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QUENCHING OF THE RADIO JET DURING THE X-RAY HIGH STATE OF GX 339−4

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ABSTRACT

We have observed the black hole candidate X-ray binary GX 339−4 at radio wavelengths before, during, and after the 1998 high/soft X-ray state transition. We find that the radio emission from the system is strongly correlated with the hard X-ray emission and is reduced by a factor of ≥25 during the high/soft state compared with the more usual low/hard state. At the points of state transition, we note brief periods of unusually optically thin radio emission that may correspond to discrete ejection events. We propose that in the low/hard state, black hole X-ray binaries produce a quasi-continuous outflow, that in the high/soft state, this outflow is suppressed, and that state transitions often result in one or more discrete ejection events. Future models for low/hard states, such as advection-dominated solutions, need to take into account the strong outflow of relativistic electrons from the system. We propose that the inferred Comptonizing corona and the base of the jetlike outflow are the same thing, based on the strong correlation between radio and hard X-ray emission in GX 339−4 and other X-ray binaries and on the similarity in inferred location and composition of these two components.

Subject headings: accretion, accretion disks — ISM: jets and outflows — radio continuum: stars — stars: individual (GX 339−4)

1. INTRODUCTION

GX 339−4 is one of only a handful of persistent black hole candidate X-ray binaries known (Tanaka & Lewin 1995). The system lies at a distance of several kiloparsecs in the direction of the Galactic center (e.g., Zdziarski et al. 1998) and exhibits a possible orbital modulation with a 14.8 hr period in optical photometry (Callanan et al. 1992), although this may in fact be half the true orbital period (Soria, Wu, & Johnston 1999a). GX 339−4 shares X-ray timing and spectral properties with the classical black hole candidate Cygnus X-1, although it exhibits more frequent state changes and a larger dynamic range of soft X-ray luminosity (Harmon et al. 1994; Tanaka & Lewin 1995; Méndez & van der Klis 1997; Rubin et al. 1998; Zdziarski et al. 1998; Nowak, Wilms, & Dove 1999; Wilms et al. 1999; Belloni et al. 1999). The system is also a weak and persistent radio source with flux densities typically in the range of 5–10 mJy at centimeter wavelengths and a flat (a spectral index of $\alpha \sim 0$ where flux density $S_\nu \propto \nu^\alpha$) spectrum (Fender et al. 1997; Corbel et al. 1997; Hannikainen et al. 1998). The radio emission is roughly correlated with both the soft (as observed with the *Rossi X-ray Timing Explorer* [*RXTE*] All-Sky Monitor [ASM]) and the hard (as observed with the *Compton Gamma-Ray Observatory* [*CGRO*] BATSE) X-ray flux in the X-ray low/hard state (Hannikainen et al. 1998). As discussed in Wilms et al. (1999), the radio emission almost certainly arises in a region larger than the binary separation, supporting an interpretation of its origin in a compact, partially self-absorbed jet, possibly of the type considered by Hjellming & Johnston (1988). Additional supporting evidence comes from the recent resolution of a compact jet in VLBA observations of Cyg X-1 (Stirling, Spencer, & Garrett 1998; de la Force et al. 1999), a source whose radio, as well as X-ray, properties appear to parallel those of GX 339−4 (Hannikainen et al. 1998; Pooley, Fender, & Brocksopp 1999).

2. OBSERVATIONS

2.1. *Molonglo Observatory Synthesis Telescope*

Occasional monitoring of GX 339−4 with the Molonglo Observatory Synthesis Telescope (MOST) at 36 cm has been carried out for several years. All the observations were calibrated, imaged, and CLEANed with the standard MOST imaging pipeline (McIntyre & Cram 1999). To moderate any errors in the calibration, we followed the procedure of Hannikainen et al. (1998), fitting three sources besides GX 339−4 in each observation, and scaling the fluxes so that the sum of these three reference sources remained constant, on the assumption that these sources do not vary. The IMFIT task in the MIRIAD software package (Sault, Teuben, & Wright 1995) was used to make point-source fits to the synthesized maps. Further details, an observing log, and tabulated flux densities will be presented in Corbel et al. (1999; see also Hannikainen et al. 1998). The MOST flux density measurements are plotted in the top panels of Figures 1 and 2.

2.2. *Australia Telescope Compact Array*

Observations of GX 339−4 have been carried out at wavelengths of 21.7, 12.7, 6.2, and 3.5 cm with the Australia Telescope Compact Array (ATCA). Observational procedures are similar to those described in Fender et al. (1997) and will be

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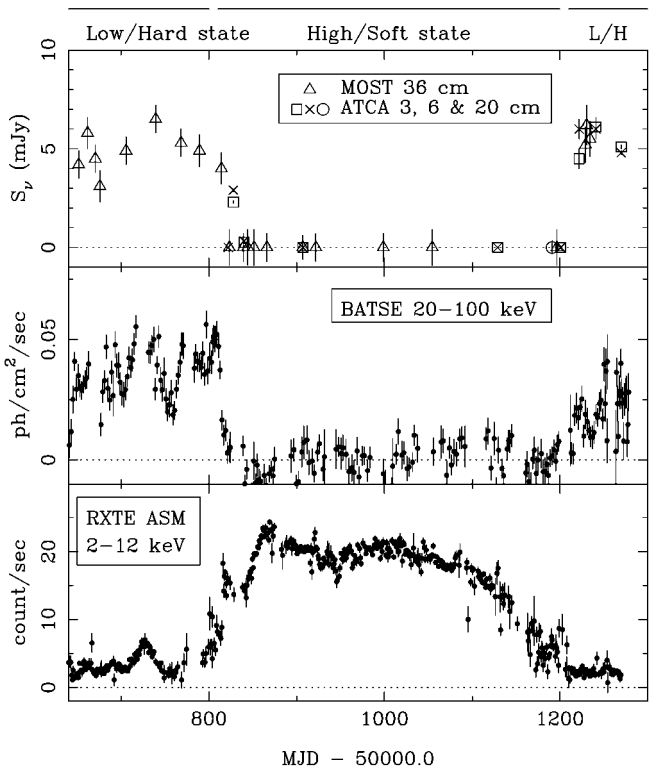

FIG. 1.—Radio, hard, and soft X-ray monitoring of GX 339−4 before, during, and after the 1998 high/soft state. The radio emission is reduced by more than a factor of 25 during this state. Unusually optically thin emission is observed just before and after the state changes, probably corresponding to discrete ejection events.

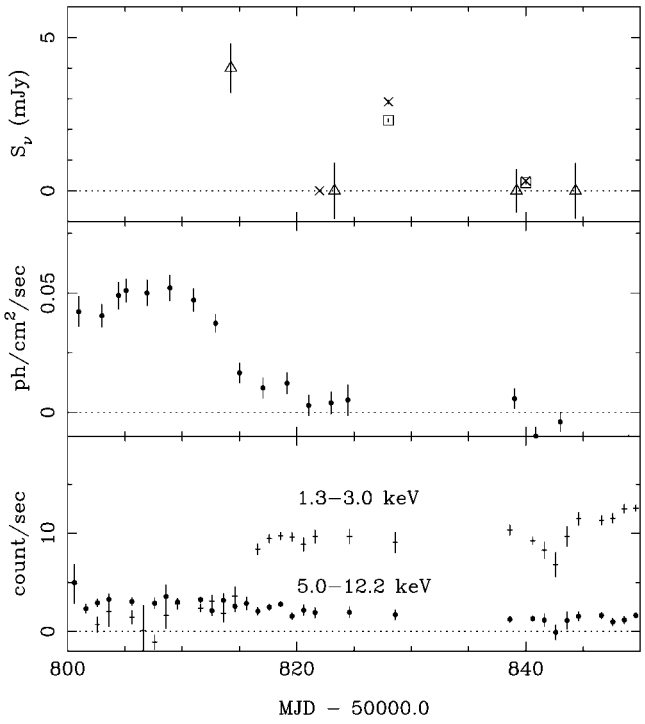

FIG. 2.—Same as Fig. 1, but with the timescale around the state transition expanded and the lowest and highest energy *XTE* ASM channels plotted to illustrate the abrupt rise in the soft (disk) component.

discussed more fully in Corbel et al. (1999). Data reduction was performed with the MIRIAD software package. The ATCA flux density measurements are plotted in the top panels of Figures 1 and 2.

2.3. *CGRO BATSE*

The BATSE experiment aboard the *CGRO* monitors the various hard X-ray sources in the sky using the Earth occultation technique (Harmon et al. 1994). An optically thin thermal bremsstrahlung model (with a fixed $kT = 60$ keV) has been used to fit the data (following Rubin et al. 1998) and to produce the light curve in the 20–100 keV energy band. We have checked for the presence of bright interfering sources in the limb that could have biased the measurement of the flux, and we have flagged suspicious data. The 20–100 keV BATSE data are plotted in the middle panels of Figures 1 and 2.

2.4. *RXTE ASM*

GX 339−4 is monitored up to several times daily by the *RXTE* ASM in the 2–12 keV range (see, e.g., Levine et al. 1996 for more details). The 2–12 keV ASM data are plotted in the bottom panels of Figures 1 and 2.

3. QUENCHING OF THE RADIO EMISSION

Figure 1 plots the radio, hard, and soft X-ray observations of GX 339−4 prior to, during, and following the transition from the low/hard state to the high/soft state in early 1998 January and the transition back to the low/hard state just over 1 yr later (see Belloni et al. 1999 for X-ray spectral and timing properties). It is immediately obvious that the radio and hard X-ray fluxes are strongly anticorrelated with the soft X-rays and are consistent with zero-measured fluxes for the majority of the observations during the high/soft state. In particular, there was no significant radio detection of GX 339−4 between MJD 50,844 and the reappearance of the radio flux on MJD 51,222, despite eight observations with MOST at 843 MHz and three observations with ATCA simultaneously at 4.8 and 8.6 GHz. The strongest limits on the radio flux in the high state are the ATCA measurements that had a typical 3 σ flux density limit of ~0.2 mJy, constraining the emitted flux density to be more than a factor of 25 weaker than observed in the low/hard state. The single most stringent upper limit, of 0.12 mJy (3 σ) from the ATCA observation on MJD 51,129, constrained the radio flux to be more than 40 times weaker than in the low/hard state.

In Figure 2, we examine in more detail the period of state transition. In addition, we plot the low (1.3–3.0 keV) and high (5.0–12.2 keV) *XTE* ASM channels, instead of simply the total intensity as in Figure 1; this illustrates clearly the dramatic increase in the soft (disk) component during the state transition. Note that from *XTE* Proportional Counter Array timing observations, we can only be certain that by MJD 50,828, the source was in the high/soft state (Belloni et al. 1999). The most dramatic decrease in the hard X-ray flux and the corresponding increase in the soft X-rays occur around MJD 50,812–50,816 (centered on New Year 1997/1998). By MJD 50,822, the radio flux density had dropped to levels undetectable with either MOST or ATCA (3 σ limit at 4.8 GHz of $\leq$0.1 mJy with ATCA); i.e., the timescale for decay from "normal" to "quenched" levels is $\leq$10 days. This is consistent with the timescales for radio/X-ray correlations reported by Hannikainen et al. (1998). However, subsequent radio observations re-

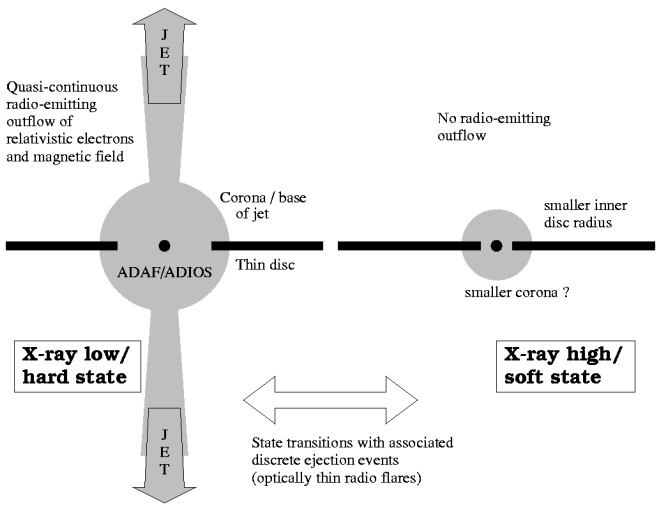

FIG. 3.—A sketch qualitatively combining the observational data with favored current models for accretion modes. In the low state (when the inner accretion region may be advection-dominated), there is a quasi-continuous radio jet; in the high state (when the hot, thin accretion disk extends much closer to the black hole), the radio jet is not present.

vealed a small resurgence in the radio flux density between MJD 50,828 and 50,840, with an unusually optically thin spectral index of ~ -0.4 (as measured on MJD 50,828). By MJD 50,844, the radio flux had again dropped to undetectable levels and was not detected again until over 1 yr later. The quenching of the radio emission simultaneously with a large drop in the hard X-ray flux, as observed with BATSE, is reminiscent of that observed in the radio jet X-ray binary Cyg X-3 (McCollough et al. 1999 and references therein).

4. REAPPEARANCE OF THE RADIO EMISSION

Observations of GX 339−4 on MJD 51,222 detected the radio source for the first time in over a year (Fig 1). The reappearance of the radio source was coincident with the end of a long ($\geq$100 days) decline in the soft X-ray flux and a sharper increase in the hard X-ray emission. This return to the low/hard state was slow compared with the corresponding transition by Cyg X-1 in 1996 that took $\leq$20 days (Zhang et al. 1997a). As in the small prequenching flare event, the spectral index immediately after the reappearance of the radio source was unusually optically thin at around -0.4 (measured on MJD 51,222). Subsequent observations have revealed a return to the flat spectrum and steady flux densities previously observed in the low/hard state. The timescale for the return from quenched to normal radio states can only be constrained to be $\leq$20 days.

5. DISCUSSION

Our observations have revealed that the radio emission from GX 339−4 is strongly suppressed during the high/soft X-ray state. This observation is in qualitative agreement with observations of an increase in the strength of radio emission from Cyg X-1 during transitions from the high/soft or intermediate states back to the more common low/hard state (Tananbaum et al. 1972; Braes & Miley 1976; Zhang et al. 1997b). In addition, Corbel et al. (1999) present evidence for previous periods of quenched radio emission in GX 339−4 that appear to correspond to periods of weak BATSE emission. We assert that it is a characteristic of the high/soft state in black hole X-ray binaries that radio emission is suppressed with respect to the low/hard state. At least one model already exists for the suppression of jet formation at high accretion rates in X-ray binaries (Meier 1996), and it may be relevant to this phenomenon. It is unclear at present how these findings relate to observations of radio emission associated with X-ray transients in outburst (e.g., Hjellming & Han 1995; Kuulkers et al. 1999) since (1) these sources may reach the physically distinct very high state (Miyamoto et al. 1991; Ebisawa et al. 1994) and (2) the radio emission in these cases appears to originate in discrete ejections, probably produced at points of X-ray state change, and as such are decoupled from the system. We note that Miyamoto & Kitamoto (1991) have proposed a jet model for the very high state of GX 339−4.

In the low/hard X-ray state, GX 339−4, in common with other black hole candidates, does not display a strong soft (disk) component (e.g., Wilms et al. 1999 and references therein). The inner regions of the accretion flow may be described by an advection-dominated accretion flow (ADAF), an advection-dominated inflow-outflow solution (ADIOS), or a "sphere + disk" geometry (e.g., Narayan & Yi 1995; Esin et al. 1998; Blandford & Begelman 1999; Wilms et al. 1999), all models in which the standard, thin, accretion disk is truncated some distance from the central black hole. A hot corona closer to the black hole Comptonizes soft photons to produce the observed hard X-ray emission. In the high/soft state, the disk is believed to extend to within a few gravitational radii of the black hole, resulting in a much increased soft, thermal X-ray component with $kT \lesssim 1$ keV. Simultaneously, the Comptonizing corona is believed to shrink and cool, resulting in a decrease and softening of the hard X-ray flux. Spectral fits to GX 339−4 data before and after the state transition under discussion are in agreement with this scenario (Belloni et al. 1999). In addition, Soria, Wu, & Johnston (1999b) present evidence that the outer accretion disk/flow, which is responsible for optical emission lines, is present in both the low/hard and high/soft states.

Adding our new observational constraint that the low/hard state produces a radio-emitting outflow, and the high/soft state does not, these models can be summarized qualitatively by a sketch such as Figure 3. The extremely strong correspondence between the hard X-rays and the radio emission in GX 339−4 and other X-ray binaries (e.g., GRO J1655−40 [sometimes; Harmon et al. 1995], GRS 1915+105 [Harmon et al. 1997; Fender et al. 1999], Cyg X-3 [McCollough et al. 1999], and Cyg X-1 [Brocksopp et al. 1999]) suggests that the regions responsible for the emission in the two energy regimes are strongly physically coupled. Therefore, we consider it likely that the corona is simply the base of the jet and that the population of relativistic electrons responsible for the radio emission (at some point farther downstream in the outflow when it becomes partially optically thin to centimeter radio emission) may be the high-energy tail of the population of hot electrons that is responsible, via Comptonization, for the hard X-rays.

We note that it is possible that the outflow continues in the high/soft state but that radio emission is not observed because of the greatly increased losses suffered by the relativistic electrons before the flow becomes (partially) optically thin to radio emission. In order for this to occur as a result of adiabatic expansion losses, the ratio of the lateral expansion rate to the jet width would need to be $\gtrsim$25 times more in the high/soft state than in the low/hard state. In order for synchrotron or inverse Compton losses to be responsible, an increase by a factor of $\geq$25 would be required in the magnetic ($\propto B^2$) or

radiation energy densities, respectively. Since current models suggest that adiabatic expansion is the dominant loss process in conical jets (e.g., Hjellming & Johnston 1988), the required increase in the magnetic or radiation energy densities would probably need to be even larger for these processes to result in the quenching of the jet.

6. CONCLUSIONS

The radio emission from GX 339−4 is found to be strongly quenched in the high/soft X-ray state, by a factor of $\geq$25, in comparison with the low/hard state. This quenching in radio emission is found to be extremely well correlated with a decrease in hard ($\geq$20 keV) X-ray emission, suggesting a strong physical coupling between the regions responsible for hard X-ray and radio emission. We propose that high/soft states in black hole candidate X-ray binaries do not produce radio-emitting outflows. Optically thin radio emission at the time of transition to and from the high/soft state implies discrete ejections of material at the point of state change, in agreement with observations of X-ray transients and more unusual sources such as GRS 1915+105. However, many of those systems are observed in the very high or poorly defined states, and the exact relation between their radio emission and that of GX 339−4 is not well understood at present. In addition, the optically thin emission observed at these periods of state transition is further evidence that the flat-spectrum radio emission generally observed in the low/hard state results from partially optically thick emission from a quasi-continuous jet. The dramatic coupling between the emission from the inner few hundred kilometers of the accretion disk and the radio emission is further confirmation that jets are generated close to the compact object.

Physical models developed to interpret the low/hard states (ADAF, ADIOS, and sphere + disk) clearly need to take into account the direct evidence for a continuous outflow in these states. Models for jet formation need to consider why such accretion geometries produce outflows whereas those envisaged to explain the high/soft state do not, and why discrete ejection events are often, perhaps always, observed at the point of state transitions in X-ray binaries.

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