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FLAVORS OF RELATIVISTIC JETS FROM BLACK HOLE BINARIES

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RESUMEN

Hoy en día se cree que los chorros relativistas son un fenómeno común en sistemas en acreción, y que están íntimamente acoplados con éstos. Se observan eyecciones de plasma relativista en el radio durante semanas, asociadas a cambios rápidos en los estados de acreción en sistemas binarios. Con observaciones recientes, se ha encontrado que estas eyecciones tienen efectos a largo plazo sobre el medio interestelar circundante, mediante la formación de lóbulos alrededor de estrellas binarias, y a través de la aceleración de partículas a altas energías.

ABSTRACT

Relativistic jets are now believed to be a fairly ubiquitous property of accreting compact objects, and are intimately coupled with the accretion history. Associated with rapid changes in the accretion states of the binary systems, ejections of relativistic plasma can be observed at radio frequencies on timescale of weeks before becoming undetectable. Recent observations point to long term effects of these ejecta on the interstellar medium with the formation of large scale lobes around binary systems and the acceleration of particles up to very high energy.

Key Words: **BLACK HOLE PHYSICS — ISM: JETS AND OUTFLOWS — RADIO CONTINUUM: STARS**

1. BLACK HOLE CANDIDATES AND X-RAY STATES

Most black hole candidates (hereafter BHC) X-ray binaries spend most of their life in quiescence and occasionally undergo episodic outbursts in which their luminosities increase by factor of millions over the quiescence levels. In outburst, they evolve through different accretion flow states, that are defined (originally) based on their X-ray spectral and timing properties. These states are mainly distinguished by the presence or absence of a soft black-body component at ~ 1 keV (arising from the accretion disk) and the luminosity and spectral slope of emission at harder energies (whose nature is still the subject of an active debate). Systems in the low-hard state (LHS) have power-law X-ray spectra with a photon index in the range 1.4–1.9, an exponential cutoff (but not always) around 100 keV, and no (or only weak) evidence of a soft thermal component. In the LHS, the power density spectrum (PDS) is characterized by a strong band-limited noise power continuum. At higher soft X-ray flux, these systems are usually found in the thermal-dominant (TD) or high-soft state. In that case, the X-ray spectrum is dominated (up to $\sim 90\%$) by the soft-thermal component, with an additional weak and steep power-law component (with no apparent cut-off) at higher energy. Very little variability is detected in the PDS of BHs while in the TD state. At much higher flux, in the steep power-law or very high state (VHS), both the disk black-body component and the steep power-law component at higher energy are detected with relative contributions that can vary significantly. The so-called intermediate state (IS) may be very similar to the VHS (Homan et al. 2001), but it occurs at lower luminosity (see also McClintock & Remillard 2006). Outside the bursting period, these systems are usually found in a quiescence state with very weak residual X-ray emission that displays many similarities with the LHS (Corbel et al. 2000; Tomsick, Kalemci, & Kaaret 2004). This implies that the quiescence state could simply be a low luminosity version of the LHS. With the detailed coverage by RXTE of spectral properties of BHs during recent outbursts, the different X-ray states can be well illustrated using a Hardness-Intensity diagram. In this case, the VHS and IS are defined as various tracks between the vertical tracks (of constant hardness) of the TD and LHS (Homan et al. 2001). For further details on the spectral states of BH, see McClintock & Remillard (2006).

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2. TWO FLAVORS OF RELATIVISTIC JETS FROM X-RAY BINARIES.

2.1. *Compact jets in the hard state*

The LHS has now been observed very frequently at radio frequencies and a radio source is almost always detected with a flat or slightly inverted spectrum (spectral index $\alpha \geq 0$ for a flux density $S_\nu \propto \nu^\alpha$) and a level of linear polarization of $\sim$ 1–2% (Marti et al. 1996; Corbel et al. 2000; Fender 2001). In addition, the radio counterpart of Cyg X$-$1 has been directly resolved into a few milliarcsecond-scale outflow during its standard LHS (Stirling et al. 2001). These properties are characteristic of a conical self-absorbed compact jet, similar to that considered for flat spectrum AGNs (Blandford & Königl 1979). Similar properties have now been observed in a growing number of persistent and transient BHs, thus suggesting that compact jets are ubiquitous in BHs during the LHS.

While the discovery of the compact jets is the result of intensive radio observations of BHCs, it is now becoming clear that the emission from relativistic jets goes much beyond the radio domain. In some BHs, the infrared flux densities are consistent with an extension of the inverted radio spectral component. The transition from optically thick to thin synchrotron emission of the compact jets occurs in the near-infrared (Corbel & Fender 2002a), implying significant infrared emission from the compact jets (e.g. Buxton & Bailyn 2004; Homan et al. 2005). The debate is still open as to whether the compact jets contribute significantly to the X-ray emission observed from BHCs. X-rays could be produced by the compact jets via direct synchrotron (Markoff et al. 2003) or synchrotron self-Compton (Markoff & Nowak 2004). The close link between the jet (measured in the radio) and the X-ray production regions is illustrated by the strong non-linear correlation (Figure 1) between the radio and X-ray emissions in the hard state (Corbel et al. 2000, 2003; Gallo, Fender, & Pooley 2003).

Similarly, an almost identical (i.e lying on the extrapolation obtained by Corbel et al. 2000, 2003; Gallo et al. 2003) non-linear coupling is observed in a large sample of supermassive black holes, if one takes into account the mass of the black hole as an additional (and natural) term in the scaling relation between radio and X-ray emission (Falcke, Körding, & Markoff 2003; Merloni, Heinz, & Di Matteo 2003). This would suggest that the same physics applies over many orders of magnitude in black hole mass and that the spectral energy distribution (SED) of

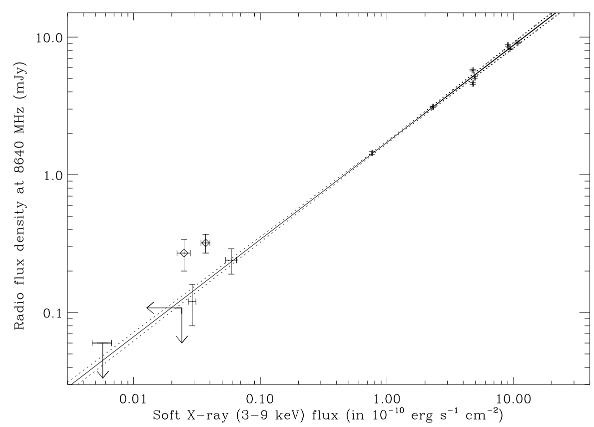

Fig. 1. GX 339$-$4 (1997-2000): Radio flux density at 8.6 GHz versus the X-ray flux in the 3-9 keV energy band (from Corbel et al. 2003).

BHs operating at sub-Eddington accretion rate could be dominated by non-thermal emission from a relativistic jet (Falcke et al. 2003).

2.2. *Transient relativistic jet ejection events*

During period of outburst activity in BHs, strong radio flares are sometimes observed around the transition from the hard state to a softer state. This is usually interpreted as synchrotron emission from relativistic electrons ejected from the system with large bulk velocities. In a few cases such jets have been directly imaged into one-sided (or two-sided) components moving away from the stationary core. In those observations, motions were detected with apparent velocities greater than the speed of light (very similar to phenomenon observed in Active Galactic Nuclei). After ejection, the moving plasma condensations are observed in the radio range for a few weeks until their emission fades below detection levels due to their expansion (Mirabel & Rodriguez 1994; Tingay et al. 1995; Hjellming & Rupen 1995).

2.3. *A unified picture of jet production*

Relativistic jets are now believed to be a common occurrence in black hole X-ray binaries (Fender 2006). Furthermore, jets are not restricted to black hole candidates, as the most highly relativistic outflow found to date is from the neutron star X-ray binary Cir X$-$1 (Fender et al. 2004a). The association of radio emission with some of the X-ray spectral states has led to the following picture. Relativistic jets exist in two flavors (as already mentionned in Sections 2.1 and 2.2) in black hole systems, namely self-absorbed compact jets (on milliarcsec scales) and discrete ejection events (on 0.1$-$10

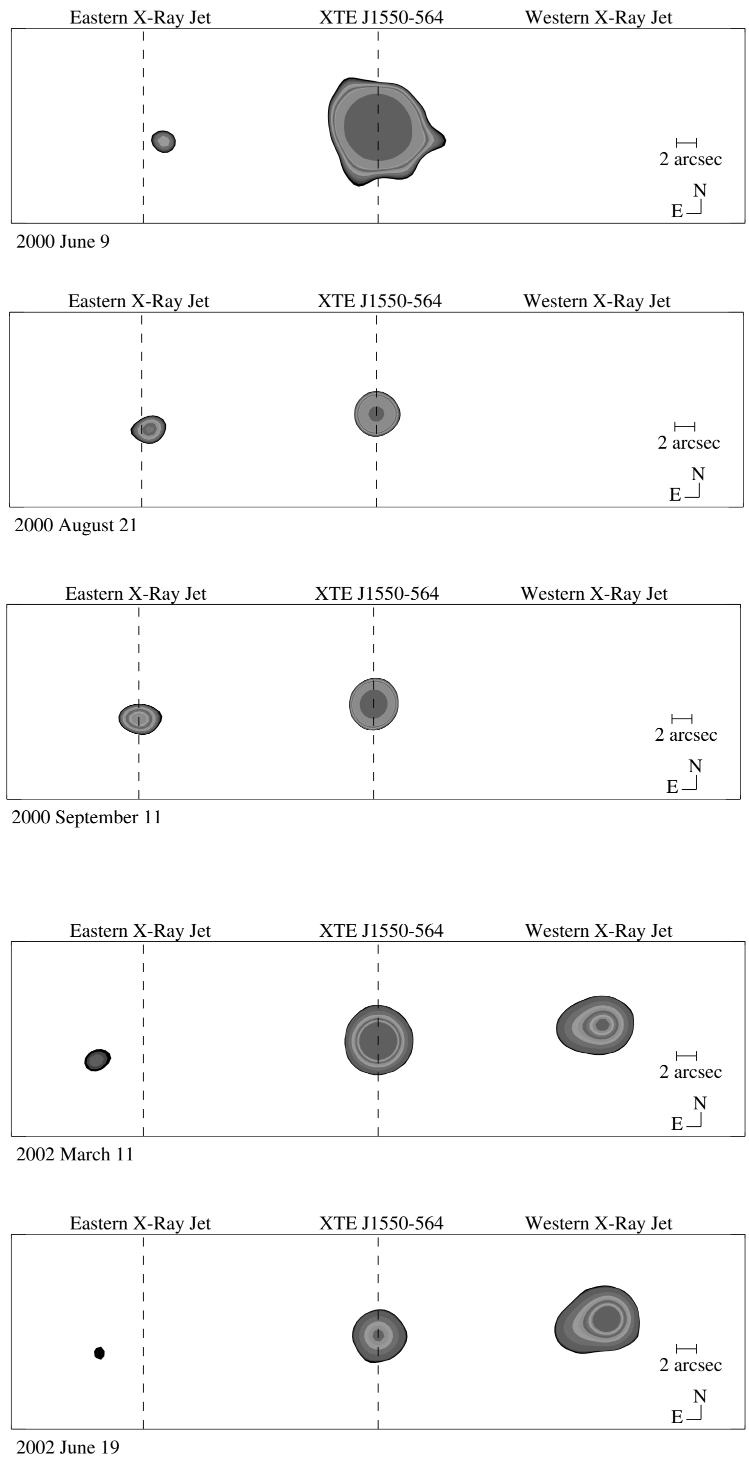

Fig. 2. Five *Chandra* 0.3-8 keV images showing the evolution of the eastern and western X-ray jets from XTE J1550–564, between June 2000 and June 2002. The observations are ordered chronologically from top to bottom, and each image is labeled with the observation date. The dashed lines mark the positions of XTE J1550-564 and the eastern X-ray jet on 11 September 2000. Adapted from Corbel et al. 2002b; Kaaret et al. 2003; Tomsick et al. 2003.

arcsec scales). The compact jets are associated with the standard hard X-ray spectral state and even possibly with the intermediate state. Massive ejection events (usually associated with what is called "superluminal jets") are usually associated with the transition from the intermediate state to the steep power-law state, i.e. the ejection occurs after the X-ray spectrum softens. Further discrete ejection events may be observed again during the steep power-law state and these are associated with hardening of the X-ray spectrum (Corbel et al. 2004; Fender, Belloni, & Gallo 2004b).

3. THE INTERACTION OF THE JETS WITH THE INTERSTELLAR MEDIUM

3.1. *Discovery of X-ray jets*

Recent X-ray observations (Figure 2) by Chandra have led to the discovery of extended (up to 30″) X-ray jet emission from the microquasar XTE J1550−564. In observations made between June 2000 and January 2003, two sources moving away from the XTE J1550−564 black hole are detected. Both the radio and X-ray emission of the western source appeared extended towards XTE J1550−564, and the morphologies associated with each wavelength matched well. The detection of optically thin synchrotron X-ray emission from discrete ejection events implies in-situ particle acceleration up to several TeV. This acceleration may be caused by interaction of the jets with the interstellar medium (ISM) (Corbel et al. 2002; Tomsick et al. 2003; Kaaret et al. 2003).

Around the same time, Angelini & White (2003) reported the detection of large scale persistent two-sided X-ray jets (Figure 3) around the (now) quiescent BHC 4U 1755−33. Recent new X-ray observations (Kaaret et al. 2006) show that the jets found in 2001 are still present in X-rays in 2004. No radio emission from this large scale jet has been yet detected, however synchrotron radiation is still a viable emission mechanism for the jets and thermal bremsstrahlung and inverse-Compton emission are unlikely on energetic grounds (Kaaret et al. 2006).

These X-ray jets are quite reminiscent of the large scale radio lobes (or jets) around the two galactic center microquasars 1E 1740.7−2942 (Mirabel et al. 1992) and GRS 1758−258 (Martí et al. 2002), implying that the formation of large scale lobes could just be the long-term result of the impact of relativistic ejecta on the ISM. It now appears that relativistic jets emit throughout the entire electromagnetic spectrum. But are the jets of XTE J1550−564 unique due to special physical conditions or should we expect to observe similar X-ray jets in other BHC? If

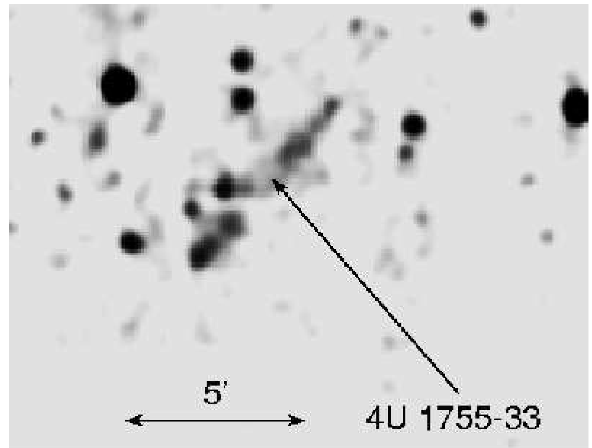

Fig. 3. *XMM-Newton* image of 4U 1755−33 (Angellini & White (2003). The arrow indicates the position of 4U 1755−33. Figure adapted by Kaaret et al. (2004).

jets containing TeV particles are common amongst BHCs, then there may be interesting consequences. The high energy particles could produce a distinctive signature in the cosmic-ray flux (Heinz & Sunyaev 2002) or produce neutrinos if the jets contain protons (Distefano et al. 2002). Furthermore, the study of X-ray jets in microquasars could add an additional bridge between the physics of jets in microquasars and those from super-massive black holes. Interestingly, a connection with Gamma-Ray Bursts has also been drawn by Wang, Dai, & Lu (2003), who showed that the evolution of the eastern X-ray jet of XTE J1550−564 was consistent with the emission from adiabatically expanding ejecta heated by a reverse shock following its interaction with the ISM.

3.2. *New Discovery of X-ray jets in H 1743−322*

H 1743−322 was discovered with Ariel 5 in August 1977 (Kaluzienski & Holt 1977) and has been precisely localized by HEAO-1 (Doxsey et al. 1977). H 1743−322 has probably been active several times during the past decades with activity observed in 1984 by EXOSAT (Reynolds et al. 1999) and in 1996 by TTM (Emelyanov, Aleksandrovich, & Sunyaev 2000). In March 2003, INTEGRAL detected new activity from IGR J17464−3213 (Revnivtsev et al. 2003) that was later found to correspond to H 1743−322. A radio counterpart was found with the VLA by Rupen, Mioduszewski, & Dhawan (2003a) and a bright radio flare (likely associated with a massive ejection event) was observed on 2003 April 8 (MJD 52738) by Rupen, Mioduszewski, & Dhawan (2003b). During outburst, H 1743−322

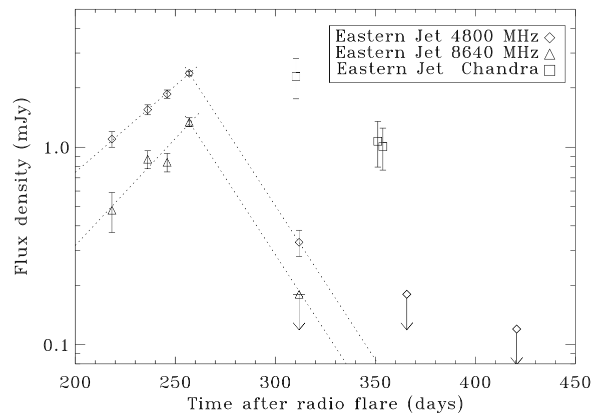

Fig. 4. Radio light-curve at 8.6 GHz (3 cm) and 4.8 GHz (6 cm) of the eastern jet of H 1743−322 as measured by ATCA. Upper limits are plotted at the three sigma level. The dotted lines illustrate the exponential fit to the rise and decay of radio emission. The *Chandra* 0.3–8 keV unabsorbed flux (times 10^6) of the eastern jet is also plotted and this indicates the dates of the X-ray observations. The x-axis is the time since the major radio flare as observed by the VLA on 2003 April 8 (MJD 52738) by Rupen et al. 2003b.

went through several X-ray states with properties typical of BHC.

In November 2003 after the end of its 2003 outburst, we noticed, in observations with the Australia Telescope Compact Array, the presence of a new and variable radio source about 4.6″ to the East of H 1743−322, that was later found to move away from H 1743−322. The light-curve of this source, combining all our ATCA observations (at 4800 MHz and 8640 MHz), is presented in Figure 4. This source was brightening from our first observations until the end of 2003. The single detection on 2004 February 13 at a much (almost a factor ten) fainter level points to a very fast decay. The maximum of radio emission was likely in January 2004. In addition to the new source to the East of H 1743−322, we note that a radio source is detected to the West of H 1743−322, almost symmetrically placed relative to the Eastern source, only on 2004 February 13 with a flux density of 0.14 ± 0.05 mJy at 4800 MHz. Despite its weak flux density, the *Chandra* data on the same day (Figure 5) confirm the existence of an X-ray source at this position and therefore strengthen the reality of the western radio source.

In 2004, follow-up X-ray observations with *Chandra* (Figure 4) led to the discovery of X-ray emission associated with the two radio sources. This likely indicates that we are witnessing the interaction of relativistic jets from H 1743−322 with the interstellar medium causing in-situ particle acceleration. This is the second discovery (Corbel et al. 2005) of moving, large X-ray jets in a Galactic black hole, after the initial discovery in XTE J1550−564 (Figure 2). The spectral energy distribution of the jets (Figure 6) during the decay phase is consistent with a classical synchrotron spectrum of a single electron distribution from radio up to X-rays, implying the production of very high energy (> 10 TeV) particles in those jets. For the first time we observe the eastern jet at radio frequencies during the rising phase (see

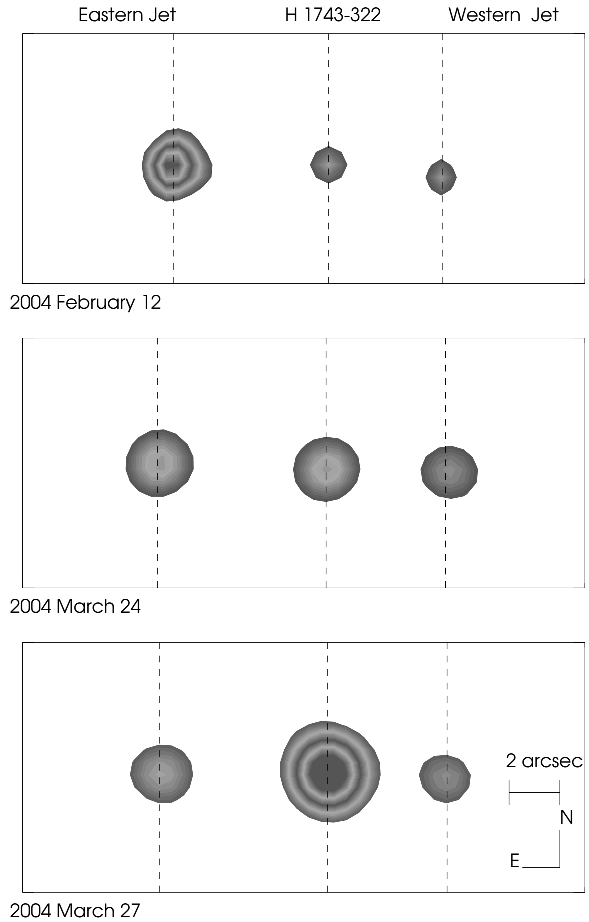

Fig. 5. *Chandra* 0.3-8 keV image of H 1743−322 in 2004 (Corbel et al. 2005). Filled contour plots produced by convolving the 0.3–8 keV Chandra images with a two-dimensional Gaussian with a width of two pixels in both directions. The vertical lines indicate the position of the X-ray sources in each observation. Each count image has been normalized by its integration time. The black hole (at the center) as well as the two jets are detected. See Corbel et al. (2006) for the discussion on the black hole X-ray emission in quiescence.

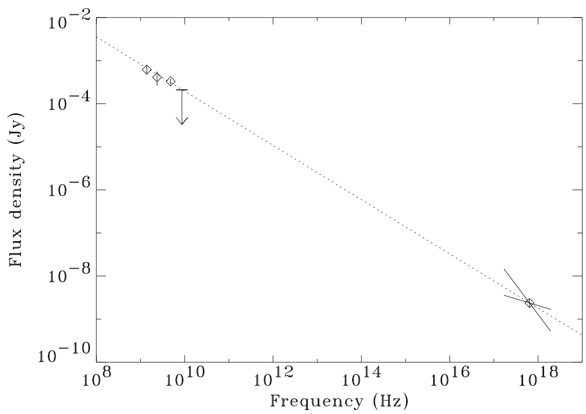

Fig. 6. Spectral energy distribution of the eastern jet of H 1743−322 on 2004 February 13 as observed by ATCA and *Chandra* during the decay phase. The "bow tie" represents the *Chandra* constraints on the flux and spectral index (-0.67 ± 0.90) of the X-ray emission. The spectral index error lines are at 90% confidence level with the column density frozen to value measured for the black hole H 1743−322. A combined fit (dotted line) of the radio and X-ray data result in a spectral index of -0.64 ± 0.02, which is typical of synchrotron emission.

Figure 4) and we found that the radio spectra were very steep (spectral index close to -1, if we define the radio flux density $S_\nu \propto \nu^\alpha$, with α the radio spectral index and ν the frequency), possibly related to the particle acceleration mechanism.

With this discovery of transient X-ray jets in H 1743−322, we can now come to the idea that such events may be a common occurrence associated with any X-ray binary in outburst. Indeed, after the original discovery of X-ray jets in XTE J1550−564 (Corbel et al. 2002b), a relativistic ejection in GX 339−4 has also been observed to later develop into a large scale jet, possibly related to the interaction with the ISM (Gallo et al. 2004). However, the western large scale jet of GX 339−4 has only been observed at radio frequencies (E. Gallo, private communication), possibly due its fast decay rate. The X-ray observation of GX 339−4 was 6 months after the last detection of the western large scale jet at radio frequencies (Gallo et al. 2004) and any X-ray emission likely decayed away before the observation.

It is unclear why the decay could be faster in some sources, but this may be related to local ISM conditions. Also, as outlined by Wang, Dai, & Lu et al. (2003), the (already) fast decay of the X-ray emission from the eastern X-ray jet in XTE J1550−564 was not consistent with a forward shock propagating through the ISM. On the contrary, if the emission was driven by a reverse shock following the interaction of the ejecta with the ISM, then the rapidly fading X-ray emission could be the synchrotron emission from adiabatically expanding ejecta. With a much faster decay in H 1743−322 or even GX 339−4, it may also be possible that the emission in these two cases is also related to a reverse shock moving back into the ejecta. In that case, it would be interesting to see if a reverse shock model (as in Wang et al. 2003) could also reproduce the flux and spectral evolution that we observed during the rise of emission of the jets of H 1743−322.

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