig. 4.1 shows a series of ejections observed with the VLA, where the vertical separation between the maps is proportional to the time between the observations. In the first four epochs of Fig. 4.1 there is a fainter pair of condensations moving ahead of the brighter ones at about the same speed, suggesting ballistic (unaccelerated) motion. On 1994 April 23 the core flared again and on 1994 April 30 a new plasma cloud appeared to the south. The plasma clouds ejected on 1994 Mar 19 had proper motions of $\mu_a = 17.5 \pm 0.3 \text{ mas day}^{-1}$ and $\mu_r = 9.0 \pm 0.1 \text{ mas day}^{-1}$. When corrected for relativistic effects, the ejection velocities were found to be $\beta \equiv v/c = 0.92 \pm 0.08$ (at a distance of 12.5 kpc), with a jet-axis inclined to the line of sight at an angle $\theta = 70^\circ \pm 2^\circ$. Using the method described in Section 2.1, Mirabel & Rodríguez (1994) derived an upper limit to the distance of $D \leq 13.7 \text{ kpc}$ (and thus establishing the Galactic origin of the source), which was then refined to $D = 12.5 \pm 1.5 \text{ kpc}$ based on H$\alpha$ observations.

The ASM has been monitoring GRS1915+105 in the 2–12 keV energy range ever since the launch of RXTE in late 1995. The long-term X-ray light curve shows highly variable behavior, from flaring states and periods of chaotic behavior (e.g. Greiner, Morgan & Remillard 1996), to "hulls", during which the emission maintained a very steady low level for periods of $\sim 20–30$ days (Morgan, Remillard & Greiner 1997). Quasi-periodic oscillations (QPO) were reported by Morgan, Remillard & Greiner (1997) — they showed that if the $67 \text{ Hz QPO}$’s arise in the inner accretion disk, this implies a central mass of $33 \text{ M}_\odot$, a very strong premise for a black hole candidate.
Figure 4.1: VLA observations of GRS1915+ 105 from Mirabel & Rodrígues (1994), showing pairs of radio-emitting clouds moving away from the central source, which is marked with a cross. The half-power beamwidth (0.2 arcsec) is shown in the top right-hand corner.
Figure 4.2: The GRS 1915+105 long-term radio, soft and hard X-ray light curves. The top panel shows the Nançay 3.2 GHz (Rodríguez et al. 1995; Mirabel et al. 1996), MOST 843 MHz (Hannikainen, Hunstead & Campbell-Wilson 1998), and GBI 2.25 GHz light curves. The arrows mark ejection epochs observed with the VLA (Rodríguez & Mirabel 1999) and MERLIN (Fender et al. 1999a). The RXTE/ASM soft X-ray (2–12 keV) light curve is in the middle panel, while the BATSE hard X-ray (20–100 keV) light curve is in the bottom panel.

Belloni et al. (1997) modelled the RXTE/PCA 2–40 keV data of GRS 1915+105 and showed that the spectral changes observed reflect the rapid disappearance of the inner portions of an accretion disk, followed by a slower refilling of the emptied region. During their observations the inner disk radius varied between 20 and 80 km. Pooley & Fender (1997) reported a clear but complex association between soft X-rays and radio emission (15 GHz), including radio QPO’s in the range 20–40 min, which they tentatively associated with the ~ 30 min QPO’s reported by Belloni et al. (1997). Vilhu & Nevalainen (1998) modelled PCA data of GRS 1915+105 as it was beginning to emerge from a hll state, using a self-consistent two-phase thermal model in which seed photons from an optically thick classical disk are Comptonized in a hot spherical corona surrounding the inner disk (Poutanen & Svensson 1996) and found the inner disk radius to oscillate between 20 and 35 km. Mirabel et al. (1998), in performing simultaneous X-ray, infrared and radio observations, found that the oscillations seen in the X-ray light curves were accompanied by synchrotron flares at infrared and radio wavelengths, suggesting the ejection of relativistic plasma clouds.

Recent Multi Element Radio Linked Interferometry Network (MERLIN) observations (Fender et al. 1999a) showed another series of ejections of discrete plasma clouds, but this time the ejection velocity was reported to be $0.98_{-0.05}^{+0.02}c$, for an upper limit to the distance of 11.2 ± 0.8 kpc, at
an inclination angle of $\theta \sim 66 \pm 2^\circ$. The ejections followed a lull state of $\sim 20$ days in both soft X-rays and the radio. A similar lull was observed in 1996, but as no radio imaging was performed, it is not known whether ejections occurred (see Section 4.1.2).

4.1.1 Light curves

The hard X-ray light curve of GRS1915+105 (Fig. 4.2) shows extended outbursts which lasted for months. On the whole, there appears to be anticorrelation between the soft and the hard X-rays; for example, the activity in the hard X-rays picks up as it is declining in the soft X-rays (e.g., MJD > 50300). In GRS1915+105 the radio mimics the soft X-ray emission: the activity in both energy ranges goes into a "lull" state (e.g., Pooley & Fender 1997), during which low steady levels of emission are present. Prior and subsequent to this lull state, there is flaring in both the radio and soft X-rays. At least on one occasion the renewal in activity after a lull state was accompanied by jet ejections (Fender et al. 1999a). There is significant hard X-ray emission prior to and during the reported ejection events, although for the event occurring on MJD 49939 the hard X-ray emission appears to increase afterwards. However, Foster et al. (1996) reported a strong positive correlation between the radio and the hard X-rays for MJD 49850–50050. Not all ejection events are accompanied by major radio flares though, as is evident from the Nangay light curve.

4.1.2 Radio spectra

Fig. 4.3 shows a reproduction of portions of the long-term radio and X-ray light curves of GRS 1915+105, in addition to the temporal evolution of two-point spectral indices derived from the MOST 843 MHz and Ryle 15 GHz data and the GBI 2.25 and 8.3 GHz data. The left-hand side (a) of the figure represents data from 1996, while the right-hand side (b) is from 1997. The arrow at the top of (b) indicates the ejection epoch reported by Fender et al. (1999a). What is significant here is that the GBI 2.25–8.3 GHz two-point spectral index shows structure during the lull phase in the radio and soft X-ray light curves. Initially, the spectrum is flat, with $\alpha \sim 0$. At the onset of the first radio flare (MJD $\sim 50725$) the radio spectrum steepens rapidly to about $\alpha \sim -0.7$. After this, the spectrum begins to flatten, until it is inverted, i.e. $\alpha > 0$, throughout the lull phase. Coincident with the second radio flare and the resumption of activity in the soft X-rays (MJD $\sim 50750$), the spectrum again steepens rapidly to $\alpha \sim -0.7$. The steepening of the spectrum, the signature of an expanding plasmon, is consistent with the MERLIN ejection epoch (Fender et al. 1999a).

No high resolution radio imaging was undertaken at the time of the radio outburst recorded with the MOST (MJD 50270–50330). However, the structure of the radio and soft X-ray light curves resemble those recorded by the GBI and the RXTE/ASM one year later. In addition, two-point spectral indices constructed from the MOST 843 MHz and Ryle 15 GHz data show the same pattern of a steepening followed by a flattening of the spectrum during the first radio flare, an inversion of the spectrum during the lull, and finally a rapid steepening of the spectrum at the onset of the second radio flare. It is tempting to suggest that an ejection event also occurred in 1996, based on the similarity of the behavior in the radio and soft X-ray light curves, and more specifically on the behavior of the spectral indices, which during both episodes indicated the formation and subsequent expansion of an initially optically thick compo-
Figure 4.3: a) GRS1915+105 in 1996 (left) and b) in 1997 (right). The top panels show the MOST and GBI radio light curves, while the middle panels show the RXTE/ASM 2-12 keV light curves. The bottom panels show the evolution of the MOST–Ryle 843 MHz – 15 GHz spectral index (left) and the GBI 2.25 – 8.3 GHz spectral index (right). Letters A–D in the MOST plot are explained in the text. The arrow in the top right-hand plot indicates the epoch of the first MERLIN ejection event (Fender et al. 1999a).

A possible scenario for the radio and X-ray behavior in GRS 1915+105 is described below.

Initially (A, in the top left-hand plot of Fig. 4.3), the relatively flat radio spectral index points to the presence of an optically thick corona. But, the optically thick component at this stage is probably not very extended, possibly only encompassing the immediate vicinity of the central compact object, because flaring behavior in the soft X-rays indicates that at least portions of the inner accretion are exposed. In addition, the presence of hard X-ray emission (Fig. 4.2; e.g. Hannikainen et al. 1999c) supports the notion of the hot corona. The sudden steepening of the spectrum coincident with the first radio flare (B, and more visible in the corresponding GBI spectral index plot) suggests that matter is being expelled from the system and subsequently expanding, possibly due to an onset of magnetic activity. The MERLIN observations (Fender et al. 1999a) showed the radio emission to be linearly polarized after the ejection event on MJD~50750, thus the synchrotron origin for the radio emission, and hence the presence of magnetic fields cannot be dismissed. For reasons not yet clear, there is a quenching of the optically thin jet, resulting in the formation of an optically thick self-absorbed corona which engulfs much of the inner accretion disk region. This is reflected in the inverted radio spectral index and in the simultaneous decrease (the hulks) in both the radio and the soft X-ray emission (C). With the second, larger radio flare, the spectral index again steepens rapidly, once more indicating that matter is expelled and is expanding. The resumption in soft X-ray activity
after the hull indicates that there is no longer any material obscuring the inner disk region. Dips in the hard X-ray light curve (e.g. Hannikainen et al. 1999c) also compound the idea that the corona has been disrupted or dispersed, maybe even forming the ejecta themselves. The behavior in the evolution of the spectral index can be compared with that found by Valtanen et al. (1988), where they examined the spectra of 27 extragalactic radio sources, including quasars, BL Lac objects and blazars. They found that all flare spectra (within observational accuracy) could be fit with that of a simple homogeneous self-absorbed source (inverted α), with a steepening in the optically thin spectrum during the final stages of the flare evolution, indicative of energy losses. They conclude that their fits are well described by a model where the flares result from shocks in an adiabatic, relativistic jet, however with some modifications, possibly a larger role for radiative losses.

4.2 GRO J1655–40

The second Galactic superluminal source to be discovered was GRO J1655–40 (Nova Sco 1994). It was first detected with BATSE on 1994 July 27 (Zhang et al. 1994) with significant flux observed up to 200 keV ($L_{0.1-400}$ keV ~ $6 \times 10^{37}$ erg s$^{-1}$ (d/4 kpc)). The source reached a luminosity of ~ 1.1 Crab in the 20–100 keV energy range by 1994 Aug 1. GRO J1655–40 remained in outburst until about 1994 Aug 15, and after a period of quiescence flared again on 1994 Sept 6 (Harmon et al. 1995). The radio counterpart was reported by Campbell-Wilson & Hunstead (1994a) following observations with the MOST at 843 MHz on 1994 Aug 6. GRO J1655–40 was detected as a strong variable radio source with a flux density of 370 mJy, and the flux density continued to increase during the monitoring, reaching 4.2 Jy on 1994 Aug 14 and 5.5 Jy on 1994 Aug 15 (Campbell-Wilson & Hunstead 1994b). Radio observations using the VLA and the Very Long Baseline Array (VLBA) (Hjellming & Rupen 1995) and the Southern Hemisphere VLBI Experiment (SHEVE) array (Tingay et al. 1995) showed repeated relativistic ejection episodes. Using the VLA and the VLBA, Hjellming and Rupen (1995) followed the evolution of the radio jets emanating from GRO J1655–40 at apparent superluminal velocities, with proper motions $\mu_\alpha = 54$ mas d$^{-1}$ and $\mu_\delta = 45$ mas d$^{-1}$. Three major ejection events on MJD 49577.5, 49584 and 49597 were observed with the VLA and three on MJD 49574±1, 49605±2 and 49668±5 were recorded with the VLBA. When corrected for relativistic effects the ejection velocities turned out to be $\beta = v/c = 0.92 \pm 0.02$, with the jet axis inclined to the line of sight at an angle $\iota = 85^\circ \pm 2^\circ$ with a position angle of $47^\circ \pm 1^\circ$. The jets rotate about the jet axis with a period of 3.0±0.2 d. Fig. 4.4 shows the VLBI images of the ejections from GRO J1655–40 (Tingay et al. 1995) and the geometry of the system as deduced from the VLA and VLBA observations (Hjellming & Rupen 1995). The distance to GRO J1655–40 was first estimated to be $\sim 3.5$ kpc based on ATCA HI observations (e.g. McKay & Kesteven 1994), and then refined to $3.2 \pm 0.2$ kpc by Hjellming & Rupen (1995) based on the kinematic model of the jets.

Optical observations led to a precise mass for the primary, $M_1 = 7.02 \pm 0.22 M_\odot$ (Orosz & Bailyn 1997), which is well above the theoretical upper limit for a neutron star. The mass of the secondary is $M_2 = 2.34 \pm 0.12 M_\odot$ and it is classified as F3 IV–F6 IV. The spectroscopic period of the binary is $P = 2^d.62157 \pm 0^d.00015$. Recently Soria et al. (1998) found a 95% lower limit of $M_1 > 5.1 M_\odot$ for the primary mass based on measurements of velocity variations in the
Figure 4.4: **Left.** VLBI images of GRO J1655–40 showing the asymmetry of the jets (from Tingay et al. 1995). **Right.** The geometry of the system (Hjellming & Rupen 1995). The twin jets rotate clockwise about the jet axis with a period of three days. $\Theta$ is the angle of the jet axis with respect to the observer and $\Omega = 2\pi/3d$ is the angular rotation rate. The jets maintain an angle of $2^\circ$ to the jet axis, which is inclined $5^\circ$ from the line of sight with a position angle of $47^\circ$.

HeII disk emission lines thought to reflect the orbital motion of the primary, hence reinforcing the notion that the primary is indeed a black hole.

Following a period of over a year of quiescence, GRO J1655–40 became active again in the soft X-rays (2–12 keV) in 1996 April (Remillard et al. 1996). The soft X-ray flux increased very rapidly, going from an upper limit of 12 mCrab on April 23 to 1.3–1.5 Crab between 1996 April 30 and May 5. The source maintained constant soft X-ray activity over the next 200 days. Contrary to expectations, hard X-ray activity only switched on after the initial rise in soft X-rays, with the BATSE 20–200 keV flux reaching a maximum, after a relatively slow rise, about 3.5 months later. In addition, the MOST recorded the tail end of a radio flare apparently coincident with the initial increase in the hard X-ray flux (Hunstead, Wu & Campbell-Wilson 1997; Hannikainen, Hunstead & Campbell-Wilson 1998).

### 4.2.1 Light curves

The hard X-ray light curve of GRO J1655–40 (Fig. 4.5) shows clearly defined multiple outbursts, especially during MJD 49500–49850. The hard and soft X-ray light curves appear to be correlated at times for GRO J1655–40 (for MJD~50100-50470), i.e. soft X-ray emission is present when the source is also active in the hard X-rays, even though with GRO J1655–40 the hard X-rays turned on only about 30 days after the soft X-rays. However, this is true only for the first soft X-ray outburst in GRO J1655–40. The second soft X-ray outburst (~ MJD 50470) is accompanied by little activity in the hard X-rays. The first three radio flares (MJD 49575–49675) follow the hard X-ray outbursts (e.g. Harmon et al. 1995; Hannikainen, Hunstead
Figure 4.5: The GRO J1655–40 long-term radio, soft and hard X-ray light curves. The top panel shows the MOST light curve plotted on a logarithmic scale (Wu & Hunstead 1997; Hannikainen et al. 1999d). The arrows mark ejection epochs observed with the VLBA (Hjellming & Rupen 1995). The RXTE/ASM 2–12 keV light curve is in the middle panel, while the BATSE 20–200 keV light curve is in the bottom panel.

& Campbell-Wilson 1998; Hannikainen et al. 1999d), and were all associated with ejection events. But, VLA observations show that the BATSE hard X-ray outburst in March–April 1995 (MJD 49770–49820) was not accompanied by any radio activity — no radio emission was detected with an upper limit of 0.5 mJy (Tavani et al. 1996). In addition, a third type of relationship is observed: after MJD 50200, the radio emission is clearly the tail-end of a flare which precedes the hard X-ray outburst (e.g. Hunstead, Wu & Campbell-Wilson 1997; Hannikainen, Hunstead & Campbell-Wilson 1998). No high resolution imaging was undertaken at this time so it is not known if there was an ejection episode.

4.2.2 Radio spectra

Analysis of the 1994 ATCA data from the time of the ejections showed the radio emission to be significantly linearly polarized immediately following the large radio outburst (MJD~49580) and ejection events (Hannikainen et al. 1999a; Hannikainen et al. 1999b), implying the presence of ordered magnetic fields, and confirming the synchrotron nature of the emission. Polarized radio emission has been reported from e.g. GRS 1915+105 following a series of jet ejections (Fender et al. 1999a), SS 433 (Hjellming & Johnston 1981b) and a recently proposed jet source and black hole candidate, 4U 1630–47 (Hjellming et al. 1999).
Figure 4.6: GRO J1655–40: Total flux density (solid line) and polarized flux density (dotted line) spectra from selected epochs during the 1994 jet ejections (Hannikainen et al. 1999b). The left-hand axes refer to the total flux density (I) while the right-hand axes refer to the polarized flux density (P). The MJD’s are marked in the individual plots.

The GRO J1655–40 total flux density spectra show a spectral downturn at low frequencies which could not be attributed to synchrotron self-absorption, and so a hybrid model, involving both synchrotron and free-free emission processes, was invoked (Hannikainen et al. 1999b). In this ‘core+lobe’ model, the core emits mainly via bremsstrahlung while the lobes, or the ejecta, emit via the synchrotron process. The behavior in the polarized flux density is reminiscent of the synchrotron bubble model mentioned in Section 2.2.4, implying the formation and expelling of ejecta; this is seen in Fig. 4.6 (top row) where the expansion of a synchrotron bubble is reflected in the increase of the polarized flux density at subsequently lower frequencies. The bottom row, on the other hand, shows a simultaneous increase and decrease in the polarized flux density at all frequencies (with the higher frequencies quenched on MJD 49589.55 and 49593.36, not predicted by the synchrotron bubble model), which is attributed to free-free emission from the core.

### 4.3 GX 339–4

The low mass X-ray binary GX 339–4 was discovered by the OSO-7 satellite in 1973 (Markert et al. 1973). The similarity of its X-ray spectrum to that of the canonical black hole system Cyg X–1 (bimodal X-ray states: high/soft and low/hard) prompted its classification as a black hole binary, supported by the rapid variability in its X-ray and optical emission (e.g. Makishima et al. 1986; Miyamoto et al. 1992; Nowak 1995). GX 339–4 exhibits four distinct X-ray states, three of which were initially identified by Markert et al. (1973): high, low and off. The high state is characterized by an extremely soft spectrum ($kT = 1$–2 keV) accompanied by
a hard power-law tail, the low state is described by a single power-law hard spectrum, and the off state is in fact a very weak hard state (Motch et al. 1985). In addition, an intermediate state between the low and the high states has been reported (Mendez & van der Klis 1997).

The optical counterpart was first identified as an 18 mag star (Doxsey et al. 1979; Cowley et al. 1991) which was subsequently found to be highly variable, with $V$ ranging from $\sim 15.4$ to $>20$. Photometric data revealed a 14.8 hour modulation which has been attributed to the orbital period (Callanan et al. 1992). Emission from the accretion disk has dominated the spectra making it difficult to obtain a definitive estimate for the mass of the compact object (Cowley et al. 1987). Distance estimates vary from 1.3 kpc (Predehl et al. 1991) to $\sim 4$ kpc (Makishima et al. 1986). Zdziarski et al. (1998) have recently constrained the distance to $D = 4 \pm 1$ kpc. Simultaneous optical and X-ray observations have shown QPOs at mean periods of $\sim 10$ s and $\sim 20$ s (Motch et al. 1983) in the X-ray low state (see Tanaka & Lewin 1995 and references therein). The relationship between optical and X-ray fluxes is not well understood. For example, in 1981 Motch et al. (1983) found anticorrelation between the 1–13 keV X-ray and optical fluxes, but correlation between the 13–20 keV X-ray and optical.

A variable radio counterpart was discovered by Sood & Campbell-Wilson (1994), which prompted a radio monitoring program undertaken with the MOST at 843 MHz. Fender et al. (1997) observed GX 339–4 at high resolution in 1996 July with the ATCA at a wavelength of 3.5 cm and reported the detection of a jet-like extension to the west of the source (Fig. 4.7), but subsequent observations failed to confirm this (Corbel et al. 1997). However, hard and soft X-ray and radio observations showed an outburst occurring simultaneously at all three wavelengths (Hannikainen et al. 1998) — this outburst was coincident with the epoch reported by Fender et al. (1997) for the jet-like extension, which suggests there truly could have been an outflow of matter from the system, unless changes in the source flux density occurred at the time of the ATCA observation resulting in the jet-like extension.
Figure 4.8: The GX 339-4 long-term radio, soft and hard X-ray light curves. The top panel shows the MOST 843 MHz light curve. (Hannikainen et al. 1998). The open triangles are upper limits. The arrow marks the possible jet-like extension reported by Fender et al. (1997). The RXTE/ASM 2–12 keV light curve is in the middle panel, while the BATSE 20–100 keV light curve is in the bottom panel.

Fender et al. (1999b) have recently shown that the radio emission (MOST and ATCA) from GX 339-4 is strongly correlated with the hard X-ray emission during the low/hard state, and highly quenched during the high/soft state. They propose that there is a quasi-continuous outflow during the low/hard state which is suppressed in the soft/high state. In particular, state transitions appear to be characterized by unusually optically thin radio emission which they suggest corresponds to discrete ejection events.

4.3.1 Light curves

In GX 339-4 (Fig. 4.8), the radio emission is correlated at times with both the hard and the soft X-ray emission, the latter being correlated with one another (Hannikainen et al. 1998). This is only true for MJD 50250–50400, as later results have shown the radio and hard X-ray emission to be strongly anticorrelated with the soft X-rays following the state transition the source underwent around MJD ~50800 (Fender et al. 1999b).
4.4 Summary

The light curves are obviously reflecting a complicated relationship between the different emission regions. Besides the light curves presented here, there are several references in the literature to simultaneous radio and X-ray observations of GRS 1915+105, GRO J1655−40 and GX 339−4. Foster et al. (1996), for example, report on GB I and BATSE monitoring of GRS 1915+105, where they found the radio emission to be correlated with episodes of enhanced hard X-ray emission. Specifically, the hard X-ray outbursts occurred during optically thick radio states. Harmon et al. (1995) examined VLA and BATSE light curves of GRO J1655−40, and found that the radio outbursts followed the hard X-ray outbursts. Fender et al. (1999b) observed GX 339−4 with the MOST, ATCA, RXTE/ASM and BATSE, and found the radio and hard X-ray emission to be consistent with zero-measured fluxes when the source was in a state of enhanced soft X-ray activity.

An increase in hard X-ray emission may be attributed to enhanced accretion processes, which could result in disk instabilities, which in turn lead to the ejection of matter from the system. This would be seen in the light curves as an increase in the hard X-ray flux, followed by a decay during which the radio intensity would increase (e.g. Harmon et al. 1995; Harmon et al. 1997), as was seen in the case of GRO J1655−40 during the 1994 ejections between MJD 49575–49675. Alternatively, hard X-ray emission could be the signature of soft X-ray photons originating in the hot central regions of the accretion disk upscattered into the hard X-ray energy range in a hot corona surrounding the central source (e.g. Shapiro, Lightman & Eardley 1976; Haardt & Maraschi 1993), and correlations between dips in the hard X-rays and the emergence of radio emission could be attributed to the disruption of such a corona by ejected material (e.g. Hannikainen et al. 1999c; Hannikainen et al. 1999d).

Table 4.1 shows the correlation between radio, soft and hard X-ray emission and ejection events. On the whole, jet ejection events in GRS 1915+105 and GRO J1655−40 and the possible event in GX 339−4 are accompanied by radio flares. Note, however, that the radio flares accompanying the first two ejections from GRS 1915+105, occurring on MJD 49382 and 49402, were less intense than the flare which occurred during the third and fourth ejections. What does stand out in Table 4.1 is that all the ejection events in GRS 1915+105 and GRO J1655−40 (and the possible GX 339−4 event) are associated with enhanced activity in the hard X-rays. But, it must be pointed out that the GRO J1655−40 hard X-ray outburst occurring on MJD 49800 (Section 4.2.1) was accompanied neither by known ejections nor by radio emission, suggesting that accretion processes leading to hard X-ray emission are not uniquely related to the ejection of plasmoids (Tavani et al. 1996).
<table>
<thead>
<tr>
<th>Source</th>
<th>MJD</th>
<th>Radio flare</th>
<th>Soft X-ray emission</th>
<th>Hard X-ray emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRS1915+105</td>
<td>49382, 49402, 49431, 49464, 49939, 50300, 50751</td>
<td>○, ○, ●, −, ●, X, ●</td>
<td>●, ○, ●, −, −, −, −, −, X</td>
<td>●, ●, ●, ●, ●, X, ●</td>
</tr>
<tr>
<td>GRO J1655−40</td>
<td>49574, 49605, 49668, 50250</td>
<td>●, ●, ●, X</td>
<td>●, ●, ●, ●, ●, X</td>
<td>●, ●, ●, ●, ●, ●, X</td>
</tr>
<tr>
<td>GX 339−4</td>
<td>50300</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 4.1: *The approximate dates of ejection events vs. recorded activity in the radio and soft and hard X-rays. The filled circles indicate a positive correlation between ejection events and major radio flares and hard X-ray activity. The open circles mark when ejections occurred, but were not accompanied by major radio flares. The X's denote that there was activity in the corresponding wavelength bands, but as no high resolution imaging was undertaken, it is not possible to verify whether an ejection event occurred. The dash means no observations are available.*
Chapter 5

Conclusions and future prospects

Jets are observed from a variety of astrophysical sources, from supermassive black holes residing in galaxies to proto-stellar objects. Understanding the mechanism behind jet ejection for one class of objects may shed light on some of the mysteries in the others. As they are strong radio and X-ray emitters, the radio-jet X-ray binaries are ideal objects for study because of their rapid time variability and their accessibility in terms of observations. Although these questions are not resolved here, we have attempted to highlight some aspects of the behavior in the light curves.

The work presented in the papers of this thesis has described the multiple facets of the radio-jet X-ray binaries, mainly concentrating on the diversity of behavior exhibited in their light curves. There is obviously a relationship between the hard and soft X-rays and the radio, although it is not a straightforward one and it is not consistent for the same source. This is also seen in blazars and optically violent variable quasars, where occasionally X-ray flares follow radio activity and at other times the opposite is true (e.g. von Montigny et al. 1997; Wehrle et al. 1998; Ulrich, Maraschi & Urry 1997, and references therein).

The succession of hard X-ray and radio outbursts observed from GRO J1655–40 during the 1994 ejection events was presumed to reflect the feeding of material into jets. However, this does not appear to be the only signature for jet ejection events as demonstrated by the soft and hard X-ray and radio light curves for GRS 1915+105 from the 1997 ejections, during which the radio and soft X-rays went into a “full” state prior to the ejection. If the jet from GX 339–4 is confirmed, then we have yet another scenario in which all three wavelengths are correlated, suggesting a common, localized origin for the photons that give rise to the observed radio and X-ray emission. The confirmed ejection events from GRS 1915+105 and GRO J1655–40 and the possible event in GX 339–4 are accompanied by major radio flares, or at least some degree of activity in the radio as in the case of the first two ejections from GRS 1915+105. However, all the ejection episodes from the three sources occurred during periods of enhanced hard X-ray emission, indicating either that accretion processes play a major role at these times or that one common property of these sources is that a corona is formed prior to the ejections.

Radio spectral indices are probably the most solid indicators of ejection events, as an inversion in the spectrum signifies the presence of an optically thick component, which could very well be the formation of the ejecta prior to being expelled. As the ejecta move away from the central source and expand the spectrum will become a pure synchrotron power law. This was seen in
GRS 1915+105 during the 1997 ejections, and based on the similarity of the behavior in the data from 1996 we speculated, in the absence of any high-resolution imaging, that an ejection may have taken place.

Polarization was observed from GRO J1655—40 and GRS 1915+105 following ejection episodes, implying the presence of an ordered magnetic field. This supports the theory that matter may be drawn away from the central source along magnetic field lines. Spectra of polarized radio emission may be used as additional tracers of ejection events, as evidenced by the polarization observations of GRO J1655—40 which showed the evolution of a synchrotron bubble component.

Although much progress has been achieved in the field of radio-jet X-ray binaries in the past few years, a great deal still remains to be done. Simultaneous radio and X-ray observations are necessary in order to unravel the relationships between the accretion disk, a possible corona, accretion processes themselves and the multiple ejections of radio-emitting plasma clouds. Although jet ejection mechanisms themselves have not been dealt with in great depth in this thesis, we have singled out some features in the multiwavelength light curves which may be used as indicators of ejection events. In order to formulate a solid framework describing jet ejections and the mechanisms behind them, we need to find more potential jet sources, or record more events from the existing ones. Pinning down the moment of an ejection event will enable high-resolution radio imaging and broad-band X-ray spectroscopy to be carried out, in the framework of Target-of-Opportunity observations, and thus tell us more about the physical conditions at the source at these times. Hopefully, on-going and future radio and X-ray monitoring programs will alert us to this possibility.
Chapter 6

Summary of the original publications

6.1 Paper I

Superluminal Radio-Jet X-Ray Sources: Binary Systems?

Paper I deals briefly with the soft X-ray and radio light curves of GRS1915+105. Recent radial velocity measurements based on optical observations had confirmed that GRO J1655−40 was a binary consisting of a compact object whose mass was greater than the theoretical upper limit for neutron stars, implying a black hole primary, and an F3-F6IV secondary (Orosz & Bailyn 1997). High absorption towards GRS1915+105 prevented the identification of an optical companion, and hence any possible radial velocity measurements which would have shed light on the nature of the source. The intention in Paper I was to search the Ryle 15 GHz radio and RXTE/ASM 2–12 keV soft X-ray light curves for any behavior that may be indicative of periodicity linked to the orbital period of a binary system. This was spurred by the fact that the plasmoid ejections observed by Mirabel & Rodríguez in 1994 appeared to occur with an interval of approximately 28 days. However, no such obvious features were visible in the light curves, and though preliminary timing analysis had been undertaken on the soft X-ray light curve, this did not produce any concrete results.

6.2 Paper II

MOST Radio Monitoring of GX 339−4

GX 339−4 was discovered with the OSO-7 satellite in 1973 (Markert et al. 1973) and was classified as a black hole candidate binary, based on the similarity of its X-ray spectrum to that of the canonical black hole Cyg X−1.

Paper II presents simultaneous radio and X-ray monitoring of GX 339−4. The MOST observed GX 339−4 at 843 MHz from 1994 April to 1997 February. During this time BATSE was monitoring it in the hard (20–100 keV) X-rays, and shortly after launch in late 1995 the ASM on RXTE started to monitor it in the soft (2–12 keV) X-rays. Due to GX 339−4’s southerly declination, the MOST was one of the few radio telescopes that could observe it regularly. At times the hard X-ray and radio emission appear to be anticorrelated, i.e. there is significant flux in the radio when the source is quiescent in the X-rays and vice versa. Radio
coverage, especially at the beginning of the monitoring, was not sufficient to firmly establish this. However, a flare occurred in all three wavelength bands in mid-1996. Correlation analyses to the three datasets showed that the fluxes in all three energy ranges were well correlated with one another, indicating that the flare occurred simultaneously at all wavelengths. Interestingly, this corresponds to the epoch when Fender et al. (1997) reported a jet-like extension from high resolution ATCA radio observations; however, this feature (shown in Fig. 4.7) has not been confirmed in subsequent observations. The simultaneity of the outbursts at all wavelengths reported in Paper II suggests that there could indeed have been an outflowing of matter at that epoch; on the other hand, however, strong artifacts introduced by phase errors in the ATCA or strong flux density variations during the observation could mimic a jet.

6.3 Paper III

MOST radio observations of GX 339−4, GRS 1915+105 and GROJ1655−40

Besides GX 339−4, described in Paper II, the MOST also monitored GRS 1915+105 in 1996 and then briefly in 1997, and observed GROJ1655−40 for a period of about three months in 1994 and then again for about a week in 1996 following the rise of a soft X-ray outburst. In Paper III, we present the long-term radio and the soft and hard X-ray light curves of GX 339−4, GRS 1915+105 and GROJ1655−40, highlighting the differences in behavior not only amongst the three sources within the three energy ranges, but also the contrasts in behavior for the same source, as in the case of GROJ1655−40. The light curves of Paper II were reproduced here, showing that GX 339−4 flared simultaneously in three energy bands. A double-peaked radio outburst from GRS 1915+105 was observed with the MOST — this is discussed further in Papers IV and V. The GROJ1655−40 data showed that in 1994, during the time of the jet ejection events reported by Hjellming & Rupen (1995) and Tingay et al. (1995) radio outbursts followed major hard X-ray outbursts. However, in 1996, a radio outburst was observed preceding the onset of hard X-ray activity. The lack of a hard X-ray precursor to the radio outburst of GROJ1655−40 in 1996 was tentatively explained as being due to the absence of a hot corona, responsible for the upscattering of soft X-ray photons into the hard X-ray energy ranges. The light curves of GRS 1915+105 and GROJ1655−40 suggest that although both sources have displayed superluminal expansion, their natures may be intrinsically different.

6.4 Paper IV

GRS 1915+105: Exploring links between radio and X-ray emission

Further analysis of the radio and X-ray data of GRS 1915+105 was undertaken for Paper IV. The MOST 843 MHz light curve from the 1996 monitoring campaign is presented here, along with the GBI 2.25 GHz light curve from a flaring episode which occurred in 1997. Two-point spectral indices were derived from the MOST and Ryle 15 GHz data, and from the two (2.25 and 8.3 GHz) GBI frequencies. The RXTE/ASM light curve was partitioned into two energy ranges, 1.3–5 keV and 5–12.2 keV, so as to obtain a hardness ratio. A power law fit was applied to the BATSE 20–100 keV spectra. In addition, previously published RXTE/PCA data (Morgan, Remillard & Greiner 1997) were utilized. The main result to emerge from this
paper was the similarity in both the radio and the soft X-ray light curves during two radio flaring episodes, occurring over a year apart. The flares were characterized by a double-peaked outburst, the second outburst being more intense than the first, separated by a "null" phase. This was accompanied, in both cases, with a null phase in the soft X-ray light curve as well. During the second flaring episode (the GBI data), MERLIN high resolution radio images showed an ejection event to have occurred (Fender et al. 1999a). No high resolution radio imaging was undertaken during the flaring episode recorded with the MOST. However, due to the striking similarity of the behavior in the light curves during the two episodes, and the fact that the radio spectral indices showed evidence of an optically thick component on both occasions, we proposed that the double-peaked outburst during the first flaring episode was the signature of an ejection event.

6.5 Paper V


In 1994, Mirabel & Rodríguez (1994) observed the ejection of plasmoids from GRS 1915+105 at apparent superluminal velocities. In Paper V we compared MOST and BATSE data from 1996 to Nançay (1.4 and 3.2 GHz) and BATSE data from 1994 in an attempt to further determine whether jet ejections occurred in 1996. The Nançay radio light curve (Rodríguez et al. 1995) showed an energetic outburst to have occurred following the third ejection. Examination of the 20–100 keV photon index derived from power law fits to the BATSE spectra indicated a hardening of the spectrum following the major Nançay outburst. The evolution of the photon index in 1996 indicated the same trend — a slight hardening in the spectrum following the first radio outburst, but due to the large errors involved, this interpretation must be treated with caution. Dips in the BATSE light curve in 1994 appear to be associated with the ejections, suggesting that the jets disrupted the corona, assuming that the hard X-ray emission is attributed to the upscattering of soft X-ray photons in a hot corona. A similar dip was observed in the 1996 BATSE light curve, coincident with the onset of the second larger radio outburst. By analogy with the 1994 data, we tentatively suggested that an ejection may have occurred also in 1996.

6.6 Paper VI

ATCA Radio Observations of GRO J1655−40

GRO J1655−40 underwent multiple ejections in August 1994 (Hjellming & Rupen 1995; Tingay et al. 1995). The ATCA observed it at six radio frequencies, and recorded a major outburst. In addition, the radio emission was found to be linearly polarized following the outburst. In Paper VI, we present the total and polarized intensity from four observing frequencies (1.4, 2.3, 4.8 and 8.6 GHz), and discuss the fact that the polarized intensity initially showed evidence of the ‘synchrotron bubble’ (van der Laan 1966; Hjellming & Johnston 1988) behavior. Two-point spectral indices constructed from the low frequencies (1.4 and 2.3 GHz) and high frequencies (4.8 and 8.6 GHz) indicated the presence of an optically thick component immediately after the outburst. We discuss the radio behavior in terms of a ‘core+lobe’ model, where the core
is taken to be the central source enveloped by an extended plasma cloud and the lobes are the expanding ejecta.

6.7 Paper VII

Radio emission from GRO J1655–40 during the 1994 jet ejection episodes

We elaborate on the GRO J1655–40 data discussed in Paper VI, by presenting the ATCA data at all six frequencies (the four frequencies mentioned above and 5.9 and 9.2 GHz), in addition to MOST and HartRAO (5 and 8.58 GHz) data. We also present the MOST data in relation to the BATSE light curve. Two major radio outbursts were observed with the MOST from the time of the ejections, and the light curve exhibited the same more-or-less exponential decay as observed with the VLA (Hjellming & Rupen 1995). However, due to better time sampling, the MOST also detected two short-duration outbursts which were not observed with the VLA. We derived two-point spectral indices from the MOST and HartRAO data, and from the MOST and ATCA datasets. Based on the temporal evolution of the spectral indices derived from the MOST and ATCA data, the validity of some of the ejection epochs presented by Hjellming & Rupen (1995) are questioned. A plot of the fractional polarization at all six frequencies shows three bubble-type features, two of which can be explained by the synchrotron bubble model. However, the third bubble-type event is in contradiction with the model. In addition, radio spectra constructed from the MOST and ATCA combined datasets showed a spectral downturn at low frequencies. Synchrotron self-absorption alone does not produce a satisfactory solution, but, owing to the presence of polarization, the synchrotron origin for the emission cannot be dismissed. We considered a hybrid model in which the spectral downturn could be due to thermal free-free emission from a compact region close to the black hole, and synchrotron emission would arise in the expanding ejecta, or lobes, hence the term ‘core+lobe’. The short-lived free-free component would be present at the onset of an ejection. The cooling timescale for free-free emission, as determined by the conditions in GRO J1655–40, agrees quite well with the duration of the short-duration burst components observed in the MOST light curve. We conclude that the core+lobe model fits the data quite well, as it also solves the problem with the third bubble-type event in the polarized emission.

Author’s contribution

The author of this thesis reduced the MOST observations of GRS 1915+105 with the assistance of R.W. Hunstead (Papers III, IV & V) and the ATCA data of GRO J1655–40 with the assistance of R.J. Sault (Papers VI & VII), and downloaded all RXTE/ASM and GBI light curves, in addition to the BATSE light curve of GRS 1915+105 (Papers III & V). The author undertook all of the analysis of the radio and X-ray data in all papers, with the participation of P. Durouchoux (Paper I), R.W. Hunstead in Papers II–VII and K. Wu in Papers VI and VII. In addition, the author was responsible for writing all sections of the papers, with the exception of Section 2 in Paper VI and Section 2 in Paper VII. Interpretation of the data was conducted with R.W. Hunstead (Papers II–VII) and K. Wu (Papers VI–VII), who provided assistance, especially in writing the Discussion sections.
Other contributions

All MOST radio observations were conducted by D. Campbell-Wilson (Papers II, III, IV, V, VII), and the ATCA radio observations of GRO J1655−40 by D.J. McKay (Papers VI and VII). Ryle Telescope radio data of GRS 1915+105 (Paper I) were kindly provided by G.G. Pooley and R.P. Fender. HartRAO radio data of GRO J1655−40 were kindly supplied by D.P. Smits (Paper VII). GBI radio data of GRS 1915+105 were downloaded from the Worldwide Web (Paper IV). All RXTE/ASM light curves were downloaded from the web (Papers I, II, III, IV & V). BATSE light curves of GX 339−4 were kindly provided by C. Robinson (Papers II & III), while the light curves of GRO J1655−40 were kindly supplied by W.S. Paciesas and S.N. Zhang (Papers III & VII); the spectra of GRS 1915+105 were kindly provided by C. Shrader and K. Watanabe (Papers IV & V). MOST observations of GX 339−4 were reduced by B. Piestrzynski (Paper II). BATSE GRS 1915+105 spectra were reduced by J. Poulalion and M. Williamson (Papers IV & V).

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