The Radio-Jet X-Ray Binaries

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We review the observational properties, from radio to X-rays, of the
eight systems for which there is strong evidence for the formation
of a radio jet in a X-ray binary system.

1 Introduction

Radio jets from an X-ray binary were first discovered from SS433 by Spencer [49] and subsequently mapped by Hjellming & Johnston [21] with the VLA. The jets had earlier been predicted on the basis of Doppler-shifting emission lines (e.g. [30]).

Over the past fifteen years the class of radio-jet X-ray binaries (RJXRB) has expanded slowly to include approximately eight sources for which there is direct observational evidence of jet formation. These systems, in approximate order of jet discovery, are:

- Cyg X-3, for which an expansion velocity of \( \sim 0.3c \) has been repeatedly measured during outbursts (e.g. [48]) but in which no observations have to date been able to resolve the motion of individual plasmons.
- 1E1740.7-2942 & GRS 1758-258, which while not definitely established as X-ray binaries, are bright hard X-ray sources near the galactic centre with spectacular arcmin-scale radio jets [37].
- LSI+61°303, a periodic radio flaring source with measured expansion following outburst [34].
- Cir X-1, another periodic flaring source which is embedded in a synchrotron structure with associated radio jets [50].
- GRS 1915+105, a spectacular X-ray and radio transient which mapping with VLA has revealed to possess relativistic jets with apparent superluminal motion, implying true velocities of \( \sim 0.9c \) [36].
Table 1  
Radio-jet X-ray sources: system properties

| Source          | Spectral class of companion | Compact object | Periodicities ('o' = orbital) | Distance (kpc) |
|-----------------|-----------------------------|----------------|-------------------------------|----------------|
| SS433           | OB (?)                      | ?              | 13 d (o), 164 d               | 8              |
| GRS 1915+105    | Red giant/dwarf ?           | black hole     |                               | 10 – 12.5      |
| GRO J1655-40    | F or G                      | black hole     | 2.6 d (o)                     | 3 – 6          |
| Cyg X-3         | W-R (?)                     | ?              | 4.8 h (o)                     | 8.5–12         |
| Cir X-1         | MS                          | neutron star   | 16.6 d (o)                    | ≥ 6.5          |
| LSI+61° 303     | Be                          | ?              | 26.5 d (o), 4 yr (?)          | ~ 2            |
| 1E 1740.7-2942  | binary ?                    | black hole     |                               | 8.5 (g.c.)     |
| GRS 1758-58     | binary ?                    | ?              |                               | 8.5 (g.c.)     |

- GRO J1655-40, a second superluminal X-ray transient, with ~ 0.9c jets resolved by southern hemisphere VLBI [54] and the VLA [23].

Only SS 433 and the two superluminal transients indisputably possess collimated outflows, while 1E 1740.7-2942 & GRS 1758-258 are not actually established as binary systems (the binarity of GRS 1915+105 has not been definitively established but seems highly likely) – in our opinion the order of reality of the RJXRB classification (with the first three beyond doubt) is: SS 433, GRS 1915+105, GRO J1655-40, Cyg X-3, Cir X-1, LSI+61° 303, 1E 1740.7-2942 & GRS 1758-258. We do not include in the list the sources GT 2318+620 [51] and GX 1+4 [28] for which RJXRB status has been claimed but the evidence is at present uncertain.

Table 1 summarises the overall properties of the RJXRBs. In the following sections we review the observational properties of these sources, looking for any common properties which might link them.

2 A multiwavelength comparison

2.1 Radio

All the sources are radio-bright, unusual in itself for X-ray binaries (some ~ 25 of the ~ 200 known X-ray binaries have been found to have detectable radio emission – see e.g. [20]). In all cases the radio emission mechanism is dominated by non-thermal synchrotron emission, characterised by very high (> 10^8 K)
### Table 2
**Summary of Radio and (sub)mm observations of radio-jet XRBs.**

|               | F$_{cm}$ quiescent/ | F$_{mm}$ quiescent/ | notes                                          |
|---------------|---------------------|---------------------|------------------------------------------------|
|               | brightest flare (Jy)| brightest flare (Jy)|                                                |
| SS433         | $\sim 0.5 / \geq 10$| $\sim 0.1$          | (1)                                            |
| GRS 1915+105  | $\sim 0.01 / \geq 1$| $< 0.01$            | (2)                                            |
| GRO J1655-40  | $< 0.01 / \geq 7$   | $-$                 | (2)                                            |
| Cyg X-3       | $\sim 0.05 / \geq 20$| $\sim 0.05 / \geq 3$| (3)                                            |
| Cir X-1       | $< 0.1 / > 3.0$     | $-$                 | (4)                                            |
| LSI +61° 303  | $\sim 0.03 / \geq 0.5$| $\sim 0.01$          | (5)                                            |
| 1E 1740.7-2942| $(< 1 / 5) \times 10^{-3}$| $< 0.11$            |                                                |
| GRS 1758-258  | $(< 1 / 5) \times 10^{-3}$| $< 0.09$            |                                                |

(1) cm – mm optically thin
(2) Radio flaring correlated with X-ray activity
(3) Radio flaring correlated with X-ray activity, mm excess
(4) Modulated at 16.6 d orbital period, decline since 1970s
(5) Modulated at 26.5 d orbital period, cm – mm optically thin

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![Green Bank radio monitoring](image)

**Fig. 1.** Two-year radio flux histories of SS 433, GRS 1915+105, Cyg X-3 & LSI+61° 303 from the NRL-Green Bank monitoring program. Note that the period for Cyg X-3 is different from that of the others in order to highlight some flaring activity.
brightness temperatures and a negative spectral index $\alpha = \Delta \log S/\Delta \log \nu$.

Fig 1 plots two-year flux histories of SS 433, GRS 1915+105, Cyg X-3 and LSI+61° 303 as observed during the (now terminated due to lack of funding) NRL-Green Bank monitoring program; table 2 summarises the radio properties of the RJXRBs.

SS 433 is a persistent bright radio source undergoing occasional outbursts during which its flux may increase by up to a factor of ten or so (e.g. [2]). The resolved radio plasmons trace out a corkscrew pattern on the sky reflecting (probably) the precession of the accretion disc [22]. Large radio outbursts may correspond to the ejection of particularly bright plasmons from the system. The emission from the source is consistently optically thin (clear from the near-constant separation of the 13.3 cm & 3.6 cm light curves for SS 433 in Fig 1), and the optically thin tail has been measured out to mm wavelengths [55].

The radio emissions from GRS 1915+105 and GRO J1655-40 share many common properties. Both systems are below the detection limits of current telescopes for the majority of the time between outbursts, and during the outbursts the flux density can increase by a factor of $> 1000$. It is during these outburst periods, correlated (to a certain extent) with X-ray flaring (e.g. [13,23]) that individual plasmons are tracked moving away from the systems at velocities of order 0.9 c [36,54]. The spectral index of emission from both sources indicates varying degrees of opacity, with absorption particularly prominent in the early stages of outbursts. Upper limits to the (sub)millimetre emission from GRS 1915+105 [55] are consistent with an optically thin spectrum. High time resolution observations of GRS 1915+105 have revealed radio QPO with periods in the range 20 – 120 min [42,43].

Cyg X-3 is a persistent bright radio source, occasionally undergoing huge outbursts when its radio flux density can increase by factors $> 50$ on timescales of days (e.g. [16] et seq). At these times the source is observed to become an expanding radio source with expansion velocity $\sim 0.3c$ (e.g. [48]). Prior to major outbursts, the radio flux from the source is often observed to drop to very low levels (e.g. [57]). Quiescent emission in Cyg X-3 from cm – mm is typically flat with a significant excess at mm wavelengths [9] indicative of absorption. During flaring sequences the emission typically progresses from absorbed to optically thin both within individual flare events and along the flaring sequence (e.g. [11]).

About the radio emission from Cir X-1, less is known. The source was observed several times in the 1970s to undergo radio flaring once every 16.6 days but has since then been declining steadily in radio luminosity (G. Nicholson, private communication). Mapping of the system has revealed it to be embedded within
Table 3
Summary of infrared observations of radio-jet XRBs

|                | $F_{2.2\mu m}$ quiescent/ brightest flare (mJy) | spectral features | notes |
|----------------|-----------------------------------------------|-------------------|-------|
| SS433          | > 50                                          | H, He I           | (1)   |
|                |                                               | (Doppler shifted) |
| GRS 1915+105   | $\leq 1 / \geq 4$                             | H, He I (flaring) | (2)   |
| GRO J1655-40   | –                                             | –                 |       |
| Cyg X-3        | $\sim 12 / \geq 50$                           | He I, He II, N    | (3)   |
|                |                                               | (Wolf-Rayet-like) |
| Cir X-1        | $\sim 15$                                     | –                 | (4)   |
| LSI +61° 303   | $\sim 400$                                    | –                 | (5)   |
| 1E 1740.7-2942 | < 0.1                                         | –                 | (6)   |
| GRS 1758-258   | < 0.1                                         | –                 |       |

(1) Modulated at 13 d orbital and 164 d disc precession periods (2) $> 1$ mag variability at JHK (3) modulated at 4.8 h orbital period, rapid flares, no H in spectrum (4) large broad flare once per 16.6 d orbit (5) modulated at 26.5 d orbital period (6) $K > 17$

a synchrotron nebula, with swept-back jets suggesting ejection from the nearby SNR G321.9-0.3 [50].

LSI+61° 303, like Cir X-1, is a periodically flaring source, this time once every 26.5 days (presumably orbital in origin) (e.g. [46]). Radio mapping following one outburst suggests an expansion velocity of several 1000 km s^{-1} [34]. During radio flares the source can increase its flux by a factor of 5 – 10, similar to SS 433.

Both 1E 1740.7-2942 & GRS 1758-258 have associated arcmin-scale radio jets [37], and while radio monitoring has been sporadic due to their relative faintness, they are clearly variable sources [31].

2.2 Infrared

Table 3 summarises the infrared properties of the RJXRBs.

SS 433 has been observed in the infrared both photometrically and spectroscopically [26,53]. Spectral studies reveal stationary and Doppler-shifted lines
(see section 2.3) while photometry reveals a modulation at the 13 d orbital period which is itself modulated in shape with the 164 d precession period. This effect is interpreted by Kodaira et al [26] as arising in infrared emission from an accretion disc of which different aspects are on view at different disc precession phases. Infrared imaging with the IRAS satellite has revealed a series of ‘knots’ which may be associated with the jets [58].

GRS 1915+105 has a variable infrared counterpart in the JHK bands (e.g. [6]), but no periodicities have been found in the modulation. Infrared spectroscopy (e.g. [4]) has revealed H & He emission lines which appear to be more prominent when the system is in an active state. High-resolution infrared imaging may have resolved the jet in GRS 1915+105 [47].

Infrared observations of GRO J1655-40 have been few due to a relatively bright optical counterpart, but the infrared flux has been seen to brighten during radio outburst and there may be evidence for ellipsoidal modulation of the secondary [3].

Cyg X-3 is a bright infrared source, which modulates in the IJHKL bands at the 4.8 hr (presumed) orbital period (e.g. [33]). Superimposed upon this modulation are often observed rapid flare events which may arise in hot (10⁶ K) gas associated with the disc/jet [10]. Infrared spectroscopy of Cyg X-3 has revealed broad Doppler-shifted emission lines reminiscent of a Wolf-Rayet star, suggesting that Cyg X-3 may be the first W-R + compact object system identified [56].

Cir X-1 has been observed to flare in the infrared at the same period as the radio emission [14], but few recent observations have been made.

There are claims that LSI+61° 303 modulates in the infrared at the 26.5 d period [41], but these remain controversial.

No infrared counterparts have been identified for 1E 1740.7-2942 or GRS 1758-258, to a limiting magnitude of ~ 17 [37].

2.3 Optical

Table 4 summarises the optical properties of the RJXRBs.

SS 433 was originally identified as a strong Hα emission-line star (hence its inclusion in the SS catalogue). Optical spectra of the source reveal many emission lines, all of which can be classified as either ‘stationary’ or ‘moving’, the latter with varying Doppler-shifts and associated with the jets (e.g. [29]). Photospheric features of the companion star are very difficult to disentangle, but
Table 4
Summary of optical properties of radio-jet XRBs

| V mag quiescent/ flaring | spectral features | notes |
|--------------------------|------------------|-------|
| SS433                    | 14.2             | H, He, C, N, Fe (1) |
| GRS 1915+105             | –                | – (2) |
| GRO J1655-40             | ≥ 17 / ≤ 14      | H, He I, He II, N III |
| Cyg X-3                  | > 24             | – (3) |
| Cir X-1                  | 20.6             | Hα (4) |
| LSI +61 ° 303            | 10.7             | H, He, Si (5) |
| 1E 1740.7-2942           | –                | – (6) |
| GRS 1758-258             | –                | – (6) |

(1) Stationary and Doppler-shifted lines, few photospheric features (2) I ∼ 24, R > 21 (3) I ∼ 21, R ∼ 24 (4) possible previous source confusion (5) ‘Shell’ Hα & Hβ (6) I > 21

may be reminiscent of an OB or W-R type star (though note there is still plenty of hydrogen in the SS 433 system). No periodically Doppler-shifting emission lines have ever been seen in another X-ray binary, and so SS 433 remains the only source for which there is direct evidence for the ejection of protonic matter at near-relativistic velocities.

GRO J1655-40 has a relatively bright, variable optical counterpart [1]. Spectroscopy of the source has revealed strong emission lines, particularly during outburst, and absorption line radial velocity studies have revealed a 2.6 d orbit and a mass function convincingly implying a black hole as the compact object [1]. Photometric variations and anomalies in the radial velocity curve around conjunction may also suggest an eclipse.

Cir X-1 is difficult to observe in the optical not only because it is a faint source but also because it lies within 2 arcsec of two other stars [38]. Apart from Hα emission (e.g. [39]) little is known about the optical counterpart to the source.

LSI+61 ° 303 has a bright optical Be-type companion star which shows photospheric absorption features as well as Hα and Hβ emission from the circumstellar disc (I. A. Steele, private communication). Attempts to determine a radial velocity curve at the 26.5 d radio period have had little success however and a good mass function has not been determined. There may be a photometric modulation at the radio period [41].

GRS 1915+105, Cyg X-3, 1E 1740.7-2942 & GRS 1758-258 have no optical
Table 5: Summary of X-ray properties of radio-jet XRBs

| Source          | X-ray luminosity in low/high states (erg s\(^{-1}\)) | spectral features | comments |
|-----------------|------------------------------------------------------|-------------------|----------|
| SS433           | \(10^{35}/10^{36}\)                                  | Fe                | (1)      |
| GRS 1915+105    | \(<10^{37}/10^{38}\)                               | Fe absorption    | (2)      |
| GRO J1655-40    | \(<10^{37}/10^{38}\)                               | Fe absorption    | (2)      |
| Cyg X-3         | \(10^{37}/10^{38}\)                                 | Fe, Si, Ne       | (3)      |
| Cir X-1         | \(10^{37}/10^{38}\)                                 |                   | (4)      |
| LSI +61° 303    | \(10^{33}/10^{34}\)                                 |                   | (5)      |
| 1E 1740.7-2942  | \(\geq 10^{36}\)                                    | 511 keV e\(^{+}\)e\(^{-}\) line? | (6)      |
| GRS 1758-258    | \(\geq 10^{36}\)                                    |                   | (6)      |

(1) X-ray jets (2) X-ray outbursts correlated with radio, hard X-ray tail (3) hardness anticorrelated with brightness, modulation at 4.8 h orbital period (4) type I bursts, QPOs, ‘Atoll’ source (5) X-ray flares once per 26.6 d orbit (6) bright in hard X-rays counterparts.

2.4 X-ray

Table 5 summarises the X-ray properties of the RJXRBs; Fig 2 shows 100-day soft X-ray flux monitoring of all of the sources with the XTE ASM.

SS 433 is a weak X-ray source by the standards of X-ray binaries, with a luminosity of \(\sim 10^{35}\) erg s\(^{-1}\). However, while the brightness and flux variations of the source may not be very dramatic, it does possess spectacular X-ray jets from which up to 10% of the soft X-ray emission of the source may arise, which appear to confirm the connection with the surrounding SNR W50 and place a lower limit on the lifetime of the jet phenomenon of several 1000 yr [59].

GRS 1915+105 & GRO J1655-40 share many similar X-ray properties as bright transient sources. Both tend to rise from obscurity to amongst the most luminous X-ray sources in the galaxy on short timescales (see Fig 2 for a nice example of GRO J1655-40 ‘switching on’). ASCA X-ray spectra of both sources also reveal iron absorption features in the range 6 – 8 keV [8]. Greiner, Predehl & Pohl [17] have discovered a dust scattering halo around GRO J1655-40 with ROSAT. High time resolution observations of GRS 1915+105 with XTE reveal very rapid and dramatic flux changes at about the same time as radio QPO were being observed [18,12].
Fig. 2. 100 days of flux monitoring of the RJXB in soft X-rays with the XTE ASM (quick-look results provided by the ASM/RXTE team). Note the rapid fluctuations in the flux from GRS 1915+105, the 'flaring' behaviour of Cir X-1, and the rapid 'switch on' in the flux from GRO J1655-40.
Cyg X-3 is a bright and persistent X-ray source, varying generally by no more than a factor of ten in X-ray luminosity (e.g. [45]), which is anticorrelated with X-ray spectral hardness (e.g. [19]). Both soft and hard X-rays are modulated at the 4.8 h period, *in phase* with the infrared modulation [33,35]. X-ray spectra of the source reveal a host of emission features, some of which modulate in strength and width in *antiphase* with the continuum [25], and which require a nebular origin for much of the X-ray emission [27]. ROSAT observations have revealed a dust scattering halo around Cyg X-3 [44], and a larger X-ray scattering structure may also exist [24].

Cir X-1 is another persistent bright source, displaying type I bursts, QPO and movement in the X-ray colour-colour diagram characteristic of an ‘atoll’ low-mass XRB (e.g. [40]). The unusual X-ray behaviour of Cir X-1 has been theorised by Oosterbrook et al [40] to arise as a result of near-supercritical accretion onto a *low magnetic field* neutron star.

LSI+61°303, like SS 433, is a weak X-ray source by comparison with the other X-ray binaries, with a luminosity of $\sim 10^{34}$ erg s$^{-1}$ (e.g. [15]). X-ray flaring once per 26.5 d orbit is interpreted as being due to supercritical accretion during periastron passage of the compact object. High time resolution observations reveal no evidence for X-ray pulsations in the system [52].

1E 1740.7-2942 & GRS 1758-258 are relatively weak soft X-ray sources but dominate the galactic centre region at energies above several hundred keV [37]. 1E 1740.7-2942 is in fact the hardest X-ray source within 1° of the galactic centre and may be associated with 511 keV $e^-e^+$ emission, hence its popular name ‘The Great Annihilator’. The 2-500 keV spectrum of 1E 1740.7-2942 is very similar to that of the black hole candidate Cyg X-1 [7].

3 Discussion

Lack of space precludes an in-depth discussion of the nature and observational properties of the RJXRBs. While the ‘class’ contains a highly varied and seemingly disparate group of systems, it should be borne in mind that it may only be the environment in the *inner region of the accretion disc* which allows/forces the formation of a radio-jet, and that jet formation may be to a large extent independent of the properties of the individual components of the binary.

We choose to briefly highlight three properties which may be common to (are at least *consistent with*) all the RJXRB:

- Presence of an accretion disc during jet formation: long required by many
theoretical models, much of the spectroscopic and photometric evidence is consistent with this scenario.

- Correlated radio – X-ray behaviour: In all sources there seems to be at least some degree of radio – X-ray correlation, though properties such as lags between flaring in the two regimes do vary.

- Low magnetic field compact object: Many of the RJXRB are convincing black-hole candidates, illustrating that the compact object does not supply the magnetic field required for the synchrotron emission (it most likely originating in material in the accretion disc). The only source for which there is direct evidence of a neutron star is Cir X-1, a source in which the unusual X-ray properties have been modelled as arising from a high rate of accretion onto a low magnetic field neutron star. Combined with a lack of detected radio emission from any X-ray pulsar, the implication is that a strong compact object magnetic field inhibits jet formation, possibly by preventing formation of a stable inner accretion disc region.

4 Conclusions

We have presented a review of the observational properties of the eight sources we consider to be radio-jet X-ray binaries. We note that while the sources vary widely in systems parameters, all data is consistent with the formation of an accretion disc during jet formation (at least), some degree of correlated radio – X-ray behaviour, and a low or non-existent (i.e. black hole) compact object magnetic field.

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