\textbf{HST Observations of GRO J1655–40 in Outburst}

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\textbf{Abstract}

We examine the results of a coordinated HST–RXTE–CGRO campaign to study the microquasar GRO J1655–40 during its 1996–7 outburst, focusing on interpretation of the overall anti-correlation seen between optical and X-ray fluxes during the early months of the outburst. Our tools include echo-mapping, optical/UV continuum spectral modelling and analysis of spectral variability. We conclude by suggesting one possible interpretation for the anti-correlation.

1. Introduction

During the early stages of the 1996–7 outburst of the microquasar GRO J1655–40, HST, RXTE and CGRO light curves reveal an enigmatic behaviour, shown in Fig. 1. Over a period of about 3 months, during which optical and UV fluxes declined steadily, the X-ray brightness of the object increased. The hard X-ray rise in particular appears almost anti-correlated with the optical/UV decline; this is difficult to reconcile with models in which the optical/UV flux is produced by reprocessing in an irradiated accretion disc, e.g. King & Ritter (1998), for which the optical flux is expected to track X-ray behaviour. Nonetheless, comparison of optical and X-ray light curves reveals correlated variability; echo mapping suggests that this is due to the disc being significantly irradiated, contrary to what the long term light curves would suggest.

Our HST data set spans 1996 May 14 to July 22, comprising five separate observations, during four of which the RXTE/PCA also observed the source. Each observation resulted in a series of spectra (spanning most or all of the 1300–9000 Å range) obtained with time resolution of 2–3 s. We will examine the evidence which these data provide for reprocessed X-rays being an important source of optical flux and suggest one way to reconcile this evidence with the apparently contradictory longer term behaviour. The hard X-ray vs. optical/UV anti-correlation may arise naturally from this interpretation.

2. RAPID Spectroscopy – an Exercise in Echo Mapping

Our HST/RXTE data from June 8 (photometric phase 0.4) shows correlated short-term variability (on timescales of seconds to minutes), with the X-ray variations leading the optical by 10–20 seconds. The combined interpolation cross correlation function is shown in Fig. 2. We interpret this correlation as due to reprocessing of a variable X-ray flux into optical/UV emission and hence perform echo mapping of the reprocessing region (Hynes et al. 1998a.) The observed lags are too short to be consistent with reprocessing on the companion star (at this orbital phase causality requires a minimum lag of $\sim 40$ s from the companion) but are of the size expected for echoes from the accretion disc. We therefore conclude that X-rays are being reprocessed into optical/UV photons in the disc. We estimate that to produce the amplitude of variability observed by HST, at least 15–20\% of the optical flux must be generated in this way.
3. Rapid SPECTROSCOPY – Making Sense of Continuum Spectra

In Hynes et al. (1998b) we considered models for the optical/UV continuum spectral evolution, shown in Fig. 3. The far-UV spectrum ($\log \nu > 15.1$) resembles the canonical $\nu^{1/3}$ accretion disc spectrum. We suggested two interpretations for the spectrum at lower energies ($\log \nu < 15.1$): thermal emission from the accretion disc, and non-thermal synchrotron emission from a compact, self-absorbed source. We will focus here on the former model. In this interpretation, we are seeing optically thick thermal emission from an object with a temperature fixed around 9–10,000 K, shrinking in area. Allowing for the contribution from the bright F-type companion star, the area required is just about consistent with a shrinking hot region of an accretion disc. The temperatures needed are consistent with gas just in the hot state of the disc instability model (Cannizzo, Chen & Livio 1995.) The shrinking area may thus be a signature of the long postulated cooling wave of this model.

With this interpretation, there remains one important question to be addressed: what is responsible for the heating of the disc? The spectrum that is seen is not purely the $\nu^{1/3}$ form expected for an approximately steady-state, viscously heated accretion disc, and instead is closer to the shape predicted for an irradiated disc (Vrtilek et al. 1990), suggesting that it may be X-ray heating which is keeping the disc in the hot state.
Fig. 3. HST optical/UV spectra dereddened assuming the Seaton (1979) extinction curve and $E_B - V = 1.2$.
The far-UV spectrum is G160L data. At lower frequencies, the spectra are composites of blue and red prism data, together with G270H/G400H spectra on May 14.

Fig. 4. A variability spectrum deduced from 1996 June 20 data, marked by points with error bars. The solid line indicates the mean spectrum for comparison; the relative normalisation of the two is arbitrary. Two models for the variability spectrum are also shown, as discussed in the text.

4. RAPID SPECTROSCOPY – What is the Spectrum Really Doing?

So far, we have compressed our data in wavelength to produce light curves and in time to examine spectra. We will now seek a compromise between spectral and temporal resolution, characterising the spectrum of the variability observed. This is only possible using very coarse wavelength binning, as our signal-to-noise ratio is low, and hence only a continuum variability spectrum can be estimated. It is immediately clear, however, that the variability spectrum is bluer than the mean spectrum, i.e., there is a higher percentage variability in the UV than at red wavelengths. This variability spectrum can be simply characterised as a blue power-law ($F_\nu \propto \nu^{0.6}$); this is a similar slope to that of the power-law component seen in the far-UV, and may indicate that this is the variable component of the spectrum. An alternative explanation, however, is that the blue variability spectrum is due to reprocessing of X-ray variability. The X-rays change the temperature of the disc and hence we would expect the spectrum to be the derivative of a black-body; the rate of change of the disc spectrum with respect to temperature. Our variability spectrum can be fit by the derivative of a 10000 K black-body, a comparable temperature to that deduced from fitting the mean spectrum. At present we cannot discriminate between these possibilities, but we anticipate that analysis of the remaining data segments will further constrain the interpretation.

5. Discussion – Putting it all Together

We have now accumulated several pieces of evidence which suggest significant reprocessing of X-rays by the accretion disc: reprocessing is seen directly through echo-mapping; the shape of the continuum optical/UV spectrum is similar to that expected for an irradiated disc; and the variability spectrum is consistent with the derivative of the mean spectrum with respect to temperature. It is natural to ask whether the overall light curves could be reproduced by any irradiation dominated model for the disc.
The most promising approach seems to be the following, hinging on the X-ray spectral state evolution, from an initially soft, mainly thermal spectrum towards the canonical two-component form (soft black-body plus hard power-law). The power-law component is widely believed to be formed by Comptonisation of soft photons, so this change is suggestive of an increasing optical depth of Comptonising material (a similar scenario, but in reverse, was considered by Mineshige (1994) for X-ray Nova Muscae). If this material takes the form of a corona above the surface of the disc, then it will affect X-ray irradiation as follows. Initially, soft X-rays will have a clear path to the outer disc and irradiation will be efficient. As the Comptonising corona thickens, the Comptonised hard X-ray flux will increase, while X-rays moving parallel to the disc will be increasingly attenuated, shielding the outer disc and hence reducing the efficiency of irradiation. This decrease in efficiency dominates over the increase in X-ray flux and so the reprocessed optical flux declines, even though the X-rays are increasing. The observed anti-correlation thus emerges. This model is not without difficulties; it requires the edge of the disc to become partly shielded from X-rays, while our line of sight to the X-ray source remains unobscured. Since this is a high inclination system, however, our line of sight does not lie very far above the disc edge, and so some fine tuning of the shielding is required. We would also predict that irradiation should be strongest on our first observation, May 14, and that we should thus see strong echoes then. In fact we see no optical/UV–X-ray correlations in the May 14 data.

An alternative which therefore remains appealing is that the optical energy budget is dominated by viscous heating, rather than by irradiation; in this case, the reprocessing that is seen is merely a perturbation to this, albeit a relatively large one, and does not drive the long-term optical evolution. Neither of these explanations for the behaviour of GRO J1655–40 during 1996 that have been suggested here can readily be rejected, and both have difficulties and features to commend them. Detailed modelling may be needed to rule one, or even both, of them out. There are clearly many questions remaining to be answered concerning this outburst and this work continues.

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7. References

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