THE OPTICAL EMISSION LINES AS A PROBE OF STATE TRANSITIONS IN BLACK-HOLE CANDIDATES

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Optical spectroscopic studies of emission lines in black-hole candidates can help us investigate state transitions in those systems. Changes in the optical line profiles reflect changes in the geometry of the accretion flow, usually associated with X-ray state transitions in the inner region. We identify at least four optical states in the black-hole candidate GRO J1655−40 in outburst, and two optical states in GX339−4.

1 Optical states in black-hole candidates

1.1 Overview

X-ray state transitions in Galactic black-hole candidates (BHCs) are usually explained with changes in the geometry and physical conditions of the inflowing matter (which could switch, for example, from a keplerian disk to a quasi-spherical inflow). See reviews by Tanaka and Lewin, Ebisawa, Titarchuk and Chakrabarti, Esin et al. Spectral changes in the X-ray irradiation from the central object can, in turn, alter the physical conditions in the accreting matter at large distances; optical emission lines are a useful probe of those regions. X-ray and optical observations are therefore complementary for a study of state transitions.

1.2 Optical states in outburst

We carried out high-resolution optical spectroscopic observations of the BHC GRO J1655−40 in outburst on various occasions between 1994 August and 1997 June, using the 3.9m Anglo-Australian Telescope and the 2.3m Australian National University telescope at Siding Spring Observatory. See Soria, Wu & Hunstead and Soria et al. for a log of our observations and further discussion of our results.

The optical line profiles show the existence of a variety of different states in the accretion inflow. We classify them into four general states with the help of a simple phenomenological model. The Hα line profiles in the four states are shown in Figure 1. We interpret:

• double-peaked emission line profiles as emission from a geometrically thin, optically thick accretion disk;

• broad, flat-topped or round-topped profiles as emission from an optically thick (τ ≳ 1) wind launched from the disk surface;

• strong outburst profiles, observed during hard X-ray flares, as emission from an extended optically thick cocoon;
Figure 1. Different Hα emission line profiles corresponding to different physical conditions in the accretion flow, in the BHC GRO J1655-40. Dark blue profile: broad, round-topped profile (observed on 1996 June 21), interpreted as emission from a disk wind. Light blue profile: double-peaked profile (observed on 1996 June 10), interpreted as emission from a geometrically thin, optically thick disk. Green profile: narrow, single-peaked profile (observed between 1994 August 30 – September 4) interpreted as emission from an optically thin, extended region above the orbital plane. Red profile: the much stronger Hα emission line observed at low resolution on 1994 September 6, during a hard X-ray flare. The line is skewed: the extended blue wing is evidence of high-velocity outflowing gas. In all four cases, the intensity is normalised to the continuum, and the velocity zeropoint is the systemic velocity ($\gamma = -142.4 \pm 1.6$ km s$^{-1}$). An underlying, broad (FWHM $\gtrsim 2000$ km s$^{-1}$), shallow Hα absorption line is also visible in the first three cases.

- narrow, round-topped profiles, whose width is inconsistent with Keplerian rotational velocities in the orbital plane, as emission from an unsteady, extended optically thin emitting region (cocoon or distribution of clouds) above the disk plane.

We have also observed the BHC GX339-4 with the 3.9m AAT and 2.3m ANU telescopes at various times between 1997 May and 1999 April (Soria, Wu and John-
ston E. Wu et al. 7). Two of the four states found in GRO J1655−40 are similar to the high-soft and low-hard states of GX339−4. We have not found a correspondence for the other two states, which appear to be associated with episodes of strong hard X-ray flares and mass ejections.

1.3 Optical states in quiescence

The optical spectra of some BHC in quiescence show only the signature of the companion star: this is the case of GRO J1655−40 and GX339−4. In other systems, double-peaked optical emission lines are always observed even when the X-ray activity is very low (corresponding to a low accretion rate). The most notable case is A0620−00, which we have observed with the 2.3m ANU telescope in 2000 January and 2001 January. The line profile is more symmetric than the disk profiles observed in outburst. We interpret this “Smak” profile (Smak et al. 8) as emission from a geometrically and optically thin accretion disk which is always present around the compact object. A more detailed discussion of this result is left to further work.

2 The four optical states of GRO J1655−40

2.1 State I: irradiatively-heated thin disk

This is the “standard” state in which an optically thick, geometrically thin disk is irradiated by the central X-ray source (Figure 3). This optical state occurs during the high-soft X-ray spectral state. A temperature-inversion layer, hotter than the underlying layers, is created at the disk surface owing to the irradiation by soft X-rays (e.g. Wu et al. 7). The emission lines are double-peaked. The velocity separations of the peaks in both the He II λ4686 and the Hα emission line profiles suggest that the accretion disk extends slightly beyond its tidal truncation radius. Broad absorption lines may come from the inner disk where internal viscous heating is more efficient and dominates over external irradiation.

GRO J1655−40 was in this state in 1996 May – early June, and throughout most of 1997. When the X-ray irradiation was very soft (e.g. before 1996 May 27 and in 1997), He II λ4686 emission was stronger than Hα emission. The Balmer emission, however, was more prominent when the X-ray spectrum was harder (Soria et al. 4). The Balmer lines were therefore likely to be emitted from deeper layers (at higher densities and lower temperatures) than the He II lines.

This state was also found in GX339−4 (Soria et al. 8), and in various other BHCs where double-peaked lines were observed. However, there are differences between the high-soft states of GRO J1655−40 and GX339−4: (a) no broad absorption lines have been observed in GX339−4; and (b) He II λ4686 was emitted from smaller radii than Hα in GX339−4, while He II λ4686 and Hα were emitted from similar radii (but at different depths) in GRO J1655−40.

2.2 State II: disk outflow

When a line is emitted in a wind from the disk surface, opacity effects tend to reduce the two peaks and to increase the intensity of the central trough in the line
profile. When the line opacity in the wind $\tau_l > 1$, the profiles become flat-topped or round-topped (Murray and Chiang). The blue wing (approaching gas in the outflow) is often more extended than the red wing (receding gas, partly shielded from the observer). The width of the flat line-top is approximately equal to the Keplerian velocity of the disk where the wind is launched.

We found evidence of a transition from disk-surface to disk-wind emission in GRO J1655−40 on 1996 June 21: the H$\alpha$ profile changed from double-peaked to round-topped without substantial changes in its FWHM. Some evidence of a (weaker) optically-thin wind (e.g. a more extended blue wing in the emission lines) was also found in our June 8 – 12 spectra. An increase in the hard X-ray irradiating flux is probably responsible for disrupting the geometrically-thin disk and driving a wind with substantial Keplerian velocity (Figure 4).

The H$\alpha$ emission line profile in GX339−4 also changed from double-peaked to round-topped with similar FWHM when the system switched from a high-soft to a low-hard state (Wu et al.). In that case, the He II $\lambda$4686 emission line profile remained double-peaked in the low-hard state, suggesting that the inner disk was not strongly affected by the wind.

### 2.3 State III: optically-thick cocoon

At very high hard X-ray illumination (e.g. during the two hard X-ray flares observed from GRO J1655−40 in 1994 early-August and early-September) there is a further increase in the Balmer line strength. The H$\alpha$/H$\beta$ ratio increases dramatically, and H I Paschen lines are seen in emission (Soria et al.). Higher-ionisation lines such as He II $\lambda$4686 and the Bowen lines disappear or are greatly weakened. The inner-disk broad absorption lines also disappear.

In a hard X-ray outburst, the outer disk can be completely evaporated into an optically-thick, extended atmosphere or cocoon because of severe X-ray irradiation (Figure 5). The disappearance of the higher-ionisation emission lines and of the broad absorption at H$\beta$ is probably due to the geometric occultation of the inner disk by the outflow (optically thick in the H$\beta$/He II $\lambda$4686 region). This is more likely to occur in systems observed at a high orbital inclination, such that the inner disk can be occulted by an inflated, opaque outer disk region.

### 2.4 State IV: optically-thin cocoon

The optical spectra of GRO J1655−40 obtained two weeks after the major hard X-ray flare of 1994 August, and two weeks after the 1994 September flare look remarkably similar. In both cases, broad absorption lines are observed at H$\alpha$ and H$\beta$, suggesting that a disk is present and observable (Figure 6). Broad, flat-topped or round-topped emission lines are detected from N II and O II, suggesting that a wind is launched from the outer disk surface. The FWHM of those lines is consistent with the Keplerian velocities in the accretion disk.

Strong, narrow emission lines are observed from H I and He II. Their widths are too narrow to be consistent with Keplerian rotation in the disk plane, and their profiles show large, irregular variability between a narrow, single-peaked and a slightly broader, double-peaked type. The kinematics of the narrow emission lines
is consistent with the orbital motion of the compact object, but the lines are, on average, blue-shifted (signature of expanding gas).

This unsteady state follows episodes of disk evaporation and matter ejection. The narrow emission lines are probably due to an extended, optically thin, inhomogeneous envelope or distribution of gas at large radii, above the disk plane. Photoionisation followed by radiative recombination would provide a mechanism for the Balmer H\textsc{i} and He\textsc{ii} emission. High-inclination systems such as GRO J1655–40 offer the best chance to detect line emission from an extended optically-thin region above the disk plane.

3 Summary

We have classified the optical spectra of GRO J1655–40, when the system is X-ray active, into four general states, based on the strength and profile of its emission and absorption lines. We showed, with the help of a simple model, the possible physical properties and the structure of the accretion inflows and outflows in those states. Two of the four states correspond to the fundamental high-soft and low-hard states seen in most transient BHCs (for example in GX339–4). The other two states appear to be associated with episodes of strong hard X-ray flares and mass ejections in the microquasar GRO J1655–40.

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Figure 2. Hα emission line profile observed from the BHC A0620−00 in quiescence. The data were taken from the 2.3m ANU telescope at SSO, on consecutive nights. The profile suggests the presence of an optically thin disk with a possible contribution from the irradiated face of the secondary.
Figure 3. Schematic representation of the accretion disk in the high-soft state of GRO J1655–40. The disk is geometrically thin, optically thick, and irradiated by soft X-rays, which create a temperature-inversion layer on its surface, at large radii. He II (labelled with 1 in the cartoon) and Balmer H I (2) lines originate in this hot chromosphere. In particular, the Balmer emission lines are likely to come from a deeper layer than He II, as their strength is associated with harder irradiation. At smaller radii, viscous heating is more efficient than X-ray irradiation. Broad Balmer absorption lines (3) originate in this region.
Figure 4. Schematic representation of the disk-outflow state, associated with harder X-ray irradiation. As in Figure 1, the label 2 indicates Balmer emission, from an outflow region at large radii, and 3 indicates Balmer absorption, from an optically-thick disk. In the low-hard state of GX339–4, He II λ4686 emission (labelled with (1)) was detected with a broad, double-peaked profile, suggesting that the inner disk was not strongly affected by the wind.
Figure 5. Schematic representation of the accretion flow during a hard X-ray flare. No signature of an accretion disk is found. The H I emission (labelled with 2) comes from an extended region optically thick to Hβ. An extended blue wing in the Hα emission line is evidence of outflowing gas. Higher-ionisation lines (labelled with (1)) are weak or absent, probably because of geometric occultation of the irradiated face of the gas.
Figure 6. Schematic representation of the system when an extended optically-thin emission region is present. High-ionisation HeII and NIII Bowen lines (1) and low-ionisation H I Balmer lines (2) are emitted from slow-rotating gas above the disk plane, possibly the residue of the earlier mass outflow and disk disruption; high-ionisation lines are emitted slightly closer to the disk plane and/or at smaller radii. Balmer absorption lines (3) come from the optically-thick disk, at small radii. Low-ionisation N II and O II lines (4) are emitted in a wind from the disk surface at large radii.