State Transitions in Black Hole Candidates

M. A. Nowak
1
1 MIT-CXC, NE80-6077, 77 Massachusetts Ave., Cambridge, MA 02139, USA

Abstract. As described in the review by Marek Abramowicz (these proceedings), accretion theory is at something of a crossroads. Many theoretical descriptions of observations have centered on the “hydrodynamic” approach of the “standard” Shakura & Sunyaev α-disk; however, recent MHD simulations of (non-radiative) accretion flow have called into question the validity of this approach. There has been a great deal of optimism that these simulations give direct insight into current observations as similar phenomena appear in both; e.g., jets, rapid high-amplitude fluctuations, etc. In comparison to real data from black hole candidates (BHC), however, these similarities are in many ways only superficial. In some aspects, simple theories agree with the observations quite well. The observed rapid variability is much more highly structured than found in simulations, and shows interesting correlations with spectra that have been interpreted in terms of simple models. On the other hand, debates have arisen over even the most basic phenomenological issues concerning, e.g., the geometry and dominant radiation mechanisms of the accretion flow. In this article I present my views of those observational properties of BHC states that most urgently need to be addressed, and I briefly discuss some of the models currently being debated.

1. States, Transitions, & Hysteresis

BHC states can be broadly classified into two categories: hard with high variability (typically low luminosity), and soft with weak to moderate variability (typically high luminosity). Historically, these have been classified as “low” and “high” states, respectively, with radio observations showing the former to be radio loud, and the latter to be (mostly) radio quiet (e.g., [7]). Examples of transitions between states are shown in Fig. 1. The “off” state appears to be a low luminosity hard state [8], and not necessarily a distinct state. The “very high state” is a high luminosity soft state wherein the flux of the hard tail, the X-ray variability, and the radio emission are elevated from the very low levels observed in moderate luminosity soft states. Compared to the hard state, the very high state radio emission is more episodic and its spectrum is steeper, evocative of the “ejection” behavior seen in GRS 1915+105 (e.g., [9, 10]). It is interesting to note that the very high state of GX 339−4, based solely on the X-ray observations, was suggested to be a jet-ejection state [11]. The “intermediate state” is somewhat ill-defined, and is similar to a very high state (i.e., increased hard tail and X-ray variability, with variable radio). This label has been applied to spectra intermediate between “high” and “very high” states, as well as to spectra occurring inbetween “hard/low” and “soft/high” states. The behavior exhibited by Cyg X-1 during its state transitions and “failed” transitions may also qualify as an “intermediate state”. (The canonical soft state of Cyg X-1, however, is it-
self in many ways reminiscent of definitions of the “intermediate state”). In this review, I will primarily refer to states as being “hard” or “soft”, rather than use the labels of off/low/intermediate/high/very high.

![Figure 1. Left: State transitions in the BHC GX 339−4, showing a simultaneous rise in soft flux with a quenching of the radio. RXTE observations of state transitions in LMC X-3, showing a clear spectral softening as the flux rises.](image)

X-ray spectra of low variability soft states are in fact remarkably well-described by simple disk models (with fitted inner disk radii comparable to the expected marginally stable orbit radii), and do not show any of the variability seen in MHD simulations. Nor do they exhibit the instability behavior normally associated with $\alpha$-disks, despite the fact that their luminosities can be $\approx 5-10\%$ of their Eddington luminosity. Although transitions between extremes of the soft state and extremes of the hard state appear to track accretion rate, the luminosity at which these transitions occur is not fixed, and in fact exhibits evidence of hysteresis. That is, a state tends to remain soft to lower luminosity levels, or hard to higher luminosity levels, if it began in a soft or hard state, respectively. This is observed in recent state transitions of GX 339−4, as well as for numerous other BHC and neutron star X-ray binaries. Very complex behavior can be seen (e.g., the “comb-like” color-intensity diagrams of XTE J1550−564), and it is unlikely that accretion rate, even accounting for hysteresis, is the sole-determinant of state transition behavior. As I further discuss below, even for a given luminosity and spectral hardness, it is not clear that any remaining spectral features (e.g., line strengths or widths) remain uniform from one instance of a given state to another.

2. Theoretical Prejudices

The observational features that seem to be of the most fundamental importance in the definitions of BHC states are the presence (or lack thereof) of hard X-ray and radio emission. The former has been appreciated for nearly 30 years; however, the intimate coupling of the radio and hard X-ray emission is something that has been appreciated for only the past 6 years or so. (See the review by Fender in these proceedings.) Theoretical models translate the presence/absence of radio/hard X-ray emission into the presence/absence of either a Comptonizing corona and/or
a synchrotron emitting jet. The latter possibility is more thoroughly discussed in the reviews of Falcke and Markoff (these proceedings; see also [19]). Here I shall predominantly focus on coronal models, especially as they relate to models of the hard state. (It should be noted that a Comptonizing corona and synchrotron emitting jet are not necessarily mutually exclusive; however, such “hybrid” models are only now beginning to receive theoretical attention.)

Coronal models are promising in that they can produce naturally both the power law photon index as well as the sharp cutoff at energies of ≈ 100 keV that are typically observed in hard state BHC. Debate, however, centers around the geometry of the disk/corona system. Several suggested geometries are shown in Fig. 2. The “sandwich geometry”, shown in the upper left, had been considered by numerous authors [24]; however, as 100% of the downward directed hard photons interact with the disk, most of which are then thermalized and re-radiated as soft photons into the corona, it is impossible to create a corona hot enough to produce sufficiently hard spectra as seen in BHC [21]. This has led researchers to postulate more “photon starved” geometries, such as the bottom three geometries on the left. In these geometries, a relatively small fraction of the hard photons intercepted by the disk are re-radiated into the corona as soft photons. The degree to which a “reflection component” is generated also varies with these geometries. The bottom left model (“pill box” or “patchy corona” geometry) yields a large amount of reflection (all the downward directed photons are intercepted by the disk), with little soft photon-cooling of the corona [22].

The spectral hardness, as represented by the photon index Γ, produced within these models is determined by temperature and optical depth of the corona, as well as by the geometry. For example, for the geometry with a spherical corona overlapping an outer disk shown in Fig. 4, the spectral hardness is partially governed by the degree of overlap between corona and disk, with greater overlap...
yielding softer spectra (e.g., \[23\]). Instead of describing spectral hardness via \(\Gamma\), one can instead refer to the coronal compactness, \(\ell_c\). Here I define this as the ratio of energy generation within the corona divided by its characteristic radius, to energy generation within the disk divided by its characteristic radius. As an example I shall return to below, for the inner corona/outer disk model shown in Fig. 2, if the disk specific energy goes as the inverse of the disk inner radius (i.e., gravitational energy), and the coronal specific energy is a fixed quantity (e.g., gravitational for a fixed inner boundary), then the compactness scales as the inner disk radius \[15\]. Higher compactnesses yield harder spectra. Again, one sees that variations of the coronal geometry can regulate the spectral hardness.

3. Correlations

It is fairly easy for a number of the above coronal models to fit a single, given observation of a hard state BHC. More stringent tests occur when multiple observations of the same, or similar, hard state BHC are considered. A number of interesting correlations arise that must be addressed by any theoretical model of these systems. Here I discuss what I consider to be among the most important of these correlations.

3.1. Flux/Spectra Correlations

Over a wide range of hard state flux, higher flux typically means softer spectra, as seen in GX 339–4 \[15\] and Cyg X-1 \[12\]. Such a correlation naturally occurs in ‘sphere+disk’ coronal models if the inner edge of the disk moves inward as accretion rate increases. The corona is more effectively cooled as the disk moves inwards, which also fits in neatly with the presumption that the moderate luminosity soft state represents a “classic” Shakura-Sunyaev type disk.

As discussed in the reviews of Falcke and Markoff, however, there is a correlation between the X-ray and radio flux, approximately given by \(F_X \propto F_{\text{radio}}^{1.4}\), i.e., the radio flux decreases more slowly than the X-ray flux. This is not currently accounted for in coronal models, although it can be accounted for if jet synchrotron radiation produces both the radio and X-ray flux (see the above cited articles).

3.2. \(\Gamma_\text{low E}:\Delta\Gamma\)

Phenomenologically, a good description of RXTE spectra of hard state BHC is given by a cutoff broken power law plus Fe line. The break energy is at \(\approx 10\) keV, and the power law hardens above the break \[24\]. Using more physical models, these spectra instead can be described by an underlying power law being reflected from a cold slab, which yields a fluorescent Fe line, an Fe edge, and a reflected continuum (e.g., \[23, 26\]). The degree of reflection is determined by the solid angle, \(\Omega/2\pi\), subtended by the cold medium as seen by the hard tail. By considering multiple observations of multiple hard state objects (including Seyfert galaxies), it has been claimed that a correlation exists between the photon index of the underlying power law, \(\Gamma\), and the degree of reflection, \(\Omega/2\pi\), with softer spectra showing greater reflection. This effect can also be seen with broken power law fits of multiple observations of a single object \[24\]. The shape of the spectrum above 10 keV changes only slightly while the soft spectral index shows a strong variation, yielding a positive \(\Gamma_\text{low E}:\Delta\Gamma\) correlation, where \(\Gamma_\text{low E}\) is the photon index of the low energy power law, and \(\Delta\Gamma = \Gamma_\text{low E} - \Gamma_\text{high E}\) \[15\].
The ability of a reflected component to phenomenologically harden a soft power law has caused some, including myself [24], to question whether or not the putative $\Gamma:\Omega/2\pi$ correlation is in fact a systematic effect. The correlation, however, appears robust and does appear in ratios of hard state BHC data to Crab nebula+pulsar observations (i.e., there is less worry about systematic uncertainties in the RXTE response matrices, or about the interdependencies of the model fit parameters; [15]). The $\Gamma:\Omega/2\pi$ correlation is implicitly assigning a theoretical interpretation, albeit a very plausible one in the context of some of the coronal models described above. The purely phenomenological $\Gamma:\Delta \Gamma$ correlation, however, does need to be addressed by any model of BHC hard states.

Even within the context of reflection, the correlation is not simple. Fig. 3 shows RXTE observations of GX 339$-$4 where the correlation appears only when considering greatly different hardnesses. If one had analyzed only the data with mid-range hardness circled in Fig. 3, the correlation would not have been seen, despite the fact that these observations span a factor of two in 3–9 keV flux and compactness. If one instead had analyzed only the three hardest (and faintest) spectra, exactly the opposite correlation would have been detected. I note that most of the circled observations in the mid-range of compactness are hard state spectra in a high flux regime dominated by “hysteresis” [15], and show a number of other properties that are “flat” on various correlation curves (see Fig.4).

GX 339$-$4 also provides an example of how spectral properties can appear to change for different instances of a given state. Prior to the 1998 soft state, the 1997 hard state showed the Fe line equivalent width to be linearly correlated with reflection fraction, whereas the 1999 hard state showed the Fe line equivalent width to be nearly uniform all the way into quiescence$^1$ (Fig. 5; [15]).

3.3. $\Gamma:f:\Delta t$

Correlations also exist between spectra and variability properties, with harder spectra typically showing lower frequency X-ray variability, both within a given source and across sources [29]. Taking the power spectral density (PSD) of X-

$^1$It has been recently pointed out that for RXTE observations, galactic ridge emission can contribute a 6.7 keV line with flux of approximately $3 \times 10^{-5}$ photons/cm$^2$/s [27]; however, here the lowest flux line has $2.7 \times 10^{-4}$ photons/cm$^2$/s, and has a substantial red wing (Fig. 5). Thus contribution from the galactic ridge is unlikely to account for the majority of the differences between the 1997 and 1999 hard states.
Nowak

Frequency $\times (\text{RMS}/\text{Mean})$

$10^{-2}$ $10^{-1}$ $1.0$ $10^0$ $10^1$ $10^2$

Frequency (Hz)

$\Delta \chi$

$-3$ $-2$ $-1$ $0$ $1$ $2$

Compactness, $l$

$0.01$ $0.10$ $1.00$

Frequency (Hz) $\Gamma$

$\nu_1$, $\nu_2$, $\nu_3$ [Hz]

$b$

$0.0$ $2.0$ $4.0$ $6.0$ $8.0$ $10.0$ $12.0$

time lag [ms]

$\nu_1$, $\nu_2$, $\nu_3$ [Hz]

Figure 4. Left: Example of a hard state PSD (GX 339−4, [28]) fit with multiple Lorentzian components. Middle: Scaling of these frequency components with coronal compactness [15]. Right: Hard state data of Cyg X-1 [12], showing photon index vs. characteristic PSD frequencies (middle), and time lag between hard and soft X-ray variability (bottom), as well as time lag vs. frequency (top).

ray variability and multiplying by Fourier frequency, these data often can be well-described by the sum of broad Lorentzians (Fig. 4). In the hard state, peak frequencies scale as a function of spectral hardness (Fig. 4 [29]). Again, increased frequency with softer spectra naturally fits in with the concept of transitioning from a radially extended corona to a Shakura-Sunyaev type disk. In GX 339−4 the frequencies approximately scale as $\propto l c^{-3/2} \propto R_{\text{corona}}^{-3/2}$, consistent with naive expectations of disk time scales being proportional to Keplerian [15]. Complications with such a simple interpretation arise, however, when considering time delays between X-ray variability in soft and hard bands. Typically, the hard variability lags behind the soft variability, with this difference decreasing for lower Fourier frequency, as shown for RXTE observations of Cyg X-1 in Fig. 4 [12]; see also the paper by Wilms et al., these proceedings). This is exactly opposite our naive expectations of time scales increasing with either the size of our hypothesized corona, or with the characteristic time scales of the disk/corona transition region. Any theoretical model must address the simultaneous correlation of spectral hardness/X-ray variability frequency/X-ray variability time lags.

4. The Fender Conjecture

One of the most important questions in black hole research is, what are the spin parameters of astrophysically observed black holes? Since the seminal work of Blandford & Znajek [30], speculation has centered around whether or not rapid (i.e., near maximal) black hole spin is required to produce a jet. The seeming ubiquity of radio jets in BHC systems, predominantly correlated with spectral state (hard spectral states appear to always produce jets), has led to what I shall call the Fender Conjecture: If rapid black hole spin is required for producing a jet, then all black holes are rapidly spinning. Clearly, an independent measurement

$^2$The person for whom this conjecture is named in no way endorses said appellation. I have, however, heard him make this suggestion in numerous talks; it is an interesting and important scientific point; and “The Fender Conjecture” has at least as much ring to it as “The Bourne Identity” or “The Corbomite Maneuver”.
of spin is required to verify whether or not jetted BHC do in fact have rapid spin. One diagnostic that has been suggested is the relativistic broadening of fluorescent Fe lines [31].

As shown in Fig. 5, broad lines can be found in BHC hard states. If such hard states do indeed represent an extended corona with a truncated disk, however, they do not give the best indication of spin via their line diagnostics. Conversely, if soft state spectra represent disks extending down to, or even within, their marginally stable orbit, they may offer better line diagnostics. This, unfortunately, is not without its own problems. Specifically, if one models soft state spectra with a combination of a multi-temperature blackbody for the soft excess and a power law for any hard tail, these two fit components tend to cross one another in the Fe line region (see Fig. 5). This leads one to worry that any fitted broad line is in fact a systematic artifact of these fits. That being said, a number of soft state BHC spectra do indeed show very strong and broad lines, so skewed to the red that they are indicative of a nearly maximally rotating hole. This can be true even when Comptonization codes are used to model the hard tail as an upscattered multi-temperature disk component. (This alleviates some of the concerns that the broad line is a systematic effect.) Fig. 5 shows such a fit to soft state spectra of GX 339−4 [15]. A clearer example of an extremely broad Fe line, again consistent with rapid spin, comes from XMM-Newton observations of the very high state of XTE J1650−500 [32]. Although at this point there have been few careful line analyses of soft state BHC spectra, there is at least a hint of rapid spin in several BHC systems.

5. Models and Prospects

A primary theoretical question is why are there two (broadly defined) states: soft and hard? As mentioned above, MHD codes show rapid variability, jets, and magnetic energy dissipation occurring high in the disk atmosphere [33]. Although observations seem to show more “regular structure” (as evidenced by the correlations, the structured PSD, etc.) than simulations, one still is led to ask why hard states collapse into structures more quiet, stable, and like a “standard” accretion disk as they enter the soft state? Advection Dominated Accretion Flow (ADAF) models of hard states [34], and references therein) only exist below
\( \approx 10\% \) Eddington luminosity, so they naturally cannot be sustained at high luminosity. This, however, does not answer why ADAFs would form at low luminosity. Advocates of ADAFs essentially have postulated what Svensson has dubbed the “Strong ADAF Principle”: ADAF solutions are preferred whenever they are physically achievable, and hence always arise at low luminosity. Taking inspiration instead from the MHD simulations, Merloni & Fabian postulate that the rate of magnetic energy deposition into the corona is strongly dependent upon the gas pressure. Given their assumptions, they show that the fraction of accretion energy deposited into the corona scales as \( \left( \frac{P_{\text{gas}}}{P_{\text{total}}} \right)^{1/4} \). Low luminosity, gas pressure disks therefore have strong coronae that collapse as the disk becomes radiation pressure dominated at high accretion rates. Two interesting points are raised here: state transitions might be most intimately tied to whether or not the accretion flow is radiation pressure dominated; here the distinction between “corona” and “jet” is not strong, possibly leading the way to consideration of hybrid models.

**Acknowledgments**

The author gratefully acknowledges numerous helpful conversations with O. Blaes, J. Chiang, P. Coppi, S. Corbel, R. Fender, T. Maccarone, S. Markoff, J. Miller, K. Pottschmidt, C. Reynolds, and J. Wilms, as well as support from the MIT-Chandra X-ray Science Center via NASA Grant SV1-61010.

**References**

1. Shakura, N. I., & Sunyaev, R., 1973, A&A, 24, 337.
2. Krolik, J. H., & Hawley, J. F., 2002, ApJ, 573, 754.
3. Hawley, J. F., & Krolik, J. H., 2001, ApJ, 548, 348.
4. Hawley, J. F., & Balbus, S. A., 2002, ApJ, 573, 738.
5. Hawley, J. F., Balbus, S. A., & Stone, J. M., 2001, ApJ, 554, L49.
6. Hawley, J. F., & Krolik, J. H., 2002, ApJ, 566, 164.
7. Fender, R., et al., 1999, ApJ, 519, L165.
8. Kong, A. K. H., Kuulkers, E., Charles, P. A., & Homer, L., 2000, MNRAS, 312, L49.
9. Pooley, G. G., & Fender, R. P., 1997, MNRAS, 292, 925.
10. Belloni, T., et al., 1997, ApJ, 479, L145.
11. Miyamoto, S., & Kitamoto, S., 1991, ApJ, 374, 741.
12. Pottschmidt, K., et al., 2002, A&A, submitted (astro-ph/0202258).
13. Wilms, J., et al., 2001, MNRAS, 320, 316.
14. Piran, T., 1978, ApJ, 221, 652.
15. Miyamoto, S., Kitamoto, S., Iga, S., Hayashida, K., & Egoshi, W., 1995, ApJ, 442, L13.
16. Nowak, M. A., Wilms, J., & Dove, J. B., 2002, MNRAS, 332, 856.
17. Haardt, F., & Maraschi, L., 1991, ApJ, 380, L51.
18. Dove, J. B., Wilms, J., Maisack, M. G., & Begelman, M. C., 1997, ApJ, 487, 759.
19. Stern, B. E., Begelman, M. C., Sikora, M., & Svensson, R., 1995, MNRAS, 272, 291.
20. McGee, P., & Zdziarski, A. A., 1999, MNRAS, 303, L11.
21. Wilms, J., et al., 1999, ApJ, 522, 460.
22. Matt, G., Fabian, A. C., & Ross, R. R., 1993, MNRAS, 262, 179.
23. Wardzinski, et al., 2002, MNRAS, submitted.
24. Nowak, M. A., 2000, MNRAS, 318, 361.
25. di Matteo, T., & Psaltis, D., 1999, ApJ, 526, L101.
26. Blandford, R. D., & Znajek, R. L., 1977, MNRAS, 179, 433.
27. Fabian, A. C., Rees, M. J., Stella, L., & White, N., 1989, MNRAS, 238, 729.
28. Miller, J. M., et al., 2002, ApJ, 570, L69.
29. Miller, K. A., & Stone, J. M., 2000, ApJ, 534, 398.
30. Esin, A. A., McClintock, J. E., & Narayan, R., 1997, ApJ, 489, 865.
31. Merloni, A., & Fabian, A. C., 2002, MNRAS, 332, 165.