RADIO-X-RAY CONNECTION FOR X-RAY TRANSIENTS AND BINARIES

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1. Introduction

The discovery of the association between relativistic radio jets and X-ray events in GRS 1915+105 (Mirabel and Rodriguez, 1994) and GRO J1655-40 showed that strong radio flares (Harmon *et al.*, 1994) in general, and jet ejection (Hjellming and Rupen, 1994) in particular, could be identified with features in hard X-ray events. This has caused us to re-think the interpretation of the radio events in X-ray transients, and has made multi-wavelength observations even more important. In this paper the focus is on the connection between X-ray and radio events as seen since 1994 in GRS 1915+105, GRO J1655-40, GRO J1719-24, GRO J1739-278, Cyg X-3, Cyg X-1, and Sco X-1.

2. The X-ray Transients with Related Radio Emission

2.1. THE 'HISTORICAL' TRANSIENTS

The first X-ray transient to be identified with the delayed appearance of a strong ($\leq$200 mJy) and decaying radio event, first seen ~10 days after the X-ray outburst, was A0620-00 (Davis *et al.* 1975, Owen *et al.* 1976). In 1988 GS 2000+25 showed (Hjellming *et al.*, 1988) a weaker ($\leq$10 mJy) event 20 days after X-ray outburst. The next three transients, GS 2023+338 (V404 Cyg) in 1989 (Han and Hjellming, 1992), GRS 1124-68 ('Nova' Muscae 1991) in 1991 (Ball *et al.*, 1995), and GRO J0422+32 in 1992 (Schrader *et al.*, 1995) showed something beside an initial rapidly decaying event ($\sim t^{-p}, 4 \leq p \leq 5$) - all three exhibited a "second stage" of radio emission with a combination of fluctuations (for the 1989 and 1992 transients) and slow ($\sim t^{-1}$) decays. The initial rapidly decaying events in GS 2023+338 and GRS 1124-68 were first detected at 1.2 and 0.2 Jy, respectively, 2 and 3 days after their X-ray outbursts; the "second stage", optically thick, decaying ($\sim t^{-1.2}$ and $\sim t^{-1}$) radio emission of these two transients was observed for 700 and 300 days, respectively. It was possible to fit the initial, rapidly decaying events with simple models of an expanding spherical bubble of synchrotron emitting relativistic electrons, but in no case was an initially optically thick rise observed.

2.2. XRTS AND XRBS WITH RELATIVISTIC RADIO JETS

GRS 1915+105 was the first galactic X-ray transient shown to eject apparently superluminal jets (Mirabel and Rodriguez, 1994). In March-April 1994 VLA observations showed that twin-jets were ejected in opposite directions, after the onset of a decay in hard X-ray emission, with apparent proper motions of 18 and 9 mas/day. Mirabel and Rodriguez (1994) showed that the relativistic proper motion and Dopper boosting equations for approaching and receding twin-jets could be used to determine that the jets have a bulk velocity of 0.92c and an inclination to the line of sight of 70°, thus explaining the apparent transverse motions of 1.4c and 0.7c for the approaching and receding jets. GRO J1655-40 was the second galactic superluminal source, also seen in 1994; it had a succession of three hard X-ray flares (Harmon *et al.*, 1994) which were associated with superluminal

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jets (Hjellming and Rupen, 1995; Hunstead *et al.* 1997) also moving with a bulk velocity of 0.92c. These twin-jets appeared to be inclined 85° to the line of sight, and had proper motions on the approaching side of 64 mas/day (Tingay *et al.* 1995; Hjellming and Rupen 1995) - the largest proper motion ever seen in any object outside of the Solar System. The VLA and VLBA images of the GRO J1655-40 jets showed complex internal structure in the jets and a change in which side was strongest. However, one of the most important things established by the BATSE and VLA/VLBA observations was that the succession of three hard X-ray events had peaks or sudden decays at the time of ejection of the relativistic radio jets.

Of course, the first relativistic jet source found in our galaxy is SS433 (Margon, 1984). Its 0.26c jets are seen in the Doppler shifts of optical (Margon, 1984) and X-ray (Watson *et al.* 1986; Kotani *et al.* 1996) spectral lines, and in proper motions in corkscrew-like (Hjellming and Johnston, 1981; Vermeulen, 1987; Vermeulen *et al.* 1989) radio emission regions. The proper motions of these mildly relativistic jets are 8.3 and 7.8 mas/day on the approaching and receding sides, and the jets precess at an angle of 20°, every 162.5 days, around a jet axis oriented 80° to the line of sight.

The galactic X-ray binary Cyg X-3 has had radio flares above 3 Jy on an average of about once a year since 1972. A Cyg X-3 flare to 10 Jy in Jan.-Feb. 1997 has been imaged with the VLBA (Mioduszewski *et al.*, 1997) and found to have a curved, one-sided jet. Using the relativistic equations for proper motion and Doppler boosting, a jet with a bulk velocity of ~0.9c oriented ~2° from the line of sight is indicated.

In Table 1 we compare the inferred properties of the four relativistic jet systems in our galaxy. GRS 1915+105 has two entries. One corresponds to the 0.92c solution preferred by Mirabel and Rodriguez (1994) and one is derived from the data they report for approaching and receding proper motions, and the observed ratio of 8 for the approaching/receding Doppler boosting factors.

The decays of the three radio events associated with relativistic jet ejection in GRO J1655-40 are similar to the decays seen for the 'historical' X-ray transients that could be interpreted as expanding spherical regions of relativistic electrons. Models for the ejection of jet segments have exactly the same decay characteristics, and have the added advantage of explaining why initial optically thick states are very seldom observed. We now believe that all transients with radio emission with strong, but rapid, decays are ejecting largely optically thin radio-emitting material in the form of linear jet segments.

2.3. THE X-RAY BINARIES CYG X-1 AND SCO X-1

The galactic X-ray binary Cyg X-1, which is widely believed to be a binary system with a black hole, was observed to have a transition between high-soft and low-hard states in 1996 which was observed in X-rays by RXTE and BATSE (Zhang *et al.*, 1997) and at radio wavelengths by the VLA. The sharp transition from a low to a high state in hard X-rays occurs exactly at the time of an increase in radio emission from about 5 mJy to a level varying around 15 mJy. Equally interesting

TABLE 1. Properties of Relativistic Jet Sources

Object	Sp. Ind.	P.M. appr. [mas/day]	P.M recede [mas/day]	$S_{appr.}/S_{recede}$	Distance [kpc]	Ejection Type	Incl. [deg.]	v/c
Cyg X-3	-0.6	5.5	(0.66)	$\geq$2100	10	Continuous	2	0.9
GRO J1655-40	-0.7	64	48	1.6	3.2	Continuous	85	0.92
GRS 1915+105	-0.8	17.6	9	8	12.5	Continuous	67	0.89
GRS 1915+105	-0.8	17.6	9	6.5	12.5	Continuous	70	0.92
SS433	-0.7	8.3	7.8	20	5.5	Continuous	80	0.26

is that the long time scale radio variations in the low-hard state of Cyg X-1 track the hard X-ray variations with a delay of $\sim$ 20 days.

The Z-source Sco X-1 has recently returned to an active radio state with flares up to 0.25 Jy. Remarkably, these brief flares over time scales of several hours seem to appear about one day after brief hard X-ray flares detected by BATSE (Robinson *et al.*, 1998).

3. Correlations between X-ray and Radio Emission

Following the discovery of the hard X-ray (HXR) to radio coupling in the 1994 flares in GRO J1655-40, there began extensive monitoring of old and new X-ray transients. The X-ray transient GRO J1719-24 was found (Hjellming *et al.*, 1996) to have radio flares occurring at the peak/decay in a recurrent hard X-ray event a few years after the first appearance of this object in 1993. The first X-ray transient detected by the RXTE ASM, GRO J1739-278, was found to have a roughly triangular-shaped X-ray event that was followed about 30 days later by a slow rise, slow decay radio event; the decays in both radio and X-rays were interrupted by additional weaker events which could have the same delay between X-ray and radio emission.

GRO J1655-40 had recurring hard X-ray events in 1995 which had no accompanying radio events; however in 1996 an X-ray event that lasted more than a year exhibited a radio flare 30 days after the rise of the soft X-ray event seen by the RXTE ASM, and roughly coincident with the rise of hard X-rays seen by BATSE (Hjellming, 1997). Following that radio event the radio source remained below detection limits except for a one day rise up to 0.6 mJy about 65 days after the radio flare.

Examining all the events in X-ray transients and X-ray binaries for which there are correlations, it seems as if there are four types of relationships between X-ray and radio events. These are listed in Table 2 with source names, identification of events, and a description of the X-ray to radio relationship. For Type 1, radio flaring, and sometimes observable jet ejection, is related to the peak, or sudden onset of rapid decay, in HXR emission. This behavior was seen in: the 1995 event in GRO J1719-24 (Hjellming *et al.*, 1996); the jet-ejection event analyzed by Mirabel and Rodrigez (1994); a few very brief events in Sco X-1 in 1997; and the Feb. 1997 event in Cyg X-3 that ejected a curved, one-sided relativistic jet. For Type 2, hard X-ray events are not correlated with radio events as seen by GRO J1655-40 in 1995. For Type 3, one has correlated hard X-ray and radio events with varying degrees of delay: closely coupled pre-flare and flare behavior of Cyg X-3 seen in all major flares form 1991 to 1997 (McCullough *et al.*, 1997); the GRS 1739-278 radio event following the X-ray event by about 30 days; the Cyg X-1 coupling of hard X-ray emission to radio with a 20 day delay; and the $\sim$1 day delay between brief hard X-ray flares and radio flares in Sco X-1. Since there were no radio images allowing us to see radio jet development in the Type 3 events, it is possible and even likely that all Type 3 events really are Type 1 events with jet ejection. Finally, a state so far seen only in Cyg X-3 is the Type 4 relationship where there is an anti-correlation (McCullough *et al.*, 1997) between the HXR and the radio whenever the radio and HXR are NOT in pre-flare or flaring states, showing smooth, long time scale variations.

4. Conclusions

From the cases where the ejection of relativistic jets are directly observed to follow peaks or sudden decays in X-ray emission, particularly hard X-rays, and the many cases where this behavior probably occurred, we conclude that there is a very close relationship between changes in, or development of, radio jets when the X-ray state of an accretion disk changes. Most of the systems where this occurs are black hole X-ray transients, black hole binaries (Cyg X-1), or systems where the presence of a black hole has not been excluded (Cyg X-3). SS433 is a relativistic jet source that also may contain a black hole. There seems to be something special about black hole systems and relativistic jets. There are tantalizing indications that this is related to Advection Dominated Accretion Flows (ADAF), where energy is advected into the event horizon of a black hole (Narayan, 1997). There is a good astrophysical basis for a coupling between the mildly relativistic electrons in ADAFs and the development of radio jets due to collimated outflows (Blandford and Payne, 1982; Meier, 1997)

TABLE 2. Types of XR-Radio Correlations

Type	Source	Events	Properties
1	GRO J1655-40	3 events in 1994	Jet ejection at Peak/Decay of Hard XRs
	GRS 1915+105	1 event in 1994	Jet ejection at Peak/Decay of Hard XRs
	GRO J1719-24	1+ events in 1995	Radio flare near Peak/Decay of Hard XRs
	Cyg X-3	Jan.-Feb. 1997	Radio jet ejected near HXR rise/peak
2	GRO J1655-40	HXR events in 1995	No radio emission
3	Cyg X-3	1991-1997 radio flares	Radio and HXR correlate in pre-flare & early flare states
	GRO J1655-40	1996 event	Strong radio flare ∼30 after X-ray flare
	GRS 1739-24	1996 flare/re-flare events	Radio follows XR, 30 day delay
	Cyg X-1	1996 soft-hard transition	Radio follows HXR, 20 day delay
	Sco X-1	A few events in 1997	Radio Flare ∼1 day after HXR event/peak
4	Cyg X-3	1991-1997 quiescent states	∼stable radio anti correlated with HXR

with subsequent shocks and further particle acceleration. Meier *et al.* 1997b have shown that there is a "magnetic" switch which naturally allows for a change between mildly relativistic jets and highly relativistic jets.

While both soft and hard X-rays can be monitored for all new and known X-ray transients and binaries, it is critical that we continue to observe the radio properties of these systems, particular with radio imaging on angular scales from mas to arc seconds.

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