GALACTIC SUPERLUMINAL SOURCES

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ABSTRACT A new class of X-ray sources was clearly established with the discovery of highly relativistic radio jets from the galactic sources GRS 1915+105 and GRO J1655-40. Both of these objects have given us a broader view of black holes and the formation of jets, yet they also show the complexity of the accretion environment near relativistic objects. The fast apparent motion of the jets, their luminosity and variability, high energy spectrum, and approximate scaling to the behavior of active galactic nuclei, certainly warrant the description “microquasar”. I present a review of the observational data on these sources, and discuss where we stand on a physical picture of GRS 1915+105 and GRO J1655-40 as taken from multi-wavelength studies. I also point out other galactic sources which share some of the properties of the microquasars, and what to look for as a high energy “signature” in future observations.

KEYWORDS: superluminal jets; X-ray transients; multiwavelength observations; microquasars; GRS 1915+105; GRO J1655-40.

1. INTRODUCTION

A new class of galactic X-ray transient sources was identified with the discovery of superluminal radio jets in GRS 1915+105 and GRO J1655-40. Recently, thanks to rapid followup radio observations, other jet sources, although not superluminal, have been observed. No evidence of X-ray bursts or coherent pulses have been found in any of these objects, and are therefore likely to be black hole candidates (BHC) (the mass of GRO J1655-40 has been measured to be about $7M_\odot$). A more recent analysis yields $4.1 < M_\odot < 6.6M_\odot$ (90% conf. limit).

Because of the physical similarity of the galactic superluminal sources to their extragalactic counterparts, they have also been called “microquasars”. An analogy drawn between jets in active galactic nuclei (AGN) and accreting binaries shows consistent scaling in luminosity, size and variability. The advantage in studying the galactic sources comes from their size and proximity; the timescale of the variations are a factor of $10^6$ shorter, and the modest Doppler boosting usually allows both the approaching and receding jets to be seen.

Here we review the experimental evidence for a relationship between wavelength bands from gamma rays to radio, with emphasis on possible temporal or spectral signatures in the high energy data for jet formation. Then, building on the framework established for AGN jets, we discuss the theoretical implications of these observations and the role of the disk magnetic field.
2. LONG TERM BEHAVIOR

GRS 1915+105 was first detected by GRANAT/WATCH in X-rays in 1992. Numerous outbursts have occurred since then, and it is likely that GRS 1915+105 has not returned to quiescence since that time. The radio counterpart was monitored sparsely until late 1993, when it was observed as a strong transient radio source (∼Jy). Prior to this, the only galactic sources known to have large radio flares were the persistent sources SS 433, Cir X-1, and Cyg X-3. The observed radio spectrum is consistent with electron synchrotron radiation, varying between flat (at lower flux levels) to and characteristically steep (higher levels) during flares. The synchrotron emission can extend at times into the infrared. In Fig. 1, we show monitoring results for GRS 1915+105 from 1996-1998 in the radio band from the Green Bank Interferometer (GBI), soft X-rays measured with the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor (ASM) and hard X-rays with the Compton Gamma Ray Observatory (CGRO) Burst and Transient Source Experiment (BATSE). We see that radio flares occur in association with hard X-ray/gamma-ray (>20 keV) outbursts. A general increase at 2.25 GHz can be seen in the 1996-98 interval. During outburst the flux density can reach 50 mJy and remain in a plateau-like state for several weeks, with occasional flares reaching 1 Jy. The soft X-ray flux (2-12 keV) has distinct quiescent and flaring substates which appear largely independent of the other bands on timescales of days or more. There is a tendency for the hard X-rays to be high during the quiescent soft X-ray states, but no direct one-to-one correlation is seen between the two bands.
FIGURE 2. The 1994 outburst of GRS 1915+105 in the hard X-ray (BATSE) and GHz radio band (VLA, Nancay and GBI). The top frame shows the photon spectral index of the X-ray emission, the middle frame, the X-ray intensity and 3.2 GHz radio flux (Nancay), and bottom: several radio bandpasses. Approximate times of radio ejection events are indicated by arrows. Figure from ref. [15].

GRO J1655-40 was discovered with BATSE in 1994 [13]. It too had several outbursts in the high energy regime; it has since returned to quiescence by 1997. Radio outbursts to several Jy were seen in conjunction with early outbursts in 1994-95, and the radio counterpart reappeared briefly in a 1996 outburst. It is the only superluminal source with an optically-determined mass function and it also has an F5-type stellar companion [4].

3. X-RAY SIGNATURE OF PLASMA EJECTION

3.1 Temporal Behavior

The excitement of discovery of GRS 1915+105 and GRO J1655-40 have now stimulated a large amount of new and valuable data on the superluminal sources. High energy observations have revealed [14] [15] evidence that accretion is definitely related to the formation of jets. In 1994 (see Fig. 2), a strong hard X-ray outburst of GRS 1915+105 was accompanied by plasmoid ejections [1] which indicated for the first time that superluminal motion was observed in a galactic source. The tendency for the hard X-ray emission to dip or decrease during the largest flares (>200 mJy) can be seen in the middle frame of Fig. 2. This was the first and only time that
direct correlations with the large flares were seen. During more recent hard X-ray outbursts as in Fig. 1, we continued to observe enhanced radio emission, but at variable intensities and generally lower than intense, longer flares shown in Fig. 2. The apparent difference in X-ray behavior between the high radio flux levels in 1994 and at times when the radio flux is lower may be due to a lack of sensitivity at high energy to the smaller/shorter ejection events.

X-ray observations with the PCA on RXTE have revealed cyclic (or approximately repeating) intensity variations consisting of flares and dips lasting a few thousand seconds in GRS 1915+105 [16, 17]. The intensity variations are accompanied by dramatic changes in spectral hardness. There is also a clear, delayed response in the infrared and radio bands [8, 9], characteristic of synchrotron radiation. This behavior is not present in all observations, and was only observed in GRS 1915+105. Occasional dips in the intensity of other sources such as GRO J1655-40 and 4U 1630-47 lasting several minutes appear to be an absorption phenomenon [10].

Belloni et al. [17] have demonstrated that the X-ray data of Fig. 3 can be ordered according to a derived value of the inner disk radius $R_{in}$, which scales according to the length of the troughs and the intensity of flares. They describe the cycle as an emptying and refilling of accretion material from the inner disk region. Although the radio flux during the flares and dips is not sufficient to prove that a jet is present, if material is being removed via a “mini-jet”, it could represent a scaled-down version of the larger events observed in Fig. 2.
3.2 Spectral Behavior

The spectral behavior of the superluminal sources, much less BHC in all their various accretion states, is not well understood. We do know that the X-ray/gamma ray range is dominated by multi-color black-body and/or Comptonization components as in other BHC [18]. The jet sources tend to exhibit a highly variable disk black-body component (from which $R_\text{in}$ was obtained for GRS 1915+105), and a high energy tail which has a high degree of independence from the soft component.

In addition, two other spectral properties are shared between the superluminal sources. Both GRS 1915+105 and GRO J1655-40 spectra show complicated Fe line profiles [19]. To interpret them as due to a single reflection, absorption, or disk-line component is difficult, but Ueda et al. [19] suggest that the features near 7 keV seen in Japanese satellite ASCA data are due to absorption by He-like and H-like iron ions in an anisotropic, hot plasma. Such a plasma may be similar to that forming the hot ion torus in AGN. The second shared property of the superluminal sources is the steep, power law spectral shape in the hard X-ray/gamma ray regime (see Fig. 4). Photon number indices in the 20-200 keV band range from $-2.5$ to $-3.5$, with spectral slopes that do not seem to change drastically or appear to be strongly correlated with luminosity as in other black hole candidates. OSSE has observed emission from GRO J1655-40 to 700 keV with no evidence of a cutoff [20]. This suggests a nonthermal origin for the emission; however, better statistics are required for confirmation.

The broadband spectral shape of the superluminal sources is usually associated with the high or ultrahigh states of BHC where the mass accretion rate may reach near-Eddington luminosities. The steep power law shape can result from Comptonization of a nonthermal electron distribution such as might be encountered inside the last stable orbit (radial bulk motion) around the black hole [21]. This model has been used successfully [22] to fit spectra for GRO J1655-40 and GRS 1915+105. The Comptonization model must have a high energy cutoff, and cannot explain emission above a few hundred keV. We point out that a number of BHC, which apparently do not exhibit jets, also have this high energy spectral shape, e.g., Nova Muscae, GRS 1009-45, and 4U 1543-47. (See Fig. 4). This may be an observational bias, due to incompleteness in historical coverage of their outbursts in radio/infrared bands.

4. THEORETICAL CONSIDERATIONS

The discovery rate of black hole transients per year is now about 5-6 from the nearly continuous coverage of all-sky monitors such as BATSE and the ASM. Two of the more recently discovered transients, CI Cam and XTE J1550-564, have bright (~100 mJy) radio counterparts. Very long baseline interferometry indicates that the radiation comes from clouds of radio-emitting plasma associated with jets. It is therefore possible that jets are common among black hole transients, although the persistent outbursting and jet production in GRS 1915+105 may be rare.
Most black hole transients, such as GRO J1655-40, tend to be active in the GHz band over the first few weeks or months of the outburst, if at all. This associates relatively large accretion rates with jet formation, typical of the high to very high states. There is also evidence that particular substates produce jets, as in GRS 1915+105, when the source is highly variable, and undergoing drastic changes in the broadband spectrum. Rapid changes in the inner disk structure may alternately produce a highly luminous disk in soft X-rays, or a fast outflow of high energy particles. For now, we do not know the origin of such substates. Likely explanations overlap with those of quasi-periodic oscillations in the accretion disk, which are beyond the scope of this paper (see contributions by Stella and van der Klis, this meeting).

Considerable theoretical work on the formation and collimation of jets has come from observations of AGN over many years. It is thought that a magnetic field is generated within the nucleus by ordered motion of accreting gas and dust. The disk magnetic field is likely to play a strong role in launching material out of the disk as well as collimating the outflow \cite{23}. This model, in its various forms, is attractive because magnetically-driven jets scale easily to any size system from binaries to AGN. Recent work with three dimensional magnetohydrodynamical simulations provides an explanation of the transient nature of the jets via instabilities in magnetic pressure dominated (low $\beta$) disks \cite{24} or magnetic “switches” from the variations in coronal particle density \cite{26}. 

![OSSE spectra for various black hole candidates. Figure from ref. \cite{20}.](image)
Currently there is no way to directly measure the strength of such magnetic fields near galactic black holes. Such fields are inferred from observations of young stellar objects and the central regions of quasars. A weakness of magnetic field models is that they provide no explanation for the presence of jets in only some systems. Various other observations in the optical and infrared suggest the presence of massive companions with high mass loss rates (such as in a brief period of evolution) that results in conditions that are conducive to jet production, similar to Cyg X-3 and SS 433.

It has also been proposed, as in AGN, that the spin of the black hole may be a critical factor in jet production. The angular momentum of the black hole causes the event horizon to shrink, and thus the inner edge of the accretion disk can extend closer to the black hole. This can increase soft X-ray production significantly. Zhang et al. [27] have proposed that the superluminal sources may contain black holes with angular momentum near the maximum allowed value. This may account for the large soft X-ray emission seen at times in the broadband spectra of the GRO J1655-40 and GRS 1915+105. It is not clear how the angular momentum of the black hole is extracted by the jet; a possible mechanism for this was given by Blandford and Znajek [24]. This scenario provides an explanation for other black holes (such as Cyg X-1 in the hard/low state and GS 2023+25) of not having prominent jets consistent with the lack of strong ultrasoft components and the steep power law tail extending into the gamma ray regime.

5. THE FUTURE

We hope to continue investigations of the known superluminal sources, as well as new sources which may become active in the future. Clearly, understanding has come by combining data from all parts of the electromagnetic spectrum. New instrumentation available soon should allow us to probe both the ion species present in accretion disks and perhaps even the composition of the jets themselves. The high energy part of the spectrum, which can be studied with both space-based and ground-based instruments, can provide more clues about the acceleration mechanism and the particle populations near black holes.

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