PROCEEDINGS OF SCIENCE

Modelling a simultaneous radio/X-ray flare from Cyg X-1

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The long-term monitoring campaign of Cyg X-1 has provided the detection of the first simultaneous radio/X-ray flare seen from that source. We investigate the physical characteristics of the event in terms of emission from a homogeneous, expanding blob of pair-plasma, superimposed on a baseline flux in both bands. We find that while the radio flare can be reconstructed under various configurations of a cooling blob, continuous (re)acceleration of particles inside the jet is necessary to sustain X-ray emission at the levels implied by the data, for the observed duration. We present major results of the modelling and discuss implications for the role of microquasar jets.

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1. Introduction

Microquasars are a class of X-ray binaries whose emitted radiation spans a wide range of frequencies. The compact object can be either a neutron star or a black hole. Radio emission commonly originates in the outflows (jets) that often accompany the process of accretion. Studying correlations between spectral and temporal properties of microquasars has revealed a connection between their X-ray hardness and their total X-ray flux, while they are in outburst. This connection is most readily apparent in a *hardness-intensity diagram* of such a source (see for example [1]), where different configurations of those properties define a corresponding spectral state.

A promising way to understand the dominant physical mechanisms is through observations of flares. Flaring is commonly observed during state-transitions, or failed state-transitions, as is many times the case for Cyg X-1 [2] and can probe the evolution of the system switching (or failing to switch) from one accretion mode to another. Especially when observations are performed in more than one frequency (notably radio and X-rays), the constraints on energetics, individual contributions of different components (e.g. disk, jet), as well system-geometry can be even stricter.

2. The Cyg X-1 flare

Observing correlated, short-timescale variability in X-rays and radio was an important goal of the observational campaign on Cygnus X-1 that started in 1999 with simultaneous observations, using the orbiting Rossi X-ray Timing Explorer (RXTE) and the Ryle Telescope in the UK. The first such detection was that of April 16, 2005, when the system was close to a transition from the *soft* to the *hard* spectral state [3]. Lightcurves in both bands can be seen in Fig. 1.

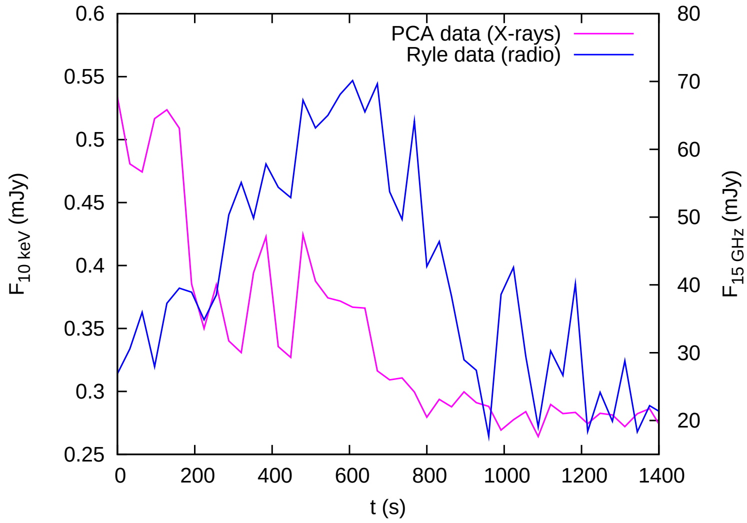

Figure 1: Lightcurves in X-rays and radio of the April 16, 2005 flare from Cyg X-1, as observed from the PCA instrument aboard RXTE and the Ryle telescope. PCA data have been rescaled to show flux at 10 keV ($2.4 \cdot 10^{18}$ Hz), while radio observations were performed at 15 GHz. For more details see [3].

3. Modelling

Motivated by the growing amount of evidence for microquasar jets contributing to high-energy radiation [4] [5], we have explored the physics of the Cyg X-1 flare by modelling emission from an episodic ejection of plasma from the black hole; i.e. a blob. The emitting particles are modelled as pairs, shock-accelerated to a power-law energy distribution with a cut-off at high energies and smoothly joined with a thermal distribution at low energies. All internal quantities (e.g. number density of particles, magnetic field) are assumed spatially homogeneous throughout the emitting region. The magnetic field energy density is close to equipartition with the internal energy density of the particles, with their ratio, however, being a free parameter, constant throughout the flare. The blob's bulk velocity is also assumed constant, forming an angle with the line of sight equal to the binary's inclination. The radiation mechanisms are synchrotron and self-Compton (SSC), while radiative and dynamical (due to expansion) energy losses dictate the evolution of the particle energy distribution in time.

Emissivity and absorption coefficient of synchrotron radiation and synchrotron, self-absorption, respectively, are calculated according to standard formulas, e.g. [6]. Inverse Compton scattering of synchrotron seed-photons is assumed optically thin, while corrections in the Klein-Nishina limit are taken into account according to [7]. The energy losses corresponding to these mechanisms are merged, as shown in Eq. 3.1, with those predicted by adiabatic expansion of a relativistic fluid.

$$\left(\frac{d\gamma}{dt}\right)_{tot} = \left(\frac{d\gamma}{dt}\right)_{syn} + \left(\frac{d\gamma}{dt}\right)_{com} + \left(\frac{d\gamma}{dt}\right)_{exp} \tag{3.1}$$

The particle distribution is binned in log-space, so that integration of Eq. 3.1 for each bin, over an appropriate time-interval[1] results in a self-consistent evolution of that distribution in time, while conserving total particle number. By integrating over solid angles and employing the proper Doppler corrections, consecutive spectra on Earth can be obtained, interpolation of which provides the resulting lightcurves.

4. Results

The radio flare can be roughly reproduced by such a model, with a single plasma-ejection and no further shocks (apart from the initial one) incorporated. A key-ingredient is the expansion of the blob that shifts the synchrotron self-absorption frequency to lower values, resulting in the progressive transition of the observing radio frequency of 15 GHz from the optically thick to the optically thin regime of the synchrotron spectrum. This transition is a combined result of the efficient cooling that low-energy particles suffer due to expansion and the decreasing column density of absorbers as the blob grows.

In Fig. 2 we present some of the consecutive spectra that result in the radio lightcurve shown in Fig. 3. The main parameters of this model are: post-shock radius of the blob $R_0 = 5 \cdot 10^{11}$ cm, power ejected from the black hole $P_{ej} = 0.033\ L_{Edd}$, initial magnetic field $B_0 = 113$ G, expansion speed $\upsilon_{exp} = 0.13\ c$.

[1] In each time-step the dominant cooling process defines what that time-interval should be, by causing the most energetic particles to lose a small fraction of their energy.

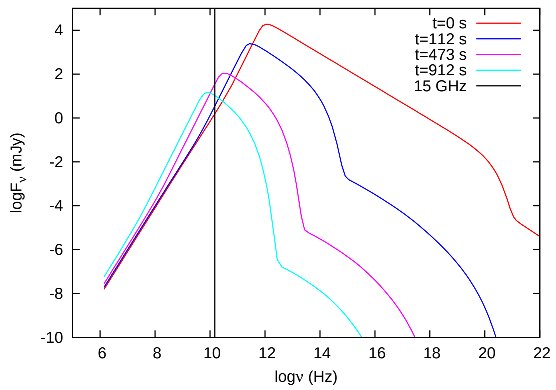

Figure 2: Evolution of SSC model-spectra corresponding to the input parameters given above.

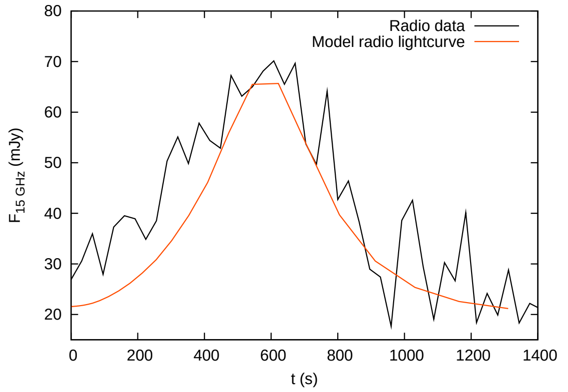

Figure 3: Model-lightcurve at 15 GHz, plotted over the radio data from Ryle telescope.

Contrary to the good results obtained for the radio, such a model presents problems when it comes to reproducing the X-ray data of Fig. 1. Namely, although in the model the X-ray flux starts (at $t = 0$ s) with a flux close to what the data suggest, it quickly drops to baseline values. This happens in $\sim$1 s, for the configuration of input parameters described above. This timescale corresponds to the cooling timescales of the particles chiefly responsible for X-ray emission.

What this result implies is that there must be an energy source that accelerates (or maintains) particles at high energies, at least for the initial $\sim$160 s during which the main X-ray event was observed. Implementation of this scenario is made by 'continuously' adding freshly shocked particles in the blob for that time-interval. The physical analogy would be that of the blob shocking downstream material as it moves along the jet axis. The presence of previously ejected material is further supported by the detected baseline flux at 15 GHz, which around the time of the flare was $\sim$20 mJy. That is higher than the flux observed during the canonical hard state of Cyg X-1 [8], when jets are considered to be prominent.

Results of such a configuration, in X-rays and radio can be seen in Fig. 4 and 5, respectively. Main parameters are: $R_0 = 4 \cdot 10^{10}$ cm, $P_{ej} = 0.055\ L_{Edd}$, $B_0 = 1416$ G, $\upsilon_{exp} = 0.2\ c$.

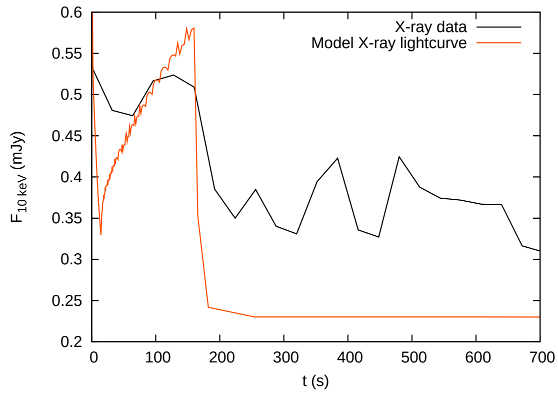

Figure 4: Comparison of X-ray data and model output for a blob that accelerates previously ejected matter, as it moves downstream. Last shock occurs at t≈160 s.

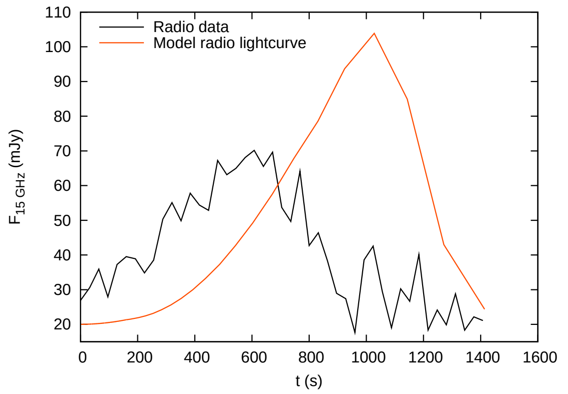

Figure 5: Corresponding radio lightcurve and data. Contrary to the prolonged time-lag, the high peak flux is not a standard feature in other runs of the model.

PoS(MQW7)090

It should be noted that the goal of this kind of models is to reproduce only the major X-ray flare, as the subsequent ones are identified as discrete ejections, from the limitations posed by the simultaneous occurrence of the radio flare. Although the model X-ray lightcurve is not a perfect match for the data, it captures basic features of the flare, like duration, peak flux and total energy output. However, the corresponding radio lightcurve (in this as well as in other runs of different input parameters) presents a delay of a factor $\sim$2 compared to the data.

5. Conclusions

The radio flare from Cyg X-1 can be reproduced by an expanding blob that emits synchrotron, without any further shocks, apart from the initial one. The duration of optically thin emission, however, will depend strongly on the cooling timescales of particles that produce it. In this case, for X-ray emission to be sustained for the duration implied by the data, a source of particle acceleration has to be employed. We modelled acceleration *along the way*, a scenario which is mainly challenged by the time-lags between flares in X-rays and radio. An alternative proposition is that a semi-steady jet is active (at least) during the X-ray main flare, thus confining the origin of X-ray emission to the regions of the jet where shocks occur. This scenario will be explored in the near future.

In all cases, emission would not extend more than $\sim 10^7\ r_g$ away from the black hole, and thus would not be resolvable. What is more, from the modelling there seems to be an anti-correlation between input energy at the base of the jet and both duration of the flare and scale of the emitting region. This provides further support to the proposition that compact, unresolved jets from black holes are responsible for the observed, flat, radio spectra [9]. These jets can also contribute to high energies and possibly even produce X-ray flares (in the case of microquasars). If verified, this will have implications on the energy-load of jets, as well as their ability to emit very high energy radiation like the one claimed to be observed from Cyg X-1 [5].

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