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X-RAY STATES AND RADIO EMISSION IN THE BLACK HOLE CANDIDATE XTE J1550−564

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ABSTRACT

We report on radio and X-ray observations of the black hole candidate (BHC) XTE J1550−564 performed during its 2000 X-ray outburst. Observations were conducted with the Australia Telescope Compact Array and allowed us to sample the radio behavior of XTE J1550−564 in the X-ray low hard and intermediate/very high states. We observed optically thin radio emission from XTE J1550−564 5 days after a transition to an intermediate/very high state, but we observed no radio emission 6 days later, while XTE J1550−564 was still in the intermediate/very high state. In the low hard state, XTE J1550−564 is detected with an inverted radio spectrum. The radio emission in the low hard state most likely originates from a compact jet; optical observations suggest that the synchrotron emission from this jet may extend up to the optical range. The total power of the compact jet might therefore be a significant fraction of the total luminosity of the system. We suggest that the optically thin radio emission detected 5 days after the transition to the intermediate/very high state is due to a discrete ejection of relativistic plasma during the state transition. Subsequent to the decay of the optically thin radio emission associated with the state transition, it seems that in the intermediate/very high state the radio emission is quenched by a factor greater than 50, implying a suppression of the outflow. We discuss the properties of radio emission in the X-ray states of BHCs.

Subject headings: accretion, accretion disks — black hole physics — radio continuum: stars — stars: individual (XTE J1550−564) — X-rays: stars

1. INTRODUCTION

The soft X-ray transient (SXT) XTE J1550−564 was first detected by the all-sky monitor (ASM) on board the *Rossi X-Ray Timing Explorer* (*RXTE*) on 1998 September 7 (Smith 1998). The outburst was characterized by a "double peaked" profile and a strong (6.8 crab) and brief (1 day) flare. XTE J1550−564 went through all canonical black hole states (Sobczak et al. 1999, 2000b; Homan et al. 2001) before its return to quiescence in 1999 May.

Low-frequency (0.08–18 Hz) X-ray quasi-periodic oscillations (QPOs) as well as a high-frequency variable (100–285 Hz) QPO were detected during some of the *RXTE* Proportional Counter Array (PCA) observations. This is the fourth black hole candidate (BHC) to display such a high-frequency QPO. Based on its strong aperiodic variability, QPOs, and X-ray spectrum, XTE J1550−564 is believed to harbor a black hole, but a mass function has still to be measured (Cui et al. 1999; Remillard et al. 1999; Wijnands, Homan, & van der Klis 1999; Sobczak et al. 2000a; Homan et al. 2001).

Soon after its discovery in X-rays, an optical counterpart was reported by Orosz, Bailyn, & Jain (1998). A brightening of 4 mag in the *V* band over the quiescence level was noted by Jain et al. (1999). Based on the interstellar absorption lines, a distance of 2.5 kpc and an optical extinction of 2.2 ± 0.3 mag have been deduced by Sánchez-Fernández et al. (1999). A radio counterpart to XTE J1550−564 has been detected at 843 MHz with a flux density of ~ 10 mJy by the Molonglo Observatory Synthesis Telescope (MOST; Campbell-Wilson et al. 1998). Subsequent radio observations indicated that the strong X-ray flare was accompanied by a large radio flare with ejection of relativistic plasma, possibly at superluminal velocities (Hannikainen et al. 2001).

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XTE J1550−564 became active in soft X-rays again on 2000 April 2 (MJD 51,636; Smith et al. 2000). The Burst and Transient Source Experiment (BATSE) on board the *Compton Gamma Ray Observatory* (*CGRO*) detected XTE J1550−564 up to 300 keV (McCollough, Wilson, & Sun 2000). Simultaneously, a new optical outburst from XTE J1550−564 was reported (Masetti & Soria 2000; Jain & Bailyn 2000).

In this paper we report Australia Telescope Compact Array (ATCA) observations of the radio counterpart of XTE J1550−564, together with daily X-ray observations performed during the 2000 outburst with *RXTE* ASM and *CGRO* BATSE. These observations have been performed in different X-ray states, and we discuss the relation of radio emission within these states.

2. OBSERVATIONS AND RESULTS

2.1. *Soft and Hard X-Ray Observations*

The ASM, on board *RXTE* (Levine et al. 1996), monitors the activity in soft X-rays of any source in the sky in three energy bands (1.5–3, 3–5, and 5–12 keV). The ASM light curve in the energy band 1.5–12 keV is presented in the top panel of Figure 1, and in the lower panel, we plot the hardness ratio (5–12 keV/3–5 keV) using 1 day averages. The 20–100 keV light curve, obtained with BATSE on board *CGRO* using an Earth-occultation technique (Harmon et al. 1992), is presented in the middle panel of Figure 1. A power-law model with a variable spectral index has been folded through the BATSE response matrix for daily flux calculation. Due to precession of the *CGRO* orbit, XTE J1550−564 stopped being occulted on MJD 51,682, a few days before the end of the *CGRO* mission.

Figure 1 illustrates the soft and hard X-ray behavior of XTE J1550−564 during the 2000 X-ray outburst. During the initial rise, the soft X-ray flux increased slowly, whereas the hard X-ray flux was already strong when the orbital configuration of *CGRO* allowed its detection by BATSE. On April 26 (MJD 51,660), we note a rapid increase in soft X-rays as well as a decrease in hard X-rays, which then settled down in a plateau until the termination of *CGRO*. The decay of this outburst was a gradual decline in soft X-rays.

Analysis of the *RXTE* ASM hardness ratio curve and *RXTE* PCA data (Miller et al. 2001) allowed us to divide the outburst into three different parts. The outburst started and finished with a hard spectrum, whereas the central part was soft, but with detectable hard X-ray emission. This can be understood as an initial low hard state followed by a transition to the intermediate state (or very high state, as this state is now recognized as a higher count-rate version of the intermediate state; see Homan et al. 2001) on April 26, and then a return to the low hard state after May 13 (MJD 51,677). Preliminary analysis of *RXTE*/PCA observations confirm a change in power-law photon index from 2.30 to 1.74 between May 16 and May 24 (Tomsick, Corbel, & Kaaret 2001). We note that SXTs are rarely observed in the low hard state in the rising phase of their outbursts.

It is interesting to note that this new X-ray outburst occurred less than a year after the discovery outburst, which took place from 1998 September to 1999 May. Before that, XTE J1550−564 was believed to be in quiescence. This

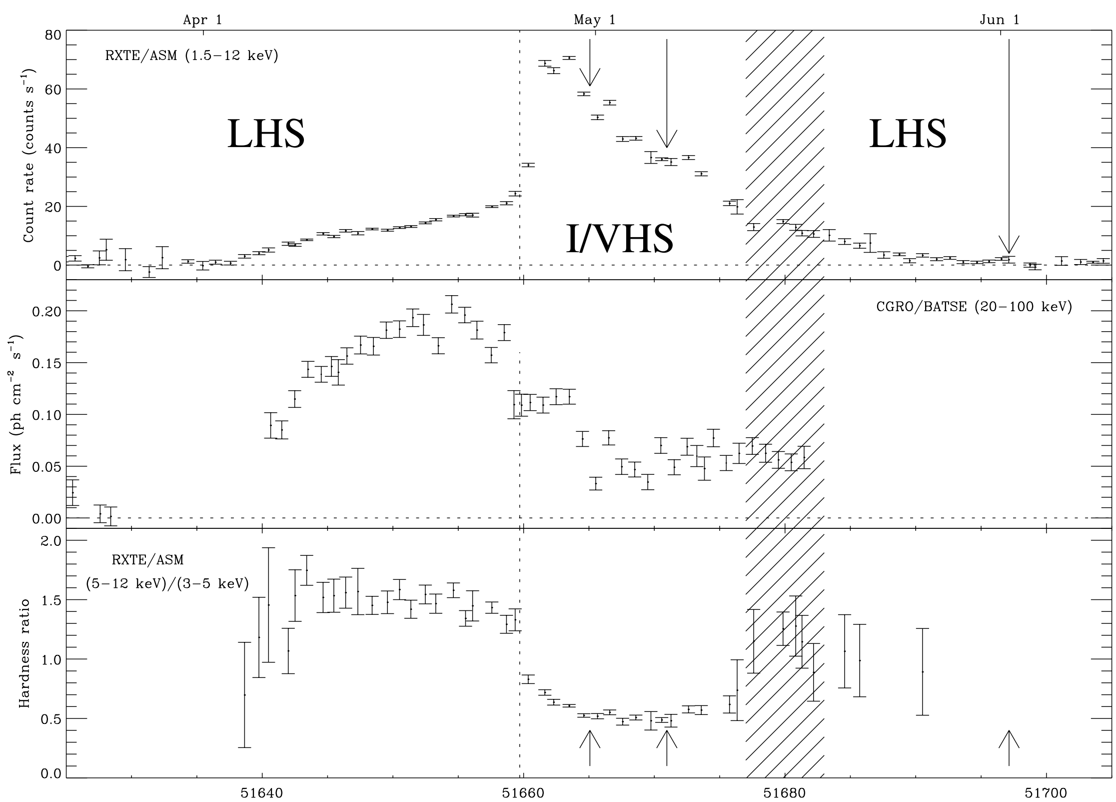

FIG. 1.—Light curve of XTE J1550−564 using 1 day averages. *Top*, *RXTE*/ASM (1.5–12 keV); *middle*, *CGRO*/BATSE 20–100 keV; *bottom*, hardness ratio (5–12/3–5 keV). Arrows indicate the dates of our ATCA radio observations, and the dotted line the likely period of the transition from the initial low hard state (LHS) to the intermediate/very high State (I/VHS). The hatched region shows the approximate date of the return to the final low hard state.

TABLE 1

ATCA OBSERVATIONS OF XTE J1550−564

Date	MJD[b] (days)	Duration (hr)	Flux Density[a] (mJy) 1384 MHz	2496 MHz	4800 MHz	8640 MHz	Spectral Index
2000 Apr 30......	51,665.07	8.0	[c]	[c]	7.45 ± 0.12	5.68 ± 0.06	-0.46 ± 0.05
2000 May 6	51,670.96	2.5	...	...	<0.10	<0.05	NA
2000 Jun 1	51,697.14	5.0	0.7 ± 0.2	0.85 ± 0.09	0.88 ± 0.08	1.30 ± 0.09	$+0.37 \pm 0.10$

[a] Upper limits are given at the 1 σ level.
[b] Date refers to the beginning of the observation.
[c] No precise flux estimate possible due to the presence of a bright supernova remnant in the sidelobes.

renewed activity is unusual for SXTs with long recurrence times (XTE J1550−564 probably belongs to this class, as it has never been detected in past years, despite sensitive surveys of the Galactic plane). A parallel can be drawn with GRO J1655−40, which also had a new outburst a few months after the end of a series of outbursts and a period of quiescence (e.g., Hameury et al. 1997 and references therein). We should also note that both systems have relatively long orbital periods: 2.6 days for GRO J1655−40 (Bailyn et al. 1995) and 1.5 days for XTE J1550−564 (Jain et al. 2001). The spectral type (F3–F6) of its stellar companion (Orosz & Bailyn 1997) and its peculiar position in the Hertzsprung gap (Kolb et al. 1997) may be responsible for the recurrent outbursts of GRO J1655−40 (but see Regős, Tout, & Wickramasinghe 1998 for alternative explanations). The spectral type of the secondary in XTE J1550−564 has not been identified yet, but photometric data are consistent with a low-mass K0–K5 star (Sánchez-Fernández et al. 1999). Its precise determination would be of great interest to understand these SXTs with repeated outbursts. If XTE J1550−564 does have a K-type optical companion, it must be evolved in order to be large enough to fill its Roche lobe. An evolved companion could conceivably be the similarity that is responsible for the repeated outbursts from these systems.

2.2. *Radio Observations*

The radio continuum observations of XTE J1550−564 were carried out using ATCA, located in Narrabri, NSW, Australia. ATCA is a synthesis telescope consisting of six antennae, each with a 22 m diameter, aligned on a 6 km east-west array. The ATCA radio observations were conducted on three different dates in 2000: April 30, May 6, and June 1. The first two observations were performed in the 0.750D compact configuration, while the last observation was carried out in the high spatial resolution 6B array. The first and third observations were made at the central frequencies of 1384, 2496, 4800, and 8640 MHz, with a total bandwidth of 128 MHz; observations were made at only 4800 and 8640 MHz during the second observation.

The amplitude and bandpass calibrator was PKS B1934−638, and the antennae gain and phase calibration were derived from regular observations (every 20 minutes) of the point source calibrators B1554−64 (at 4800 and 8640 MHz) and B1549−790 (at 1384 and 2496 MHz). The editing, calibration, Fourier transformation, deconvolution, and image analysis were performed using the MIRIAD package (Sault, Teuben, & Wright 1995). Because of the proximity of a very strong (~145 Jy at 1 GHz) supernova remnant (G326.3−1.8) close to the field of view, the shortest baselines have not been used in the analysis of the data at 1384 and 2496 MHz. The ATCA flux densities of XTE J1550−564 are tabulated in Table 1.

The first ATCA observation (on MJD 51,665) allows a detection of the radio counterpart at a weak level of 7.45 ± 0.12 mJy and 5.68 ± 0.06 mJy at 4800 and 8640 MHz, respectively. For a flux density $S_\nu \propto \nu^\alpha$, a spectral index of $\alpha = -0.46 \pm 0.05$ is derived. Before this first

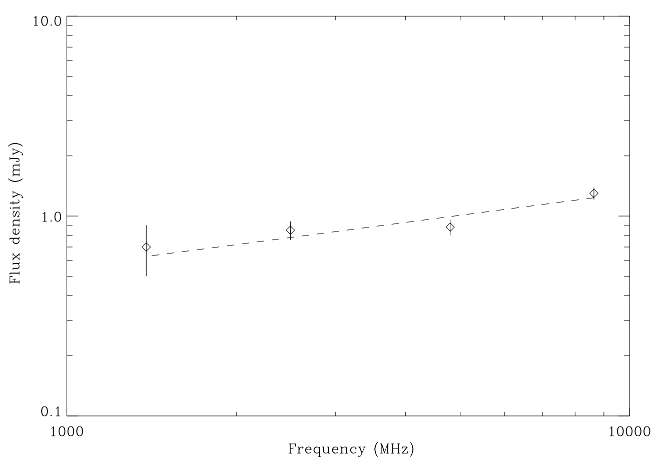

FIG. 2*a*

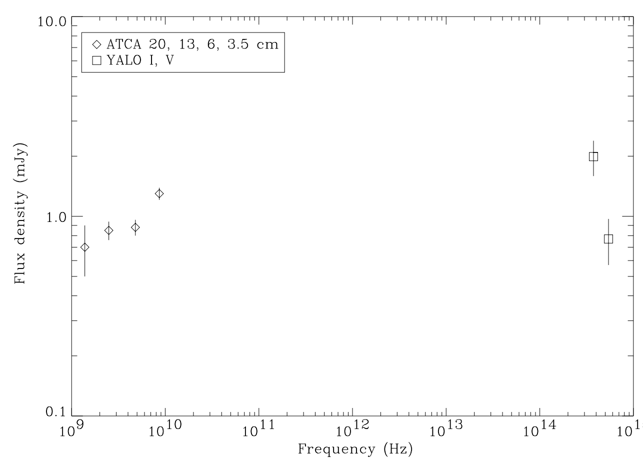

FIG. 2*b*

FIG. 2.—(*a*) Radio spectrum on 2000 June 1. The dotted line is the best-fit function $S_\nu \propto \nu^\alpha$ with $\alpha = +0.37$. (*b*) Radio and optical (V, I) measurements of XTE J1550−564 on June 1. The optical data originate from the Yale 1 m telescope (dereddened using an optical extinction of 2.2 ± 0.3 mag).

ATCA observation, the MOST performed several observations while XTE J1550−564 was in its initial low hard state, and detected the radio counterpart at a level of 8–15 mJy at 843 MHz. The second ATCA observations performed during the intermediate/very high state (on MJD 51,670) did not reveal significant radio emission from XTE J1550−564 with a strong 3 σ upper limit of 0.15 mJy at 8640 MHz.

After a transition back to the low hard state, we performed our third ATCA observation (on MJD 51,697) at nearly the end of the X-ray outburst. Radio emission is again detected at a level of ~ 1 mJy at all four frequencies. The spectrum is slightly inverted with a spectral index of 0.37 ± 0.10 (Fig. 2*a*). The best position of the radio counterpart is α(J2000) = $15^{h}50^{m}58^{s}.7$ and δ(J2000) = $-56°28'35''.2$, with a total uncertainty of $0''.3$; it is consistent with the position of the optical counterpart (Jain et al. 1999).

3. DISCUSSION

3.1. *A Compact Jet in the Low Hard State*

The detection (on June 1st) of a radio source with an inverted spectrum (spectral index of 0.37 ± 0.10) while XTE J1550−564 was in the low hard state is reminiscent of the behavior of the few other BHCs (transient or persistent) that have been observed at radio frequencies in the low hard state. Indeed, the persistent BHCs from our galaxy Cyg X-1 (Brocksopp et al. 1999), GX 339−4 (Corbel et al. 2000) and GRS 1758−258 (Lin et al. 2000), are found most of the time in the low hard state and are detected in radio with a flat (spectral index ~ 0.0) or inverted spectrum (and also probably 1E 1740.7−2942). Among the SXTs, we should note that GS 2023+338 (Han & Hjellming 1992), GRO J0422+32 (Shrader et al. 1994), GS 1354−64 (Brocksopp et al. 2001), and XTE J1118+480 (Hynes et al. 2000; Fender et al. 2001) have been detected with similar properties (see discussion in Fender 2001). XTE J1550−564 should now be added to this list.

A flat or inverted radio spectrum can be interpreted as an optically thick synchrotron emission from a compact and conical jet, following the model of Hjellming & Johnston (1988). In this model, the higher frequencies come from the base of the compact jet, where the optical depth is the highest. Low-frequency radio emission arises from the region further from the base. Summing all contributions over the spatial extent of the jet results in a flat or inverted spectrum. Recent Very Long Baseline Array (VLBA) imaging of a compact jet in the radio core of Cyg X-1 (Stirling et al. 2001) confirms this interpretation. The stronger orbital modulation of the higher frequencies also favors this scenario (Pooley, Fender, & Brocksopp 1999). The physical size of these compact jets is believed to be of the order of ~ 10 AU at 8.6 GHz (corresponding to the mas angular scale). More VLBA observations of BHC in the low hard state should increase the number of compact jet detections.

It is expected that the flat spectrum must cut off at high frequency. The spectrum of Cyg X-1 is flat up to 220 GHz (Fender et al. 2000). But in the case of GX 339−4 and XTE J1118+480 (Hynes et al. 2000; Fender et al. 2001), the inverted radio spectrum probably extends up to the near-infrared range. In Figure 2*b*, we show the simultaneous radio and optical observations of XTE J1550−564 taken on 2000 June 1 (see Jain et al. 1999, 2001 for a discussion of the YALO data). XTE J1550−564 is detected at $V = 18.9 \pm 0.1$ mag and $I = 16.7 \pm 0.1$ mag. An optical extinction of $A_V = 2.2 \pm 0.3$ mag (Sánchez-Fernández et al. 1999) has been used to deredden these data. Considering the uncertainties in the optical extinction, the spectral index between the two optical bands (-2.6 ± 1.0) appears to be nonthermal and is not compatible with the thermal spectrum of an optically thick accretion disk (spectral index greater than $+0.3$ in the optical range). It is therefore possible that a significant fraction of the optical, near-IR emission in XTE J1550−564 during the low hard state is (optically thin) synchrotron emission from the compact jet. If this interpretation is correct, the cutoff frequency lies in the near-infrared range (as in GX 339−4 and XTE J1118+480).

Using the June 1 observations, the radio luminosity (1–10 GHz band) of the compact jet is $\sim 7 \times 10^{28}$ ergs s^{-1} for a distance of 2.5 kpc. The luminosity of the compact jet in the radio band during the first part of the outburst may be an order of magnitude higher, as XTE J1550−564 was detected at a level of 8–15 mJy at 843 MHz with MOST. Assuming that the inverted spectrum extends to the near infrared ($\sim 10^{14}$ Hz), as discussed above, we find that the total radiative luminosity of the compact jet would be of order $\sim 2 \times 10^{34}$ ergs s^{-1} for the June 1 observation, several percent of the 2–20 keV band X-ray luminosity of 5×10^{35} ergs s^{-1} measured on the same day (Tomsick et al. 2001). Furthermore, taking into account the internal energy of particles within the jet and relativistic bulk motion is likely to increase the total power required to energize the jet (a precise estimate would require knowledge of the inclination angle of the jet). Thus, the compact jet is probably very powerful, with a total power close to the bolometric luminosity of the system (accretion disk and corona).

3.2. *Discrete Ejection Events at a State Transition*

The first ATCA observation was performed 5 days after the transition from the low hard state to the intermediate/very high state. XTE J1550−564 is detected around ~ 6 mJy, but contrary to the low hard state, the radio spectrum has a spectral index of -0.46 ± 0.05, indicative of optically thin synchrotron emission. It is likely that this optically thin emission is due to a discrete ejection of relativistic plasma at the time of the state transition when the accretion disk is unstable. We would then be detecting the decaying radio emission from this event, and the emission from XTE J1550−564 would be low, consistent with our nondetection of radio emission later in the intermediate/very high state. During the second part of the 1998–1999 X-ray outburst, Homan et al. (2001) also reported an optically thin synchrotron event after a state transition. Similar discrete ejection events have been inferred during state transitions in GX 339−4 (Corbel et al. 2000). It is possible that almost all X-ray binaries (including neutron star systems) produce similar weak radio events during state transitions (see also Hjellming & Han 1995 and recent work by Fender & Kuulkers 2001).

We note that it was hypothesized that the transition to the very high state was accompanied by massive superluminal ejections (Fender 2000) and bright, flaring radio events. These new ATCA observations rule out such an interpretation, as no bright ejection event was observed. The formation of these superluminal ejection events might possibly require a transition from a quiescent state to a very high state, i.e., a large and rapid increase of the mass accretion rate, and not a transition from a state where significant accretion is already occurring (such as the low hard state). Indeed, the discovery outburst of XTE J1550−564 was a transition from quiescence to a very high state. A bright radio event was detected after the transition and possibly resolved in two components moving at apparently superluminal velocities (Hannikainen et al. 2001).

3.3. *Quenched Radio Emission in the Intermediate/Very High State*

The second ATCA observation was performed when XTE J1550−564 was in the intermediate/very high state. At that time, XTE J1550−564 was not detected with ATCA at 4800 and 8640 MHz with a 3 σ upper limit of 0.15 mJy at 8640 MHz, i.e., a reduction of radio emission by a factor greater than 50 if we take into account the MOST detection in the initial low hard state. This is the first time radio observations of a BHC have been performed during an intermediate (or very high) state. Radio observations in this state are particularly important because usually, the radio emission is dominated by the decaying, optically thin synchrotron emission associated with the quiescent/active state transition (and therefore decoupled from the black hole/disk system); here, we view the intrinsic radio properties of the system in this state.

This nondetection is similar to the quenching of the compact jet of GX 339−4 during the 1998 high soft state (Fender et al. 1999). Following the discussion in Fender et al. (1999), it indicates that the compact jet is probably physically suppressed in the intermediate state. These new constraints lead us to conclude that, from a radio point of view, the intermediate (or very high) and high soft states are identical. We should note that Belloni et al. (1999) classified the 1996 outburst of Cyg X-1 as an intermediate state. At that time, radio observations (only performed at the end of the intermediate state, when Cyg X-1 was returning to its standard low hard state) revealed an increase of radio emission (Zhang et al. 1997), probably indicating that the radio emission was indeed lower in the intermediate state, as observed here in XTE J1550−564.

In the low hard state, there is a strong coupling between the compact jet and the luminosity of the corona (see Brocksopp et al. 1999 for Cyg X-1; Corbel et al. 2000 for GX 339−4). Despite the fact that the intermediate state has significant hard X-ray emission, it is not a sufficient condition to sustain the emission from the compact jet (the power-law index is different between the low hard state and the intermediate/very high state, but the hard X-ray emission is currently believed to originate from the corona in both states). Therefore, the low hard state does produce radio emission via a compact jet, whereas the states with a stronger soft component (high soft and intermediate/very high) lead to the quenching of these compact jets for a reason that is not understood. Evaporation processes in the standard geometrically thin disk, below a certain accretion rate, may possibly lead to coronal outflows (e.g., Meyer, Liu, & Meyer-Hofmeister 2000). It is also possible that high magnetic energy dissipation might be responsible for the formation of outflows (and therefore a compact jet above the corona) in the low hard state, whereas the soft states would be dominated by viscous energy dissipation in the accretion disk (e.g., Beloborodov 1999; Poutanen 1999; Di Matteo, Celotti, & Fabian 1999).

4. CONCLUSIONS

Radio emission was detected from XTE J1550−564 on two occasions during its 2000 outburst. Like other BHCs, observed (too rarely) in the low hard state, the radio spectrum of XTE J1550−564 is inverted. This likely implies that the radio emission is synchrotron emission from a compact jet. The total power in the compact jet may be a significant fraction of the total accretion luminosity. The intermediate/very high state (like the high soft state of GX 339−4) is characterized by a quenching of this compact jet. It appears that low hard states in BHCs produce compact outflows, whereas the states with a strong soft component from the accretion disk lead to suppression of a radio-emitting outflow. State transitions are accompanied by discrete ejection of relativistic plasma. More multiwavelength observations of BHCs in the low hard state are needed in order to understand the physics of these compact jets.

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