HST Observations of X-Ray Transients

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Abstract

Results from an HST/multiwavelength campaign on the 1996 outburst of GRO J1655-40 are reported. We find evidence for an approximately isothermal outer disk in GRO J1655-40 during the decline from outburst, possibly indicating the outer disk being maintained in the hot state. HST observations of GRO J0422+32 made 2 years after outburst reveal a sharply peaked optical/near UV spectrum, providing strong evidence for non-thermal emission.

1. Introduction

This paper summarises results from our HST/multiwavelength campaign on the 1996 outburst of GRO J1655-40, and near quiescent 1994 observations of GRO J0422+32. Our primary goal is to probe and understand the mechanisms causing the dramatic luminosity evolution in these systems.

2. GRO J1655-40

The superluminal jet source GRO J1655-40 has undergone repeated outbursts since its 1994 discovery. We mounted a coordinated HST and RXTE campaign between 1996 May 14 and July 22. Fuller descriptions of these observations and their interpretation are given in Hynes et al. (1998a,b).

2.1. The 1996 Broad Band Spectral Evolution of GRO J1655-40

Modelling of the 2175Å feature yields E(B-V)=1.2 ± 0.1 (Hynes et al. 1998a). Figure 1 is the 1996 May 14 dereddened UV-optical spectrum. Though the UV portion of the spectrum is consistent with the $\nu^{1/3}$ power-law predicted
Fig. 1. The dereddened spectrum of GRO J1655-40. The spectral slope changes dramatically at $\log \nu \sim 15.05$ ($\lambda \sim 2600$Å). The dashed line shows a $f_\nu \propto \nu^{1/3}$ fit to the UV data. Adapted from Hynes et al. 1998a.

by the steady-state blackbody disk model, the optical ($\lambda > 2600$Å) spectrum rises to longer wavelengths in contrast to the predictions of the model. Ignoring the $\lambda > 2600$Å data, a $\nu^{1/3}$ model can be fit to the UV data, implying a mass transfer rate of $1 \times 10^{-7} M_\odot \, \text{yr}^{-1} \leq \dot{M} \leq 7 \times 10^{-6} M_\odot \, \text{yr}^{-1}$, if the compact object mass is $7 M_\odot$ as the quiescent observations imply (Orosz and Bailyn 1997, hereafter OB97). The dominant source of uncertainty in this $\dot{M}$ arises from the extinction correction. Assuming an accretion efficiency of 10%, the Eddington rate is $\dot{M}_{\text{Edd}} = 1.6 \times 10^{-7} M_\odot \, \text{yr}^{-1}$, so near the peak of the outburst this interpretation of the UV spectrum implies $\dot{M} \approx \dot{M}_{\text{Edd}}$.

We need to invoke something other than a pure steady-state optically thick accretion disk to explain the optical light. The shape of the spectrum is qualitatively suggestive of an irradiated disk; irradiation can alter the temperature profile of the outer disk producing a rise in flux towards longer wavelengths as illustrated in Fig. 2a. The multiwavelength light curves for the outburst (Hynes et al. 1998a) do not support a simple irradiation model: the optical and UV flux declines while the X-ray flux rises. Nonetheless correlated X-ray and optical/UV variability was detected (see section 2.3 and Fig. 3a) indicating at least some of the optical/UV flux is due to reprocessing in the disk.

While the optical fluxes fell by about a factor of three between our first and last visit, the colour temperature remained almost constant, dropping from 9800 K to 8700 K; the effective emitting area dropped from $5.0 \times 10^{23}$ cm$^2$ to $2.2 \times 10^{23}$ cm$^2$ (Hynes et al. 1998a.) The well constrained system parameters for GRO J1655-40 (OB97, Hjellming and Rupen 1995) imply the total available
emitting area is \( \sim 5 \times 10^{23} \text{ cm}^2 \), so it is possible to explain the optical emission at the peak of the outburst as thermal emission, but only if both the secondary star and the majority of the disk area have essentially the same temperature. In this scenario, the \( \nu^{1/3} \) UV component can, however, still be attributed to the hot inner regions of the disk.

While noting that the spectral shape is strongly dependent on the adopted reddening correction, our optical spectra appear more strongly peaked than a single temperature blackbody, so we considered non-thermal emission mechanisms (Hynes et al. 1998a, especially Fig. 7 and 11). Self-absorbed synchrotron emission from a compact cloud of relativistic electrons produced good fits to the optical component. Attributing substantial optical flux to this compact non-thermal source relieves the requirement for a large isothermal emitter in the system. But while the synchrotron models fit better than black bodies, they have an extra free parameter, and there is no external check comparable to that provided by the emitting area required for the black body interpretation. The intrinsic VRI band linear polarisation (\( \sim 3\% \)) detected in July 1996 (Scaltriti et al. 1997) seemed consistent with the hypothesis of optical synchrotron emission. Subsequent phase-resolved polarisation measurements (Gliozzi et al. 1998) seem, however, to indicate an extended polarisation region, inconsistent with the possible compact non-thermal source. The lack of optical dips during near-total X-ray dips (Fig. 3b) provides further evidence against a compact central source for the optical continuum. Hence, on balance a thermal origin for the optical continuum seems most likely.

Indeed, the DIM may require a large isothermal outer disk for a long-period system like GRO J1655-40. Since the disk in such a system is large, the temperature for a steady state disk falls below the minimum temperature for the hot, high viscosity, state long before the outer disk is reached. Even for an Eddington mass transfer rate in GRO J1655-40 the temperature drops below that of the hot state at a radius less than a quarter of the Roche lobe radius. This means that there is no global steady-state solution for \( \dot{M} \leq \dot{M}_{\text{Edd}} \). It is not clear what will happen to the temperature distribution in such a case, but it is possible that in outburst much of the outer disk could be maintained just in the hot state. Hence one might expect the outer disk to appear as an approximately constant temperature, shrinking area emitter as the decline proceeds. This hypothesis awaits tests with self-consistent numerical modeling of the DIM in long period systems.
2.2. A Disk Wind?

We found likely P-Cygni profiles in the UV resonance lines (Fig 2b). The peak to trough separation is $\sim 5000$ km s$^{-1}$, slightly larger than seen in outbursting dwarf novae. Line profiles produced by biconical accretion disk winds were calculated by Shlosman and Vitello (1993) who found ‘classical’ P Cygni profiles only for inclinations around 60–70$^\circ$, in striking agreement with the inclination determined for GRO J1655-40 (OB97). We conclude that there was likely a biconical accretion disk wind at the peak of the UV outburst, when $\dot{M} \sim \dot{M}_{\text{Edd}}$.

2.3. Light Echoes

Correlated rapid variability between the optical/UV and X-ray emission occurred in simultaneous RXTE and HST data from 1996 June 8 (Fig. 3a). The mean delay of the optical/UV was up to 25s (Hynes et al. 1998b). Hence, the correlations are likely due to reprocessing of the X-rays into optical and UV emission, the delay being due to the finite light travel time between the X-ray source and the reprocessing regions. The lag of up to 25s is consistent with reprocessing in the accretion disk. At the binary phase of the observations, lags of greater than 40s are expected for light echoes from the mass donor star. The
Fig. 3. a) The combined interpolation cross-correlation function of our 1996 June 8 HST/RXTE observations of GRO J1655–40. Dashed lines denote $3\sigma$ limits on spurious correlations. There is a clear correlation with a lag $\sim 20$-sec.
b) HST and RXTE light curves from 1996 June 20, showing two X-ray dips, but no corresponding optical dips.

lack of a reprocessing signal from the mass donor star may imply that the X-ray absorbing material in the accretion flow is sufficiently vertically extensive to effectively shield it from direct X-ray illumination. For the Roche geometry deduced by OB97, this implies $H/R$ is at least $\sim 0.25$ along the line of centres.

3. GRO J0422+32

HST observations of this target covering the vacuum UV and the entire optical region were obtained on 1994 August 25 and 26, approximately two years after the first observed outburst, and seven months after the last reported reflare (Callanan et al. 1995). A full discussion of these data is given in Hynes and Haswell (1999). Figure 4a shows the R band light curve including the point deduced from our spectrum. The vertical marks above the light curves indicate the times of mini-outbursts according to the suggestion (Augusteijn, Kuulkers, and Shaham 1993, Chevalier and Ilovaisky 1995) that they recur on a 120 day period. Our observation clearly lies above the subsequent points, and it appears we saw the end of a previously unreported mini-outburst or of an extended plateau.

Figure 4b shows the spectrum after dereddening and subtracting the mass donor star flux, hence represents the intrinsic accretion spectrum. The spectral shape in Fig. 4b is distinctive: there is a pronounced peak in the optical at $\sim 4500\text{Å}$; and since the interstellar reddening towards this system is moderate, $E(B-V) = 0.3 \pm 0.1$, it is unlikely that this is an artifact of an improper red-
Fig. 4. a) The R band light curve of the outburst of GRO J0422+32, adapted from Fig. 1 of Garcia et al. (1996). Vertical marks indicate observed or extrapolated times of mini-outburst. Our measurement clearly lies significantly above the subsequent photometry, and is consistent with the expected time of a mini-outburst. b) The near quiescent accretion spectrum from GRO J0422+32: dereddened data after subtraction of the companion contribution. The best fitting black body (dashed) and self-absorbed synchrotron (solid) spectra are overplotted. The data below 4000 Å ($\log \nu > 14.88$) has been averaged into 25 Å bins for clarity. The large error bars at low frequencies are systematic and arise from assuming a $\pm 1$ pixel miscentring uncertainty. Dotted lines indicate the effect of varying the assumed E(B-V) value by $\pm 0.1$. From Hynes and Haswell 1999.
dening correction. The best fitting black body shown in Figure 4b is clearly less sharply peaked than the observed spectrum from GRO J0422+32, while a simple self-absorbed synchrotron spectrum can successfully reproduce the continuum shape. We stress, however, that this model is very simplistic and conclude simply that the continuum spectrum is highly suggestive of a self-absorbed synchrotron source, rather than black body emission. When compared with advective models, in which the quiescent optical continuum is dominated by synchrotron emission, the agreement between model and data is encouraging (Esin 1998).

4. Discussion and Future Work

The advective models for quiescent black hole transients predict that the inner disk is replaced by a hot, optically thin, quasi-spherical flow. Figure 4b reveals strong evidence for non-thermal optical emission in GRO J0422+32 near quiescence; this does not necessarily confirm particular detailed advective models, but supports the general scenario. We plan to perform detailed comparisons of our GRO J0422+32 spectrum with the latest models.

We also considered the possibility of non-thermal emission in the optical light from GRO J1655-40 during the decline from its 1996 outburst. In this case, however, it is alternatively possible to attribute the optical spectra to thermal emission, as the sharply peaked spectral shape is dependent on the exact details of the (large) reddening correction. The non-appearance of an optical modulation during near-total X-ray dips shown in Fig 4b suggests that the X-ray source is far more compact than the source of the optical continuum, supporting the standard thermal interpretation of the optical continuum.

At the peak of the optical/UV light curves in 1996, the UV spectrum from GRO J1655-40 was consistent with an Eddington-rate mass transfer through the UV emitting parts of the disk. At this time, however, the X-ray luminosity was less than ~0.1 L_{Edd}. This apparent discrepancy may be partly due to outflow from the inner regions of the disk: Fig. 2b shows likely P-Cygni profiles indicating a disk wind with velocity ~5000 km s^{-1}.

In both sets of observations described here, the vacuum UV spectrum was of low signal to noise ratio. Our single UV spectrum of GRO J1655-40 proved informative, despite the effects of the large reddening. We have our multiwavelength network poised to observe newly discovered transients, and anticipate obtaining high quality UV/optical spectra through decline. With this program we should be able to address many of the outstanding issues regarding the temperature structure, morphology, irradiation behaviour, and outflow characteristics of these systems.
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