

The variable radio counterpart and possible large-scale jet of the new Z-source XTE J1701-462

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ABSTRACT

We report radio observations, made with the Australia Telescope Compact Array, of the X-ray transient XTE J1701-462. This system has been classified as a new ‘Z’ source, displaying characteristic patterns of behaviour probably associated with accretion onto a low magnetic field neutron star at close to the Eddington limit. The radio counterpart is highly variable, and was detected in six of sixteen observations over the period 2006 January – April. The coupling of radio emission to X-ray state, despite limited sampling, appears to be similar to that of other ‘Z’ sources, in that there is no radio emission on the flaring branch. The mean radio and X-ray luminosities are consistent with the other Z sources for a distance of 5–15 kpc. The radio spectrum is unusually flat, or even inverted, in contrast to the related sources, Sco X-1 and Cir X-1, which usually display an optically thin radio spectrum. Deep wide-field observations indicate an extended structure three arcminutes to the south which is aligned with the X-ray binary. This seems to represent a significant overdensity of radio sources for the field and so, although a background source remains a strong possibility, we consider it plausible that this is a large-scale jet associated with XTE J1701-462.

Key words: ISM:jets and outflows; radio continuum:stars

1 INTRODUCTION

The relation between accretion and outflow is a key topic in modern high energy astrophysics and offers us a unique opportunity to understand the physics of distant, supermassive black holes in active galactic nuclei (AGN) by studying nearby, rapidly varying objects such as X-ray binaries. Much of the focus in recent years has been on black holes and how accretion scales between those of mass $\sim 10M_{\odot}$ in XRBs and those of mass $\geq 10^5M_{\odot}$ in AGN (Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004; see also Maccarone, Gallo & Fender (2004); Körding, Corbel & Falcke 2006; Wang, Wu & Kong 2006; McHardy et al. 2006).

However, the neutron star XRBs represent an extremely valuable ‘control sample’. These systems also produce dramatic jets (e.g. Fomalont et al. 2001; Fender et al. 2004) over a wide range of accretion rates (Migliari & Fender 2005). By comparing the two classes of object we can test the necessity of black hole-specific physics, such as event horizons and static limits, on the observed phenomena of accretion and jet production (e.g. Körding, Fender & Migliari 2006).

The ‘Z sources’ are the six (or seven, if you include Cir X-1) most luminous neutron star X-ray binaries in our galaxy, persistently accreting at close to the Eddington limit (within a factor of a few). Their name comes from the characteristic pattern traced out in X-ray colour-colour diagrams [CDs] (Hasinger & van der Klis 1989; van der Klis 2006 and references therein). All Z sources are detected in the radio band with approximately the same radio luminosity (Penninx 1989; Fender & Hendry 2000). Penninx et al. (1988) discovered a relation between the three branches of the ‘Z’ in the CD and the strength of the radio emission (see Migliari & Fender 2006 for further discussion and references). The two Z sources in which the radio emission has been spatially resolved, Sco X-1 and Cir X-1, are both found to be associated with highly relativistic flows energising slower-moving radio emitting components (Fomalont et al. 2001; Fender et al. 2004). In particular, the most relativistic flow yet identified in our galaxy is associated with the neutron star jet source Cir X-1 (Fender et al. 2004) which sometimes displays X-ray spectral and timing characteristics similar to that of the Z sources. SS 433 may also display this characteristic of an unseen, fast flow energising slower-moving knots (Migliari et al. 2005), which is not something which has been observed in any *bona fide* black hole candidate.

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Epoch	Detection	Start UT	Stop UT	Hr on target	$S_{4.8GHz}$	$S_{8.6GHz}$	X ?	X-ray state
A	yes	Jan22 21:56	Jan22 23:00	0.98	0.3 ± 0.15	0.4 ± 0.1	no	HB/NB
B	yes	Jan24 22:25	Jan25 05:40	6.32	0.37 ± 0.06	0.36 ± 0.05	partial	upper → lower HB
C	poss	Jan25 23:15	Jan26 00:54	1.49	< 0.18	< 0.27	yes	FB
D	poss	Jan29 04:18	Jan29 05:23	0.93	< 0.24	< 0.42	no	upper HB
E	no	Feb05 03:20	Feb05 05:02	1.34	< 0.24	< 0.33	no	mid HB
F	yes	Feb06 18:37	Feb06 21:35	2.58	0.67 ± 0.09	0.55 ± 0.07	no	NB / FB
G	no	Feb07 20:10	Feb07 21:04	0.75	< 3.5	< 1.0	no	FB
H	no	Feb11 01:37	Feb11 01:57	0.34	< 0.42	< 0.8	no	mid HB
I	no	Feb12 00:45	Feb12 01:49	0.98	< 1.8	< 0.9	no	upper HB
J	no	Feb18 19:31	Feb18 21:00	1.19	< 0.15	< 0.3	no	mid / lower NB
K	yes	Feb20 18:40	Feb20 21:06	1.91	0.2 ± 0.1	0.35 ± 0.1	no	mid NB
L	no	Mar06 19:23	Mar06 21:05	1.33	< 0.27	< 0.27	no	NB / FB vertex
M	yes	Mar08 16:30	Mar08 21:00	3.96	1.26 ± 0.05	1.60 ± 0.07	yes	NB / HB
N	yes	Mar13 15:19	Mar13 22:53	6.64	0.32 ± 0.03	0.35 ± 0.06	no	HB
O	poss	Mar20 12:10	Mar20 22:00	8.35	< 0.15	< 0.15	no	mid / lower NB
P	no	Apr 23 14:51	Apr 23 20:39	5.02	< 0.05	< 0.1	no[?]	FB

Table 1. Summary of radio observations of XTE J1701-462. Column 1 gives the Epoch label, which is used in the discussion in the main text, and also Fig 1. Column 2 indicates whether or not there was a detection of the radio source; only for those unambiguous detections, where yes is indicated, do we provide flux densities. Columns 3-5 give start and stop times and total hours on-source. Columns 6 and 7 give detections or upper limits at 4.8 and 8.6 GHz respectively (note that in some cases we have indicated detections which appear to be less than three times the error – this is due to uncertainties in the flux calibration for short observations, and does not indicate the reliability of the detection; this particularly applies to epochs A and K). All measurements are based upon naturally-weighted maps, and all upper limits are 3 times the r.m.s. noise in the area of the source. Column 8 indicates whether or not the observation was strictly simultaneous with an observation by RXTE, and column 9 indicates our best estimate of the branch or branches of the Z occupied by the source at, or close to, the time of the radio observation.

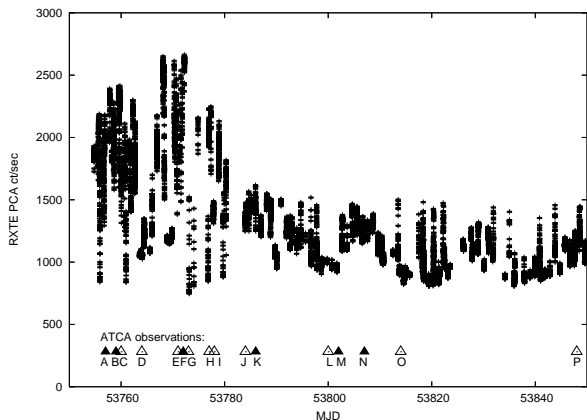


Figure 1. RXTE PCA monitoring of XTE J1701-462 over the period 2006 Jan-April, the first 100 days of the outburst. The epochs of the sixteen ATCA radio observations in this period are indicated – only at epochs marked by filled symbols are there unambiguous radio detections of the X-ray binary.

1.1 XTE J1701-462: a new, transient, Z source

XTE J1701-462 was discovered by the RXTE satellite as a bright new X-ray transient on 2006 Jan 18 (Remillard et al. 2006). X-ray observations soon indicated that it was likely to be a ‘new’ Z source (Homan et al. 2006a,b). An infrared counterpart was reported (Maitra et al. 2006; Maitra & Bailyn 2006), which was found to be coincident with a radio source (Fender et al. 2006), although formally inconsistent with a localisation from the Swift X-ray Telescope (Kennea et al. 2006). Subsequent localisation to better than one arcsec with *Chandra* confirmed the association with the optical / infrared / radio counterparts (Krauss et al. 2006).

Homan et al. (2007) recently reported the first two months’ of RXTE observations of the source, summarising the evidence for its classification as a new Z source. Colour-colour and Hardness-Intensity diagrams (CD, HID respectively) are commonly used to

identify patterns of X-ray behaviour in galactic accreting X-ray sources (e.g. Homan & Belloni 2005; van der Klis 2006). In Homan et al. (2007) it was noted that the pattern XTE J1701-462 traced out in the CD / HID changed significantly on at least nine occasions in the first 70 days of the outburst. In particular it was noted that for the first ~ 25 days of the outburst (i.e. up to around 2006 Feb 16 / MJD 53782) the source was ‘Cyg-like’, and subsequently most ‘Sco-like’, these labels referring to apparent subgroups within the Z sources (see Homan et al. 2007 for more details).

2 OBSERVATIONS

XTE J1701-462 was observed at sixteen epochs with the Australia Telescope Compact Array (ATCA) between 2006 Jan 22 – April 23. All observations were made simultaneously at 4.8 and 8.6 GHz. A log of these observations is presented in table 1, and Fig 1 indicates the observation epochs on a lightcurve of the X-ray emission. Many of the observations were very short (nine of the sixteen were less than 1.5 hr on source) which resulted in some difficulties in mapping the source. Six of the observations (A, B, F, K, M, N) resulted in unambiguous detections.

No polarised signal was detected at any time, with an upper limit on the linear and circular polarisation of $\leq 6\%$ for epoch M, when the source was brightest.

Data reduction was performed with the MIRIAD package (Sault, Teuben & Wright 1995). In most cases naturally weighted, cleaned maps, were used for image analysis. We were able to produce a combined map from all the data using visibilities calibrated individually at each epoch. Fig 2 presents a 4.8 GHz map of the field of XTE J1701-462 in which all sixteen datasets were combined, resulting in slightly more than 24 hr on-source. The radio counterpart of XTE J1701-462 is clearly detected at RA 17:00:58.43 Dec -46:11:08.44, with an uncertainty of about 0.3 arcsec in each coordinate.

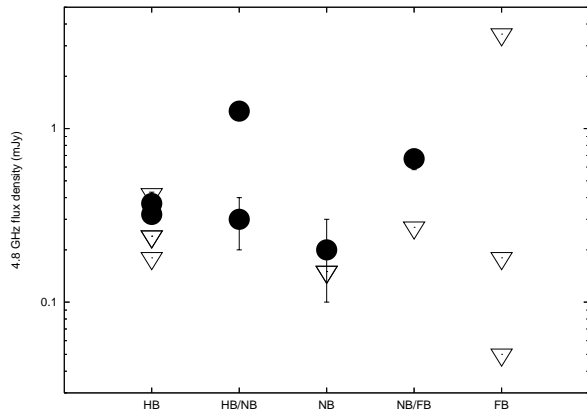


Figure 2. Radio detections (filled circles) and upper limits (open triangles) as a function of our estimate of the branch / branches of the Z the source was on at / close to the time of the radio observations (see table 1). The results are consistent with, but do not independently establish, the relation claimed for the Z source GX 17+2, in which radio emission is strongest on the HB/NB, and suppressed on the FB.

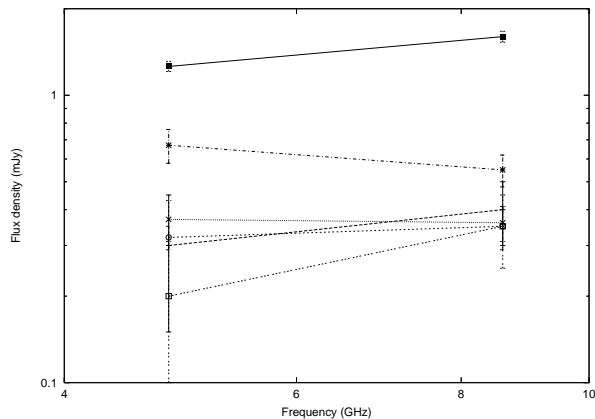


Figure 3. Two-point radio spectra for XTE J1701-462 for the six unambiguous detections. The spectra are generally flat or inverted, in contrast to the optically thin emission usually associated with transients. If real, this indicates that when the radio emission is detected the jet is currently being generated in regions with significant synchrotron self-absorption (i.e. the base of the jet close to the neutron star).

3 DISCUSSION

3.1 Coupling between radio and X-ray emission

In order to compare the radio and X-ray properties of XTE J1701-462, we have made an estimate of which part of the 'Z' the source was on at or close to the time of each radio observation. XTE J1701-462 was observed 97 times with RXTE between 2006 Jan 22 - March 20, and once on 2006 April 23, providing simultaneous X-ray coverage for three of our radio observations and X-ray coverage within a few hours for the others. The RXTE observations before March 20 were all classified according to their timing properties and position in X-ray colour-colour diagrams by Homan et al. (2007) and a separate analysis of the 2006 April 23 RXTE observation was done for this paper. The location along the Z tracks was estimated for the RXTE observations that were closest in time to our radio observations, by determining their position (upper/middle/lower) along the branches of full Z tracks that were traced out in various time intervals (see Fig. 3 in Homan et al.

2007). These estimates are indicated in Table 1. The radio detections and upper limits are also indicated as a function of branch of the Z in Fig 2.

Our observations appear to indicate that XTE J1701-462 is most likely to be detected as a radio source when on the horizontal or normal branches (HB, NB) of the Z. There are no detections on the flaring branch, including the most stringent upper limit (observation P). This is consistent with the behaviour noted first for GX 17+2 by Penninx et al. (1988) and possibly universal for all Z sources (Penninx 1989). These periods of relatively strong radio emission almost certainly correspond to the formation of jet-like outflows and/or their interaction with the surrounding medium (as directly observed in the Z/Z-like sources Sco X-1 and Cir X-1; Fomalont et al. 2001; Fender et al. 2004). In particular, based primarily on results for Sco X-1, Migliari & Fender (2006) suggest that the HB / NB vertex may correspond to the point at which the most powerful eject events occur, and that the jet is suppressed on the FB.

The Z sources are likely to be accreting persistently (in most cases) at close to the Eddington limit. It may be useful to compare them to black hole X-ray binaries accreting at comparably high Eddington ratios, such as GRS 1915+105. Both classes of object make dramatic and rapid state transition and are associated with episodic production of powerful relativistic jets. Such objects may, in turn, be our best 'local' equivalents of quasars accreting at very high rates at redshifts of $z \geq 1$. Therefore careful comparison of objects such as XTE J1701-462 with black holes accreting at high rates may provide our best test of the effects of e.g. event horizons, static limits on accretion and jet formation.

3.2 Spectral index

The two-point radio spectra of these detections are plotted in Fig 3. It is interesting to note that for the majority of the radio detections of XTE J1701-462 the source radio spectrum is flat / inverted (spectral index $\alpha \geq 0$, where $S_\nu \propto \nu^\alpha$). This seems to be in contrast to most emission associated with transient outbursts from X-ray binaries which generally has an optically thin spectrum ($\alpha \leq -0.6$). Optically thin emission is also observed in Cir X-1 (Fender et al. 1998; 2004) and Sco X-1 (Fomalont et al. 2001), although in both sources episodes of flat-spectrum core emission has been seen. The flat/inverted radio spectrum is in fact more reminiscent of the steady, flat-spectrum radio emission observed from black holes in hard X-ray states (Fender 2001), although Migliari & Fender (2006) do suggest that it should also be observed in hard state neutron stars. Such flat-spectrum emission is believed to arise in a partially self-absorbed jet (Blandford & Königl 1979; Kaiser 2006). Given the rather poor coverage and weak source in most cases, there remains some uncertainty in these spectral index measurements. If the spectrum is genuinely flat or inverted it implies the ongoing production of a compact jet and not, for example, shocks in diffuse regions well separated from the binary. The limits on the polarisation ($\leq 6\%$ in Stokes Q, U, V) are consistent with the self-absorbed jet model – measured linear polarisations for flat-spectrum jets in black hole X-ray binaries are at the few % level (Fender 2001 and references therein).

3.3 Luminosity and distance

As noted above, it is a defining characteristic of Z sources that they are accreting at near to (sometimes in excess of) the Eddington limit

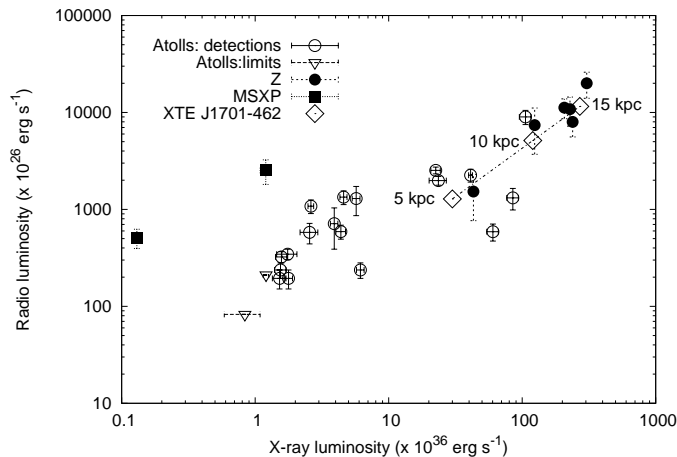


Figure 4. Radio luminosity as a function of X-ray luminosity for neutron star X-ray binaries. The Z sources are the most luminous group of objects in both bands. The locus of XTE J1701-462, around the time of our observation M, is indicated for three different distances.

for a 1.4 solar mass neutron star, and that they are relatively strong radio sources. Migliari & Fender (2006) plotted the radio luminosity as a function of X-ray luminosity for all neutron star X-ray binaries with radio counterparts, and indeed found the Z sources to be the most luminous in both bands. In Fig 4 we plot the same sample with a point representing XTE J1701-462 at each of three distances: 5, 10 and 15 kpc. The point is based upon the estimated flux of $\sim 10^{-8}$ erg s $^{-1}$ cm $^{-2}$ for observation phase G in Homan et al. (2007), which is close in time to our observation M. We have chosen a mean flux density for this period of ~ 0.5 mJy. We note that while this estimate of the mean radio flux does not take into account non-detections, nor did the estimates of Fender & Hendry (2000) on which the points for the other Z sources are based. Based solely on this rough comparison, it seems reasonable to conclude that XTE J1701-462 lies at a distance of ~ 10 kpc, with an error of a factor of two. Compare this to a different approach in Homan et al. (2007), where a distance of ~ 15 kpc was derived.

3.4 An ultrarelativistic jet and a large-scale nebula ?

Finally, the similarities with the other Z sources, in terms of the X-ray properties and their relation to the radio emission, suggest that XTE J1701-462 may harbour a relativistic jet like those resolved in Sco X-1 (Fomalont et al. 2001) and Cir X-1 (Fender et al. 2004). Future high angular observations with ATCA and Australian e-VLBI (Philips et al. 2007) may resolve and track the variability of such a jet.

Furthermore, Cir X-1 has an arcmin-scale radio nebula which seems to be powered by the central jet (Stewart et al. 1991; Tudose et al. 2006), as do a number of black hole X-ray binaries (e.g. Mirabel et al. 1992; Corbel et al. 2002). In order to investigate whether XTE J1701-462 may have a similar large-scale radio structure, we created a deep image by summing all of the available data (Fig5). Several fairly strong sources are clearly detected to the south of XTE J1701-462, and are approximately lined up back towards the X-ray binary. Peak fluxes for XTE J1701-462 and the sources A–D are listed in Table 2, measured from naturally weighted summed maps at both frequencies. The spectral index is also given, and indicates that sources A–D are all nonthermal in nature, with an apparent trend of steepening spectra with increasing

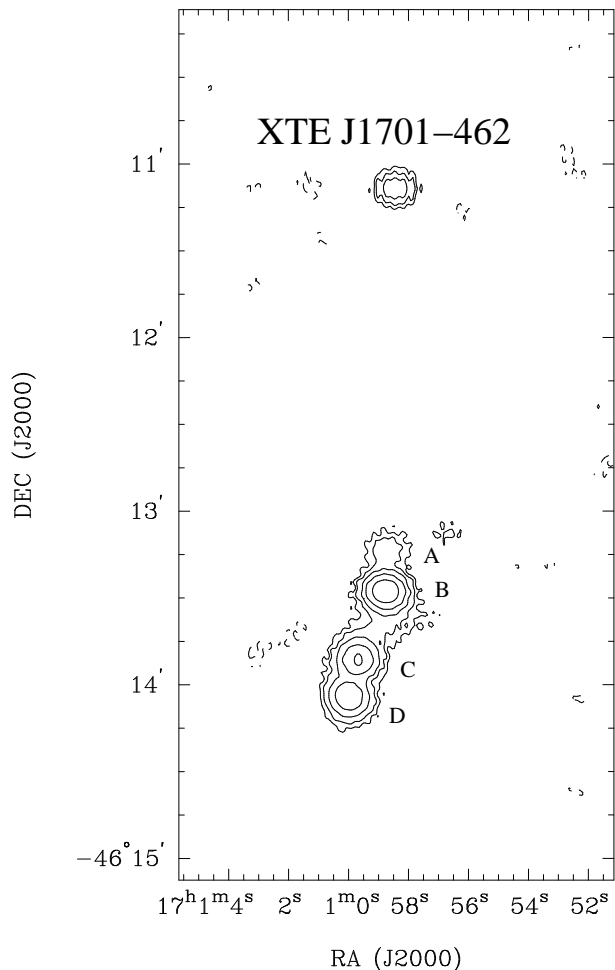


Figure 5. Summed radio image from all sixteen epochs of ATCA observations (24.1 hr on source). The radio counterpart of XTE J1701-462, unambiguously detected in at least one third of the observations, is indicated to the north of the figure. This radio source is entirely consistent with the *Chandra* localisation reported by Krauss et al. (2006). There is clearly a complex of radio sources about three arcmin to the south, and aligned towards, the X-ray binary. Peak fluxes for XTE J1701-462 and components A–B from this map are given in Table 2. The image is at 4.8 GHz and the contours are at (-3,3,6,12,24) times the r.m.s. noise of 28μ Jy.

Table 2. Peak fluxes and spectral index of XTE J1701-462 and sources A–D at 4.8 and 8.6 GHz as measured from the summed, naturally weighted maps.

Source	$F_{4.8}$ (mJy/beam)	$F_{8.6}$ (mJy/beam)	$\alpha_{4.8-8.6}$
XTE J1701-462	0.6	0.7	+0.3
A	0.3	0.2	-0.7
B	2.5	0.9	-1.7
C	2.0	0.5	-2.4
D	1.5	0.3	-2.7

distance to the south (although resolution effects may play a role if the structure also becomes more diffuse to the south).

Note that while variations in the flux of XTE J1701-462 between epochs could cause artefacts in such a combined map, we consider it highly unlikely that they could produce the extended structure seen in Fig5. Furthermore, this structure is visible to a varying degree in longer individual runs (runs B, F, M, N, O and P). The obvious initial interpretation of this structure is that it is an un-

related background radio source, probably extragalactic. However, based on the source counts from the ATESP 5 GHz deep survey (Prandoni et al. 2006), we would only expect ~ 0.05 sources in the 1.5-2.5 mJy range in a region the size of the map presented in Fig 5. Sources B, C and D are all in this range. In addition, if we consider that sources A–D are a single extended source, for the integrated flux density, ~ 5 mJy, the ATESP survey indicates a mean angular size of $\lesssim 10$ arcsec, much less than the $\gtrsim 60$ arcsec angular extent of the source(s). Furthermore, the SIMBAD¹ database lists no catalogued objects at this location. XTE J1701-462 appears to lie in a region of the sky which is overdense in bright, compact, 5 GHz radio sources.

The possibility must therefore be considered that the source to the south may be related in some way to the X-ray binary. If so, it appears to take the form of a curved, one-sided radio jet (there is no comparable structure to the north). At an angular separation from the X-ray binary of three arcmin and a distance of 5-15 kpc, the physical separation of components A–D from XTE J1701-462 greater than 10^{19} cm, which at face value seems to rule out an association with the 2006 January outburst, as apparent velocities greater than $80c$ would be required (but see Fender et al. 2004 for the intriguingly similar case of Cir X-1). Further radio observations to look for variability and more diffuse structure are planned, as are observations at other wavelengths.

4 CONCLUSIONS

In 2006 January a new X-ray transient, XTE J1701-462, was discovered, and rapidly established to display the characteristics of a Z-type neutron star X-ray binary. In this paper we report on the variable radio counterpart to this X-ray source, which demonstrates a coupling between X-ray state (branch of the Z) and radio luminosity similar to that of the other Z sources. By analogy with Sco X-1 and Cir X-1, we interpret this as telling us about the connection between accretion flows and the production of a relativistic jet. Fortunately, since its activation, XTE J1701-462 has remained a bright X-ray source (as of 2007 May) and provides us with a new laboratory in which to study these phenomena. Furthermore, there is some evidence that the source is powering a large-scale radio jet, which hints not only at phases of past activity but also at the possibility of a nebula which may be used to constrain the integrated jet power and provide a further direct comparison between jets from neutron stars and those from black holes.

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