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Spectra and fast multi-wavelength variability of compact jets powered by internal shocks

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The emission of steady compact jets observed in the hard spectral state of X-ray binaries is likely to be powered by internal shocks caused by fluctuations of the outflow velocity. The dynamics of the internal shocks and the resulting spectral energy distribution (SED) of the jet is very sensitive to the shape of the Power Spectral Density (PSD) of the fluctuations of the jet Lorentz factor. I used both Monte-Carlo simulations and semi-analytical methods to investigate this dependence. It turns out that Lorentz factor fluctuations injected at the base of the jet with a flicker noise power spectrum (i.e. $P(f) \propto 1/f$) naturally produce the canonical flat SED observed from radio to IR band in X-ray binary systems in the hard state. This model also predicts a strong, wavelength dependent, variability that resembles the observed one. In particular, strong sub-second variability is predicted in the infrared and optical bands. The complex timing correlations observed between the IR/optical light curves and the X-rays can then be used to probe the accretion/ejection connection on short time-scales.

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Steady compact jets are probably the most common form of jets in X-ray binaries. They appear to be present in all black hole and neutron star binaries when in the hard X-ray spectral state. They have an approximatively flat Spectral Energy Distribution (SED) extending from the radio to the mid-IR (e.g. Fender et al. 2000; Corbel & Fender 2002; Chaty et al. 2003; Migliari et al. 2010). These flat spectra are usually ascribed to self-absorbed synchrotron emission from conical compact jets (Blandford & Königl 1979) under the assumption of continuous energy replenishment of the adiabatic losses. The compensation of these energy losses is crucial for maintaining this specific spectral shape (Kaiser 2006).

Internal shocks provide a possible mechanism to compensate the adiabatic losses by dissipating energy and accelerating particles at large distance from the black hole. Internal shocks caused by fluctuations of the outflow velocity are indeed widely believed to power the multi-wavelength emission of jetted sources such as γ-ray bursts (Rees & Meszaros 1994; Daigne & Moscovitch 1998), active galactic nuclei (Rees 1978; Spada et al. 2001), or microquasars (Kaiser, Sunyaev & Spruit 2000; Jamil et al. 2010). Internal shocks models usually assume that the jet can be discretised into homogeneous ejectas. Those ejectas are injected at the base of the jet with variable velocities and then propagate along the jet. At some point, the fastest fluctuations start catching up and merging with slower ones. This leads to shocks in which a fraction of the bulk kinetic velocity of the shells is converted into internal energy. Part of the dissipated energy goes into particles acceleration, leading to synchrotron and also, possibly, inverse Compton emission.

In fact, the energy dissipation profile of the internal shocks is very sensitive to the shape of the PSD of the velocity fluctuations. Here, we assume that the PSD of the Lorentz factor of the jet has a power-law shape with index α: $P(f) \propto f^{-\alpha}$. I used a code similar to that of Jamil et al. (2010) to explore the dependence of the photon spectrum on α. Fig 1 shows that the dissipation profile along the jet and the profile of the specific energy of the flow are very sensitive to α. For larger α the fluctuations of the Lorentz factor have, on average, longer time-scales and therefore more dissipation occurs at larger distances from the black hole. For the case $\alpha = 0$ (i.e. white noise) we can see that most of the dissipation occurs very close to the black hole and then the dissipation rate decrease very quickly (like $z^{-5/3}$). As a consequence the specific energy profile is steep ($\propto z^{-2/3}$) and therefore the adiabatic losses are not compensated. The photon spectrum is strongly inverted, with a slope $\simeq 0.65$ i.e more inverted than most of the observed spectra. On the other hand, one can see from Fig. 1 that for $\alpha = 1$ (i.e. flicker noise) the dissipation profile scales like z^{-1} and the specific energy profile is flat. In other words, the internal shocks compensate exactly for the adiabatic losses. As result the SED is flat over a wide range of photon frequencies. In fact, this result can also be obtained analytically (Malzac 2012). The case of flicker noise fluctuations of the jet Lorentz factor may therefore be relevant to the observations of compact jets.

In fact this type of fluctuations is not unexpected and the PSD of the long term X-ray light curve of black hole binaries is usually close to flicker noise (Gilfanov & Arefiev 2005). An interesting feature of the internal shock model is that it naturally predicts strong variability of the jet emission. Figure 2 shows sample light curves and power spectra obtained from the simulation with $\alpha = 1$. The jet behaves like a low-pass filter. As the shells of plasma travel down the jet, colliding and merging with each other, the highest frequency velocity fluctuations are gradually damped and the size of the emitting region increases. The jet is strongly variable in the optical and IR bands originating primarily from the base of the emitting region and become less and less variable at

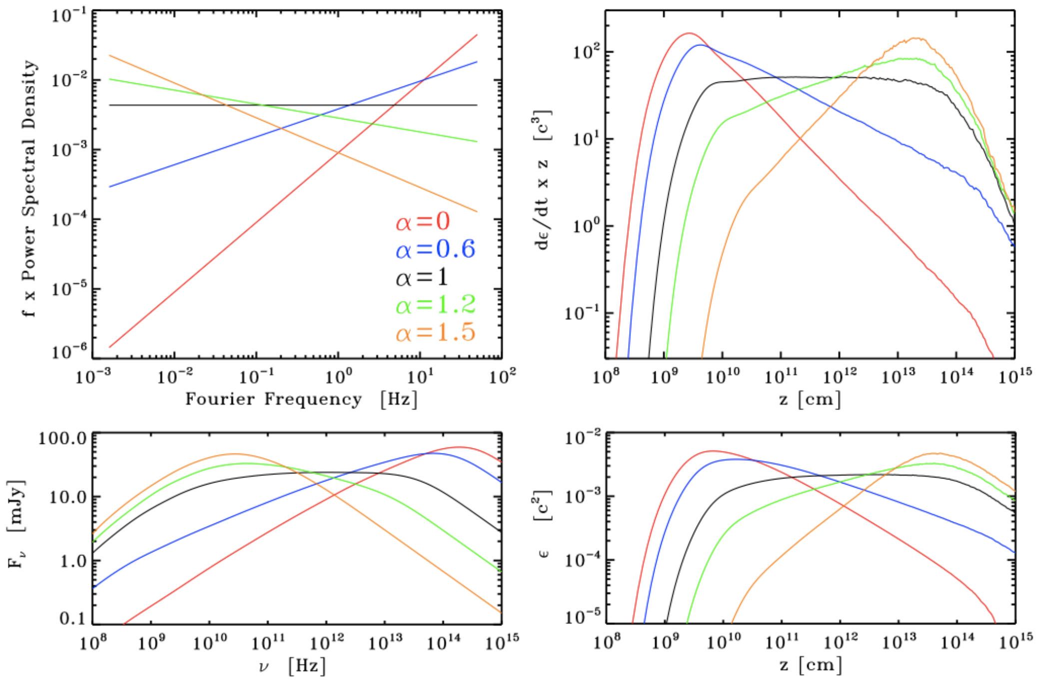

Figure 1: Simulation of the internal shock model with a power-law PSD of the Lorentz factor fluctuations ($P(f) \propto f^{-\alpha}$). The top left panel shows the the shape of the injected PSDs (in units of rms^2/mean^2), for the indicated values of the α index. Then, moving clockwise, the other panels show, as a function of distance from the base of the jet, the time averaged dissipation rate per unit mass times the distance and divided by c^3, the specific energy profile in units of c^2 respectively and finally the jet SEDs in *mJy*. The SEDs are calculated for an inclination angle of 40 degrees and a distance to the source of 2 Kpc.

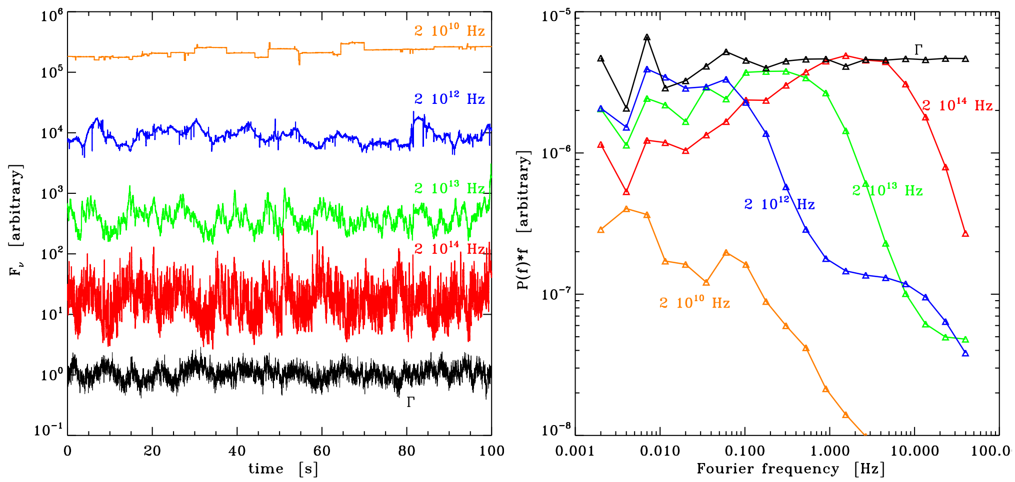

Figure 2: Synthetic light curves (left, rescaled) and power spectra at various indicated frequencies resulting from the simulation with $\alpha = 0$. The injected fluctuations of the Lorentz factor are also shown.

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longer frequencies produced at larger distances from the black hole. The observations also show significant flickering in the Infrared and optical band (Kanbach et al. 2001; Casella et al. 2010; Gandhi et al. 2010). At least part of this fast IR/optical variability is likely to arise from the jet, possibly through internal shocks.

Internal shocks driven by flicker noise fluctuations can therefore produce not only the flat SED of compact jets in X-ray binaries, but also other properties such as the flux amplitude or the location of the break frequency. The model also predicts strong multi-wavelength variability that appears to be similar to that observed.

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