

HST Observations of Black Hole X-Ray Transient Outbursts

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1 Introduction

Black hole X-ray transients (BHXRT; also known as Soft X-Ray Transients and X-Ray Novae; see Tanaka & Shibazaki 1996) contain a compact object accreting from a low-mass star via Roche lobe overflow and an accretion disk. They differ from other X-ray binaries in that significant X-ray emission is seen only in well defined outbursts lasting up to two years and recurring on timescales of decades. The currently favored model for these outbursts is a variant of the disk instability model originally developed for dwarf nova outbursts (Cannizzo 1999). In $> 70\%$ of cases, the compact object is dynamically measured to be a black hole (Charles 1998). These objects are thus the best place to study stellar mass black holes. In particular, there has recently been much theoretical work on advective accretion flows, and variations on this theme, in which the black hole ‘silently’ accretes material through its event horizon with little emission (Narayan, Mahadevan & Quataert 1998). The reality of such flows remains controversial.

The first *HST* observations of a BHXRT were of X-ray Nova Muscae 1991 through Director’s Discretionary Time (Cheng et al. 1992). After this, a formal target-of-opportunity program was established to study BHXRT outbursts, originally using FOS and now STIS. The current program contains 20 STIS orbits spread over 7 visits spanning the first 150 days of outburst. Our goals include: to monitor changes in the 1100–10300 Å spectrum through the outburst; to obtain a high-quality far-UV spectrum to study the typically rich emission line spectrum; to use the near-UV spectrum to fit the 2175 Å interstellar absorption feature and determine the interstellar reddening; and to obtain UV data in TIMETAG mode for comparison with simultaneous RXTE X-ray light curves and echo mapping. For initial visits on a bright target we also use medium-resolution echelle modes to obtain UV line spectrum with velocity resolution $< 10 \text{ km s}^{-1}$.

2 GRO J0422+32

The first target for the target-of-opportunity program, GRO J0422+32 was discovered in August 1992 by *CGRO*/BATSE. The primary is likely a 4–12 M_{\odot} black hole and the companion an M0–M4 dwarf in a 5.1 hr low-inclination orbit. The outburst lightcurve is the best studied of any BHXRT. GRO J0422+32 was observed by *HST*/FOS in a single visit at the end of the outburst, in 1994. A full description of this observation is given by Hynes & Haswell (1999).

The outburst behavior, illustrated in Fig. 1, is complex, dividing into two phases spanning two years. The early plateau phase (~ 200 d) showed a steady exponential decline. The later phase shows the same decay rate at lower level, with several superposed mini-outbursts. Two mini-outbursts were definitely detected, separated by 120 d. The near-quiescent *HST* observations appear to have detected a third mini-outburst, or a flat plateau at end of outburst. This occurs ~ 240 d after the previous mini-outburst, consistent with twice the 120 d recurrence time.

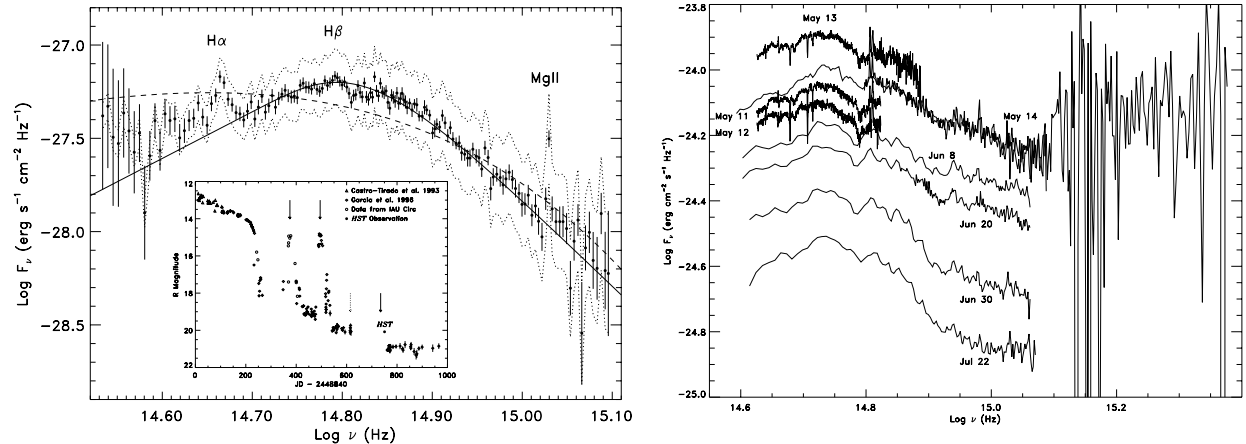


Figure 1: Left: Dereddened *HST* spectral energy distribution (SED) of GRO J0422+32 near quiescence, with the spectrum of the companion star subtracted. Models are a black body (dashed) and self-absorbed synchrotron emission (solid). Inset shows the outburst lightcurve, and the timing of the *HST* observation. Right: Dereddened SEDs of GRO J1655–40 at several epochs. Spectra from May 11–13 are from the AAT, others are *HST*.

The dereddened spectral energy distribution (SED) peaks at blue wavelengths. It appears sharper peaked than a black body; a self-absorbed synchrotron spectrum fits much better. Advective accretion flow models predict that optical emission is dominated by synchrotron, with similar peak wavelength to that seen. The *HST* observation may therefore indicate that an advective flow has already formed at the end of the outburst.

3 GRO J1655–40

This object was discovered by *CGRO*/BATSE in July 1994. The system is believed to comprise a 5–7 M_{\odot} black hole and an F-type subgiant companion in a 2.6 d orbit. Several outbursts occurred until 1997, during the first of which relativistic jets were ejected. The outburst optical and X-ray fluxes are not well correlated. In 1996, *HST* saw optical and UV fluxes drop whilst X-rays rose (Hynes et al. 1998a). This is difficult to reconcile with simple outburst models with optical/UV emission produced by reprocessing of X-ray emission via disk heating. Echo mapping indicates at least some reprocessing (see below); the most likely solution is that reprocessing gets less effective later on. A change in the irradiation geometry, e.g. through warping of the disk (Esin, Lasota & Hynes 2000), could drive such a change.

The dereddened spectral energy distributions (Hynes et al. 1998a) are very different to other systems (e.g. XTE J1859+226 shown below). There is an optical component, peaking at $\log \nu = 14.6$ –14.9 which appears to be at least partly from the companion, since this is larger and hotter than in other black hole systems. The residual optical spectrum looks like a relatively cool irradiated disk. This makes sense, as a large orbital period implies a large disk with an edge far from the X-ray source. The far-UV component looks more like the $\nu^{1/3}$ spectrum of a viscously heated disk, but the transition between optical and UV is sharper than expected.

Coordinated *HST* and *RXTE* observations revealed correlated X-ray and optical/UV variability (Hynes et al. 1998b). We were able to cross-correlate the two light curves and derive optical lags of 10–20s, likely indicating light travel times within the system. This is too short to originate on the companion star for which a minimum lag of ~ 40 s is expected at the orbital phase observed. Lags of 0–30s are expected from reprocessing in the disk. It thus appears that either the companion is shielded from X-rays, or for some other reason does not reprocess variability.

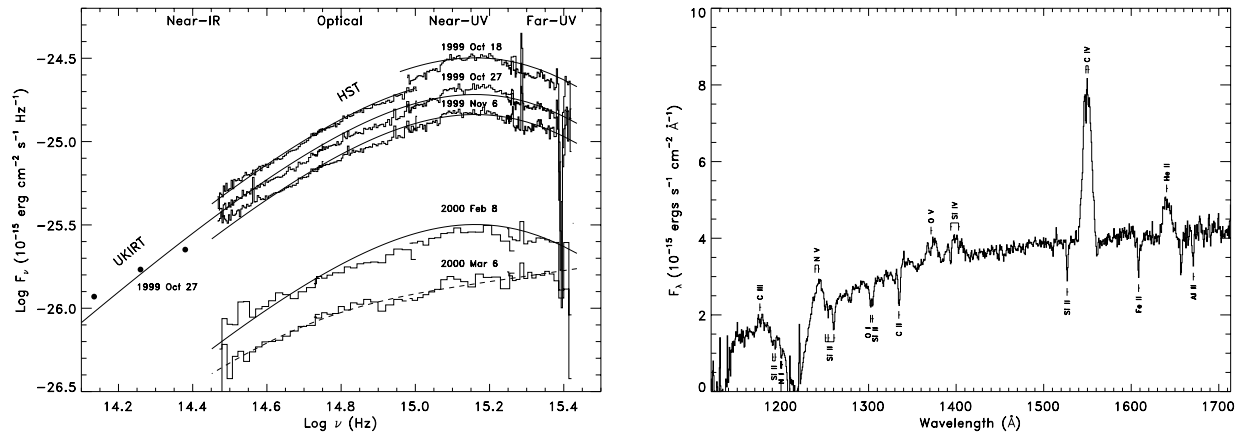


Figure 2: XTE J1859+226. Left: Broad band IR–UV SED at several epochs, corrected for interstellar reddening. See text for details of the models applied. Right: Average far UV spectrum, uncorrected for reddening. Identified lines are marked.

4 XTE J1859+226

XTE J1859+226 was discovered in October 1999 by *RXTE*. The compact object is likely a black hole but neither this, nor the nature of the companion have been confirmed. An orbital period of 6.7 hr has been suggested (Uemura et al. 1999). The fast rise, exponential decay lightcurve is typical of BHXRTs, although the initial rise was slower than normal.

Fitting the broad 2175 Å interstellar feature yields an interstellar reddening of $E(B - V) = 0.58 \pm 0.07$ (Hynes et al. 1999). We used this value to deredden the spectra and derive the intrinsic SEDs shown in Fig. 2. SEDs from early in the outburst could be well fitted by simple X-ray heated disk model, $T \propto R^{-3/7}$. The derived edge temperature remains constant as the system fades, implying that the edge of the hot region moves inward as the X-rays decline, likely either indicating a cooling wave or a self-shielding effect. The last SED is better fitted by a viscously heated disk model with an edge temperature of ~ 8000 K, consistent with disk instability models.

The far-UV spectrum is rich in broad emission lines, with superposed sharp interstellar absorption. CIV, HeII, NV, OV and SiIV lines are definitely seen. CIV shows emission to 4000 km s^{-1} . Ly α shows very broad absorption, extending to 12000 km s^{-1} .

5 Our New Target: XTE J1118+480

XTE J1118+480 was discovered in March 2000 as a very weak X-ray transient, although activity had started in January. The optical counterpart is bright ($V \sim 13$), making the X-ray to optical flux ratio exceptionally low. The source is at high latitude ($+62^\circ$) and situated near the Lockman Hole, resulting in very low absorption. This combination of brightness and low absorption makes it ideal for UV spectroscopy, and so we have been able use the UV echelle modes of STIS.

HST observations have been ongoing since April 8, with coordinated *RXTE* and *EUVE* coverage. We have found that the IR–UV continuum is very flat (constant F_{ν} ; Haswell, Hynes & King 2000, Hynes et al. 2000). The UV spectrum shows emission lines of HeII, NV and SiIV, but carbon and oxygen are absent. This likely indicates that the material being transferred from the companion has been processed by the CNO cycle within the interior, and hence that the envelope has been lost (Haswell, Hynes & King 2000). The source

exhibits remarkable rapid variability on timescales of seconds at all wavelengths where such variations can be detected. This includes the UV where STIS TIMETAG mode allowed resolution of variability up to 1 Hz or higher. A strong correlation is seen between the X-ray and UV light curves, with the UV lagging by 1–2 s behind the X-rays (Haswell et al. 2000).

6 Conclusions

HST has now observed a number of BHXRTs in outburst. Progress has been made towards understanding these objects, but new questions have been raised, both by observations and theoretical developments. The wide wavelength coverage and reliable flux calibration of *HST* make it an unrivalled tool for determining the IR–UV spectrum of BHXRTs. The diversity of SEDs observed so far, however, indicates that more than one source of optical/UV emission may be present, and careful modeling will be required to unambiguously separate these contributions. These include an accretion disk heated either by viscosity or X-ray irradiation, the companion star and possible synchrotron emission. Exploitation of *HST*'s rapid spectroscopy capability via echo-mapping provides additional clues to locate the emission source within the binary, as demonstrated for GRO J1655–40 and potentially for XTE J1118+480. These and other techniques allow us to watch the evolution of the components of the binary through an outburst, and hence improve our understanding of the outburst mechanism and the nature of accretion onto black holes.

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