Chapter 4:
Outflows from stellar black holes

https://doi.org/10.1017/S1743921324000437 Published online by Cambridge University Press

Black Hole Winds at All Scales
Proceedings IAU Symposium No. 378, 2024
G. Bruni, M. Diaz Trigo, S. Laha & K. Fukumura, eds.
doi:10.1017/S1743921324000437

The role of outflows in black-hole X-ray binaries

Nikolaos D. Kylafis[1,2] **and Pablo Reig**[2,1]

[1]University of Crete, Physics Department, 70013 Heraklion, Greece
email: kylafis@physics.uoc.gr

[2]Institute of Astrophysics, FORTH, 70013 Heraklion, Greece
email: pau@physics.uoc.gr

Abstract. An outflow, from the hot inner flow, in black-hole X-ray binaries is always expected due to the positive Bernoulli integral in the hot inner flow. We have demonstrated that, if one considers this outflow as the place where not only Comptonization occurs, but also radio emission, many observed correlations, including the long-standing one between radio and X-rays, can be explained with one simple model.

Keywords. X-ray binaries, black holes, outflows, jets

1. Introduction

Black-hole X-ray binaries (BXHRBs) exhibit many observational correlations, the most prominent being the correlation seen in the hard state between the radio flux F_R, say at 8.6 GHz, and the X-ray flux F_X, say between 2 and 10 keV (Hannikainen et al. 1998; Corbel et al. 2000, 2003; Gallo et al. 2003; Bright et al. 2020; Shaw et al. 2021). In the so-called "standard track", the correlation is of the form $F_R \propto F_X^{\beta}$, where $\beta \approx 0.7$ (Gallo et al. 2003; Corbel et al. 2003)) or $\beta \approx 0.6$ (Corbel et al. 2013). Radio and X-ray emission occurs also in the hard-intermediate state, but the relation between the two has not been studied yet.

The standard picture of the accretion flow in BHXRBs in their hard and hard-intermediate states is that it consists of a geometrically thin, optically thick, outer disk (Shakura & Sunyaev 1973)) and a hot inner flow, which is geometrically thick and optically thin (Narayan & Yi 1994, 1995; Abramowicz et al. 1995). This hot inner flow is taken as the corona in many models. It is, unfortunately, not widely recognized that, due to the positive Bernoulli integral of the hot inner flow, a mildly relativistic outflow *must* emanate from it (Blandford & Begelman 1999; Kazanas 2015). In other words, *the Comptonizing corona is not static, but an outflowing one*. This has tremendous implications.

Contrary to the mainstream, where people use a static corona, few people examine an outflowing corona (see, however, Beloborodov 1999). An important exception is the Jet Emitting Disk/Standard Accretion Disk (JED/SAD) model (Marcel et al. 2019; Barnier et al. 2002). We have been promoting the idea that Comptonization in BHXRBs takes place mainly in the outflow (outflowing corona). Our picture explains naturally a number of correlations, some of which have not been explained by any other model. Due to the magnetic field that is needed for the ejection of the outflow (e.g., Blandford & Payne 1982), the outflow emits also radio waves. Since it is the same electrons that do the Compton upscattering of the soft photons and the radio emission by synchrotron, it is not surprising that the radio and the X-rays are correlated.

For the radio – X-ray correlation, we restrict ourselves to GX 339-4, because it is well studied and we have modeled various correlations exhibited by this source (Reig & Kylafis 2015; Kylafis & Reig 2018; Kylafis, Reig, & Papadakis 2020).

2. The model

Guided by the observations, our model consists of a *parabolic* outflow with two symmetric lobes, where both Comptonization and radio emission occur. Soft photons from the accretion disk enter the outflow at its bottom and inverse Compton scattering produces the observed power law in hard X-rays. The same electrons that do the Compton up-scattering, also emit radio waves. Details of the model can be found in our work over the last 20 years (Reig, Kylafis, & Giannios 2003; Giannios, Kylafis, & Psaltis 2004; Giannios 2005; Kylafis et al. 2008; Reig & Kylafis 2015; Kylafis & Reig 2018; Reig et al. 2018; Reig & Kylafis 2019; Kylafis, Reig, & Papadakis 2020; Reig & Kylafis 2021; Kylafis, Reig, & Tsouros 2023, submitted to A&A).

3. Results

Despite its simplicity, our model explains quantitatively many correlations and observations, some of which have not been explained by any other model. These are:

1) the energy spectrum from radio to hard X-rays for the source XTE J1118+480 (Giannios 2005),

2) the $F_R - F_X$ correlation in GX 339-4 (Kylafis, Reig, & Tsouros 2023, A&A, submitted),

3) the time-lag – Fourier frequency correlation in Cyg X-1 (Reig, Kylafis, & Giannios 2003),

4) the correlation between the time-lag and the photon-number spectral index Γ in GX 339-4 (Kylafis & Reig 2018) and other sources (Reig et al. 2018),

5) the fact that this correlation depends on the inclination of the source (Reig & Kylafis 2019),

6) the phase-lag – cutoff-energy correlation observed in GX 339-4 (Reig & Kylafis 2015),

7) the narrowing of the auto-correlation function with increasing photon energy seen in Cyg X-1 (Giannios, Kylafis, & Psaltis 2004),

8) the correlation between the Lorentzian frequencies in the power spectrum and the photon-number spectral index Γ in Cyg X-1 and GX 339-4 (Kylafis et al. 2008),

9) the photon-number spectral index as a function of phase of the type-B QPO in GX 339-4 (Kylafis, Reig, & Papadakis 2020),

10) the outflow provides a natural *lamppost* for the hard X-ray photons that return to the disk, where reflection and reverberation occurs (Reig & Kylafis 2021), and

11) last but not least, the outflow model may explain naturally the observed X-ray polarization in BHXRBs, since most of the matter of the outflow is at its bottom, i.e., as a "slab", and a slab is invoked to explain the polarization in BHXRBs (Krawczynski et al. 2022; Kylafis, Reig, & Tsouros 2023, A&A, submitted).

All of the above correlations are explained with only two parameters of the outflow: the radius R_0 at its base and the Thomson optical depth $\tau_{||}$ along its axis. For all the observations and correlations above, these two quantities vary in our model in the same narrow ranges $10 \lesssim R_0/R_g \lesssim 1000$ and $1 \lesssim \tau_{||} \lesssim 10$.

4. Conclusions

According to the statistician George E. P. Box, "All models are wrong, some are useful". Due to its simplicity and its various successes, our model might be useful.

https://doi.org/10.1017/S1743921324000437 Published online by Cambridge University Press

References

Abramowicz, M. A., Chen, X., Kato, S., & Regev, O. 1995, ApJ, 438, L37
Barnier, S., Petrucci, P.-O., Ferreira, J., et al. 2022, A&A, 657, A11
Beloborodov, A. M. 1999, ApJ, 510, L123
Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Bright, J. S. Fender, R. P., Motta, S. E., et al. 2020, NatAs, 4, 697
Corbel, S., Coriat, M., Brocksopp, C., et al. 2013, MNRAS, 428, 2500
Corbel, S., Fender, R. P., Tzioumis, A. K., Nowak, M., McIntyre, V., Durouchoux, P., & Sood, R. 2000, A&A, 359, 251
Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, A&A, 400, 1007
Gallo, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60
Giannios, D. 2005, A&A, 437, 1007
Giannios, D., Kylafis, N. D., & Psaltis, D. 2004, A&A, 425, 163
Hannikainen, D. C., Hunstead, R. W., Campbell-Wilson, D., & Sood, R. K. 1998, A&A, 337, 460
Kazanas, D. 2015, ASSL, 414, 207
Krawczynski, H, Muleri, F., Dovciak, M., et al. 2022, Science, 378, 650
Kylafis, N. D., Papadakis, I. E., Reig, P., Giannios, D., & Pooley, G. G. 2008, A&A, 489, 481
Kylafis, N. D., & Reig, P. 2018, A&A, 614, L5
Kylafis, N. D., Reig, P., & Papadakis, I. 2020, A&A, 640, 16
Marcel, G., Ferreira, J., Clavel, M., et al. 2019, A&A, 626, A115
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Reig, P., & Kylafis, N. D. 2015, A&A, 584, 109
Reig, P., & Kylafis, N. D. 2019, A&A, 625, 90
Reig, P., & Kylafis, N. D. 2021, A&A, 646, 112
Reig, P., Kylafis, N. D., and Giannios, D. 2003, A&A, 403, L15
Reig, P., Kylafis, N. D., Papadakis, I. E. & Costado, M. 2018, MNRAS, 473, 4644
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shaw, A. W., Plotkin, R. M., Miller-Jones, J. C. A., et al. 2021. ApJ, 907, 34

https://doi.org/10.1017/S1743921324000437 Published online by Cambridge University Press