

A Disk–Jet interaction model for the X–Ray Variability in Microquasars

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ABSTRACT

We propose a simple dynamical model that may account for the observed spectral and temporal properties of GRS 1915+105 and XTE J1550-5634. The model is based on the assumption that a fraction of the radiation emitted by a hot spot lying on the accreting disk is dynamically Comptonized by the relativistic jet that typically accompanies the microquasar phenomenon. We show that scattering by the jet produces a detectable modulation of the observed flux. In particular, we found that the phase lag between hard and soft photons depends on the radial position of the hot spot and, if the angle between the jet and the line of sight is sufficiently large, the lags of the fundamental and its harmonics may be either positive or negative.

Subject headings: accretion, accretion disks — radiation mechanisms: non-thermal — stars: individual (GRS 1915+105, XTE J1550-5634) — X-rays: stars

1. Introduction

Microquasars are a subset of the broader class of X–ray novae in which the flaring radio counterpart is resolved into relativistic jets. It is universally acknowledged that they are binary galactic systems formed by a black hole (BH) accreting mass at the expense of a donor-star. Remarkable examples of these systems are given by GRS 1915+105 (Greiner et al. 1996; Morgan et al. 1997; Chen et al. 1997; Munro et al. 1999; Belloni et al. 2000) and XTE J1550-564 (Wijnands et al. 1999; Sobczak et al. 2000). Their distinctive features are the extremely wide range of variability modes and the presence of alternating phases of dramatic variability and of remarkably regular behavior. Quasi Periodic Oscillations (QPOs) have been observed in an incredibly large interval of frequencies. In the case of GRS1915+105, radio observations show superluminal expansion (Mirabel and Rodríguez

1994), usually interpreted in terms of emission from gas expanding at relativistic bulk speed (Fender 1999). The more recent mass estimate of the BH gives $M \approx 14 M_{\odot}$ (Greiner et al. 2001).

The X-ray flux consists of a sum of a soft thermal component from the accreting disk (THC), peaking at a temperature $\lesssim 1$ keV, and a high energy component (HEC) extending up to ≈ 100 keV. This last part of the spectrum has often, but not always, the form of a power-law tail. The relative amplitude of these two components is strongly variable and this can be explained in terms of a sudden destruction and subsequent slow replenishment of the inner part of the accreting disk (Belloni et al. 1997). This event marks the transition from a state which is characterized in large part by a multi-temperature black body emission from a standard disk, to a state in which the emission is due to a semi-evacuated disk lacking of its most luminous inner region.

While it is generally accepted that the THC is associated to the disk, the origin of the hard tail is presently less certain. In fact, although the upscattering of photons by a hot corona can account for many of the observed properties, there is still an open debate about the possible relevance of the Comptonization by bulk motion. (Zdziarski et al. 2001; Titarchuk & Shrader 2002; Reig et al. 2001), or of repeated Compton scattering of seed photons from the disc off electrons with a hybrid, thermal/non-thermal distribution (Gierlinski et al. 1999; Zdziarski et al. 2001). Both processes, in fact, produce similar effects, and any attempt to fit observational data with theoretical results rarely gives unambiguous answers. Moreover, all current models suffer from a number of drastic approximations and contain so many geometrical and physical parameters (mass of the BH, accretion rate, size of the disk, location, density and temperature of the corona, etc.) to make extremely difficult any accurate quantitative comparison.

A possible solution of this distressing situation can be found by considering second order effects, and among these we count time lag measurements. In fact, an astonishing feature of the proto-typical microquasar GRS 1915+105 is the tight correlation between the 0.5–8 Hz QPO and its spectral properties and variability (Reig et al. 2000). Even more impressive is the gradual decrease of time lag between hard (5–13 keV) and soft (2–5 keV) photons from initially positive values (hard photons arrive later than soft photons) to negative values (soft photons are delayed). It is well known that thermal Comptonization by a uniform hot corona cannot account for negative lags as well as for the observed decrease in the hard color as the disk inner radius r_{in} moves inwards. To circumvent this problem Nobili et al. (2000) proposed that the evaporation of the inner portion of the accreting disk leads to the formation of an approximatively spherical, non-uniform cloud filling the central region. During the replenishment of the semi-evacuated part of the disk the cloud, assumed not uniform in

temperature and density, becomes more and more compact, following the inward motion of the disk edge. Initially the cloud is large and marginally thick to electron-scattering. Photons generated by the disk are upscattered in the inner and hotter regions, emerging with a positive time lag. In later stages, the cloud is much more dense, with the consequence that in its central regions photons reach a Bose-Einstein equilibrium, and are then downscattered when they propagate through the outer and cooler shells. In this latter configuration lags turn out to be negative. Their calculations succeeded to reproduce some of the features of GRS 1915+105, but cannot explain, e.g., the apparent alternating negative and positive phase lags between the harmonics of the QPOs observed in some microquasars (Wijnands et al. 1999).

In this paper we propose a simple alternative model, showing that also dynamical Comptonization by the jet on the radiation emitted by an accretion disk can account for some of the observed properties of the source. The model is alternative also to other interpretations of the timing properties of microquasars based on dynamical Comptonization effects in converging flows (Laurent and Titarchuk 2001). The geometrical setting of our model is discussed in the next section, while in section 3 we present a numerical simulation based on a Monte Carlo technique.

2. The Model

One of the defining characteristics of microquasars is the fact that they exhibit relativistic ejection of matter. From the observations of superluminal expansion in GRS 1915+105, Fender (1999) inferred a bulk ejecta velocity $\beta = v/c \gtrsim 0.95$ and a mass outflow rate $\dot{m} \gtrsim 10^{18} \text{ g s}^{-1} \approx \dot{M}_{Edd}$. The question of what the accelerating mechanism really is, is still unanswered. The most probable hypothesis is that the plasma ejection is driven and collimated by magnetic fields anchored to the disk (see, e.g., ?)]hei00). This implies that the accelerating engine should be effective near the central black hole, thus making reasonable the assumption that the plasmoids do attain their maximum velocity already at a few gravitational radii. A rough calculation shows that the inner portion of a jet with an opening angle $\Theta_J \approx 0.2$ radians becomes optically thick to electron scattering for $\dot{m} \gtrsim 0.1 \dot{M}_{Edd}$, we then argue that during the active state a small but non-negligible fraction of the photons emitted by the disk is scattered by the electrons on the jet. It should be noted that, whether a photon acquires or loses energy depends on the angles of scattering and ultimately, on the position of the source, the height where scattering occurs and the inclination with respect to the observer. As an example, let us consider a monochromatic source of photons lying on the equatorial plane at a radial distance r . For reasons of simplicity, let us assume that

photons directed toward the axis undergo a single scattering at some height z before leaving the region, as illustrated schematically in Figure 1. If $\varepsilon = h\nu$ and $\varepsilon_1 = h\nu_1$ are the initial and final photon energy respectively, and $\xi = z/r$, we have

$$\varepsilon_1 = \frac{1 - \beta \cos \theta}{1 - \beta \cos \theta_1} \varepsilon = \frac{\varepsilon}{1 - \beta \cos \theta_1} \left(1 - \frac{\beta \xi}{\sqrt{1 + \xi^2}} \right) \quad (1)$$

where θ is the angle between the axis and the photon direction before the scattering, and θ_1 is the fixed angle of observation. From equation (1) we see that the ratio $\varepsilon_1/\varepsilon$ may be either larger or smaller than unity, depending on the value of ξ . Then photons may gain or lose energy depending on the height at which they are scattered. Of course, in a less schematic view, we need to consider the emission from the whole disk. Moreover scattering does involve an extended portion of the jet and obeys to a probabilistic law that depends on the gas density. As it will be shown in Section 3, adopting a more realistic configuration and assuming a cold relativistic jet (i.e. the electron thermal velocity much lower than the bulk velocity) Comptonization by bulk motion leads to the formation of a diluted black-body energy distribution. This distribution is roughly similar to the familiar multicolor spectrum of the unperturbed disk, but differs from it because its maximum is shifted to higher frequencies and it has a more extended hard tail. One cannot exclude, however, the possibility that the inner portion of the jet is heated by, e.g, turbulence, radiative friction or magnetic dissipation. If these mechanisms are capable of maintaining electrons in nearly virial equilibrium with the bulk motion, the combination of thermal and dynamical Comptonization leads to the formation of a power-law tail that is practically indistinguishable from that produced by a hot corona.

This model has also implications on the timing properties of the observed radiation. In fact, photons scattered at different z -coordinates describe different path lengths, arriving at infinity with different energies and delays. A straightforward calculation yields the following functional relation between the phase delay (in radians) and the geometrical parameters (we ignore an inessential constant related to the travel time of the radiation from the source to the Earth):

$$2\pi\nu_k(t_{obs} - t) = \frac{1}{\sqrt{r}} \left[\sqrt{1 + \xi^2} - \xi \cos \theta_1 + \sin \theta_1 \sin \phi \right] \quad (2)$$

where ϕ is the angular coordinate of the point source, t and t_{obs} the time of emission and observation, respectively. In equation (2), $m = M/M_\odot$ and r is in units of $r_g = GM/c^2$ (here and in the following all distances will be expressed in gravitational units).

Let us consider now an orbiting source of radiation localized on the disk, such as a hot spot, a spiral shock, or any other steady perturbation, lasting with an approximate constant flux for a time much longer than the orbital period ν_k^{-1} , with $\nu_k = 3.22 \times 10^4 m^{-1} r^{-3/2}$

Hz. The formation of this kind of instabilities, where a substantial fraction of the accretion energy is dissipated, is discussed e.g. by Tagger and Pellat (1999). They are associated with the development of powerful standing waves in moderately magnetized disks and are similar, in some aspects, to the Great Red Spot in Jupiter. Because the differential (Thomson) cross section is proportional to $1 + \cos^2 \Theta'$, with

$$\cos \Theta'(t) = \cos \theta' \cos \theta'_1 - \sin \theta' \sin \theta'_1 \sin(2\pi\nu_k t), \quad (3)$$

the total flux measured by distant observer consists of the superposition of a nearly constant background plus a modulated component due to the reprocessed radiation. In equation (3) primed angles are measured in the electron local rest frame, and are related to the corresponding unprimed quantities via the standard Lorentz transformations. For the sake of simplicity, and because we are mainly interested in the non linear effects in the harmonic functions, we will not consider here the possibly weak variation of luminosity associated with the orbital revolution of the source and caused, for instance, by the kinematic Doppler shift. We point out that, in addition to the quadratic dependence given by equation (3), there is a further element of non linearity in the signal. This effect is caused by the dependence of the arrival time of the signal on the angular coordinate ϕ of the source. At any given instant t_{obs} , the *scattered* component of the observed flux varies as $1 + \cos^2 \Theta'(t(t_{obs}))$, where $t(t_{obs})$ is a non linear function of the time of observation, obtained by inverting equation (2) with $\phi = 2\pi\nu_k t$. As shown in Figures 2 and 3, this double non linear variation generates a number of harmonics with different signs for the lags. The curves were obtained simply applying a standard PDS technique to the function $\cos^2 \Theta'(t_{obs})$. These figures are only representative, because the strength and the relative sign for the lags of the fundamental and sub-harmonics turn out to depend sensibly on the model parameters, i.e. the outflow velocity β , the place of emission r , the range in z where scattering occurs and, finally, the direction θ_1 between the mean electron bulk velocity and the line of sight. Although the first and second harmonics seem to exhibit preferentially lags of the same sense, we cannot exclude that a different parametrization could produce lags with opposite sign.

Unfortunately the sensitivity of the results to so many parameters is rather troublesome and represent a severe obstacle for a reliable test of the model. Yet, we cannot exclude that precisely these intricate relationships cause the complex evolutionary behavior of microquasars.

3. A Monte Carlo simulation

The results obtained in the previous section can qualitatively explain some spectral and temporal properties of microquasars. In particular, Figure 3 seems to suggest the existence

of a time correlation between different harmonics, but no definite conclusion can be drawn, for example, about the absolute value of the delays. In fact, a number of geometrical and physical effects have been neglected in the previous analysis and need to be included in a more quantitative study. Among others, we mention: 1) a non monochromatic spectrum from the point source; 2) a thermal component of the electron velocity in addition to the bulk velocity; 3) an extended portion of the jet where radiation is effectively scattered; 4) the dependence of the (multi) scattering processes on the optical depth, τ_ℓ , evaluated along the effective optical path. Moreover, it is likely that the formation of a hot corona above the disk modifies the spectral distribution of photons causing, at the same time, an additional (positive) time delay. Non uniform electron velocity, density and temperature distributions along the jet are additional causes of uncertainty.

To carry out a more quantitative, though preliminary test, we used a Monte Carlo code to study the radiation emitted by a Shakura-Sunayev disk (Shakura and Sunyaev 1973), without any color correction, plus a conical jet expanding with a constant bulk velocity $\beta = v/c = 0.95$ for $z > z_{min} = 15$. The exact value of z_{min} turns out not to be critical unless the inner edge of the disk is near the BH horizon. The disk was truncated at $r_{in} \geq 6$. The code is fully general-relativistic, i.e. photon trajectories are evaluated following the effective null geodesics in a Schwarzschild metric, with a mass of the central BH $M = 14M_\odot$. Compton scattering is calculated using the Klein-Nishina cross section and taking into account for both thermal and electron bulk motion. For $z > z_{min}$ the gas density is assumed to vary with the polar coordinate θ_p as $\rho \propto \rho_0 \cos^n \theta_p / z^2$, with $n = 10$. This strong angular dependence was introduced for computational reasons and for ensuring an appropriate narrow configuration of the outflow. As expected, the results of our computations depend sensibly on the optical thickness $\tau_\ell \propto \rho_0$ (or the mass loss rate \dot{m}), but are only weakly dependent on n .

In this preliminary investigation our main goal is to evaluate the apparent time lag of the signal between soft and hard bands and the radiation spectrum generated by the whole configuration (i.e. disk plus jet). The best results were obtained considering the outflow to be hot and adiabatically expanding. In particular, we have adopted a temperature at the base of the jet $T_0 \approx 30$ keV, decreasing outwards as $r^{-4/3}$. This implies that far from the central black-hole only Comptonization by bulk motion is effective. Higher values of the temperature or higher Lorentz factor are clearly admissible and would cause the formation of a harder or even inverted tail in the spectrum. However, because an accurate comparison of our results with observations is out of the scope of the present investigation, we have not varied this parameter.

To compute the timing properties and the emitted spectrum respectively two separate approaches have been adopted. In a first series of computations we considered a thermal

point source at $T_{em} = 10$ keV, orbiting on the equatorial plane at r_{em} . In this case only the scattered radiation was considered, because it constitutes the variable component of the observed flux. The arrival time of each photon was calculated evaluating the total path length from the point of emission to the fiducial infinity. In a second series of runs we computed the total spectrum storing all photons emitted by the adjacent elementary rings of the truncated disk. Most of these photons arrive directly to infinity and form a multicolor black body spectrum, corrected for the Doppler and gravitational effects. Only a small, but significative fraction of the radiation emitted by the disk is scattered by the jet. As illustrated in the top panels of Figures 4, in presence of an efficient Comptonization by bulk motion the resulting spectrum is sensibly modified with respect to the unperturbed multicolor distribution. In fact, despite the fact that scattered photons are a minority of all emitted photons, they dominate the high energy part of the spectrum. This effect is more evident when the source is far out ($r_{in} \gg 6$) and the angle of observation is large, because it is a direct consequence of the special geometry of the configuration and of the radial decrement of the gas density in the jet. In fact, a straightforward calculation shows that, under these conditions, photons emitted by the disk at r are mostly scattered between $z_1 \approx r/2$ and $z_2 \approx 4r$, while, at the same time, photons gain or loose energy if θ_{obs} is larger or smaller than $\arctan(r/z)$ [see eq. (1)].

It should be noted that, as with thermal Comptonization, the resulting shift of the spectrum towards higher energy might cause an underestimation of the color radius of the disk resulting from observations. Whether the color radius should or should not be a good estimate the actual inner edge of the disk still remains an open question. Indeed, several observations and theoretical investigations seem to play in favor of larger values of the inner edge of the disk (Vernière et al. 2002; Merloni et al. 2000). On the other hand, it is known that the energy spectra of microquasars in their high-state may be fitted with an optically thick accretion disk with a disk color temperature that is significantly higher then other non-jet black hole candidates, such as Cyg X–1 and LMC X–3 (Ebisawa et al. 2001).

Finally, bottom Panels of Figure 4 show the effect of the scattering on the time delay between hard ($10 < h\nu < 60$ keV) and soft ($1 < h\nu < 10$ keV) photons. As expected, the delay turns out to be positive when the source is located far from the axis, while it is negative for small enough values of r_{em} . The amplitude of the delay is consistent with observations.

To conclude this section, we wish to emphasize that the mechanism at the basis of our model requires the presence of collimated outflows. While radio observations of microquasars seem to suggest a strong link between low/hard states and jets, the situation is still uncertain concerning the high/soft case. Nevertheless, this may not be unreasonable considering that sporadic plasma emission could occur also during high states without forming visible radio

jets, unless some conditions on density, magnetic field, time-scales of electron acceleration, etc, are satisfied.

Clearly, in absence of powerful ejections of matter the observed spectrum has the form of a multitemperature black body (we do not consider here the possible presence of a hot corona above the disk). As discussed above, Comptonization by bulk motion of the radiation emitted by the disk causes an increase of the disk color temperature. The effectiveness of this process depends largely on the bulk Lorentz factor. However the spectral form is partly affected also by the mass loss rate \dot{m} , mainly because an increase/decrease of \dot{m} increases/decreases the extension of the optically thick portion of the jet. Therefore, in our interpretation we expect that what we are observing is the result either of the particular state of the accretion disk or of the physical conditions of plasma ejections.

It is interesting to note that GRS 1915+105 is observed in three basic states A, B and C (Belloni et al. 2000). State A is characterized by a lower disk temperature. State B (the very high state) corresponds to an accretion disk like the high/soft state A, but with a higher temperature and a steep power-law component. State C (the low/hard state) corresponds to the instability period. Are these three classes associated with configurations formed by a disk extending down the most stable orbit without any appreciable mass ejections (state A), a full disk like state A but with a moderate collimated outflow (state B) and, finally, a configuration formed by a disk missing of its innermost part plus a compact and extended plasma jet (state C)? Answering this crucial question is premature at this stage because it requires a more accurate modeling of both the disk and the jet structures, as well as a detailed multiwavelength analysis of the evolutionary sequence of X-ray binaries. We expect to do this in the future.

We further note that inverse Comptonizing processes accompanying discrete ejection events might produce strong oscillations of the hard part of the spectrum on very short timescales, leaving practically unchanged the disk soft component. This effect might be able to account for the observed fast A-B/B-A transitions in GRS 1915+105 (Belloni et al. 2000).

4. Discussion and conclusions

The high mass loss rates currently inferred from observations of microquasars imply that the inner region of the relativistic outflow is optically thick to electron scattering. If this is the case, under some conditions Comptonization of the radiation emitted by an accreting disk produces, by bulk motion of a relativistic jet, observable effects that might account for a number of peculiar properties of microquasars. If confirmed, the model proposed here might

shed light on the surprising link between the QPO phenomenon and the overall emission properties of these sources. It is remarkable that the different signs for the lags of different harmonics find here a natural explanation, at variance with thermal Comptonization models which produce lags with the same sign for all the harmonics. Moreover, from the idealized model described in Section 2, we can expect a dependence of the of the intensity of the processed signal on the energy, since both the energy of the scattered photons and the (geometrical) cross section of the jet varies with the height. However, to check if this is able to reproduce the tight power/energy correlation for the high-frequency QPO's, with the correct sense, requires a more accurate and extensive Monte Carlo analysis. This is matter of a future work.

Finally we may note that, if the speed of ejecta is large enough, the Comptonization of photons by bulk motion leads to the formation of a hard tail, without the high-energy cutoff which distinguishes the thermal models. This because there no selective effect due to the decreasing of the Klein-Nishina cross section with the electron velocity. It is also very interesting to note that the need of a large inclination angle of the jet is a discriminating aspect of our model. The discovery of systems with alternating phase lags but with no evidence of relativistic outflows, or with jets observed at small angles, would rule out the present model, playing in favor of a thermal interpretation.

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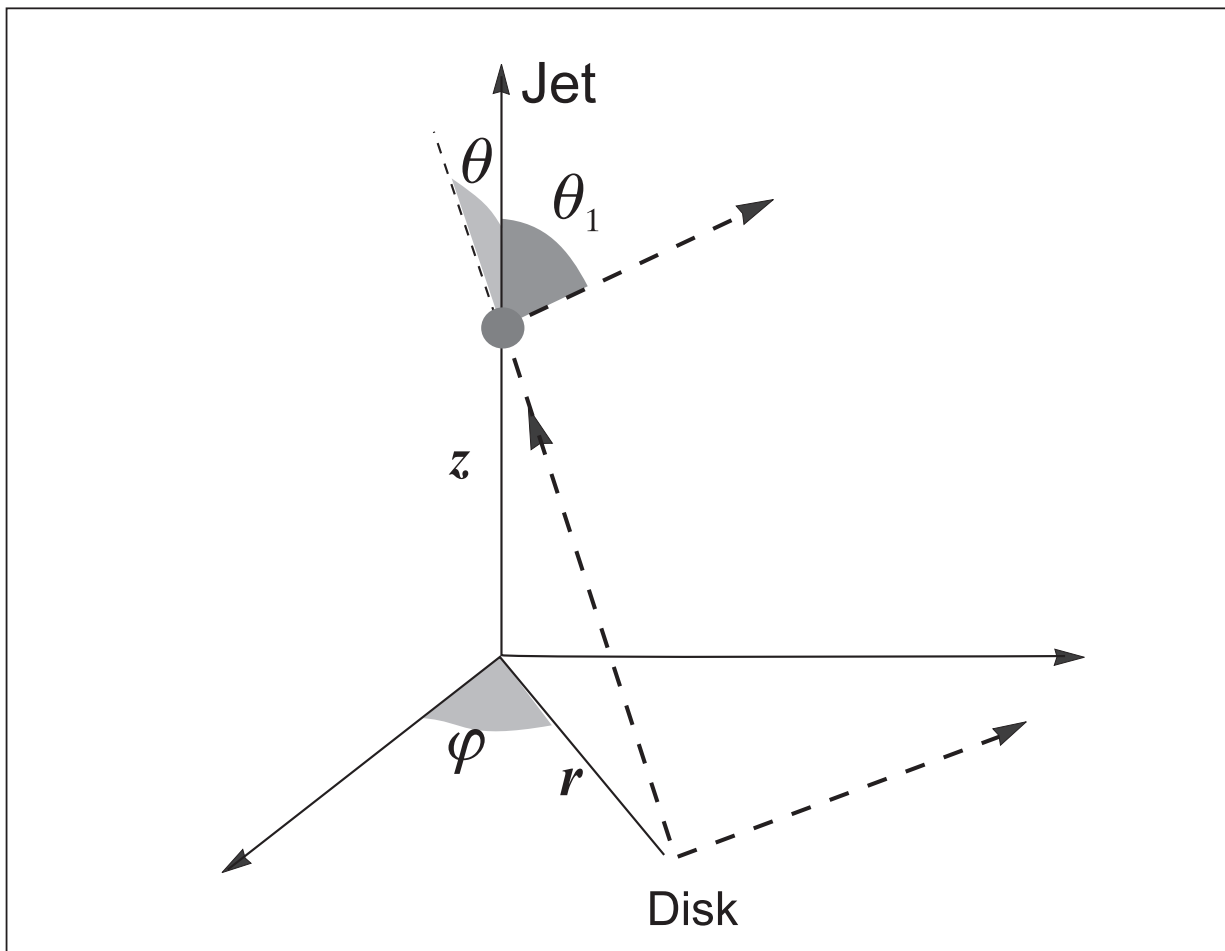


Fig. 1.— A schematic view of the model discussed in the text.

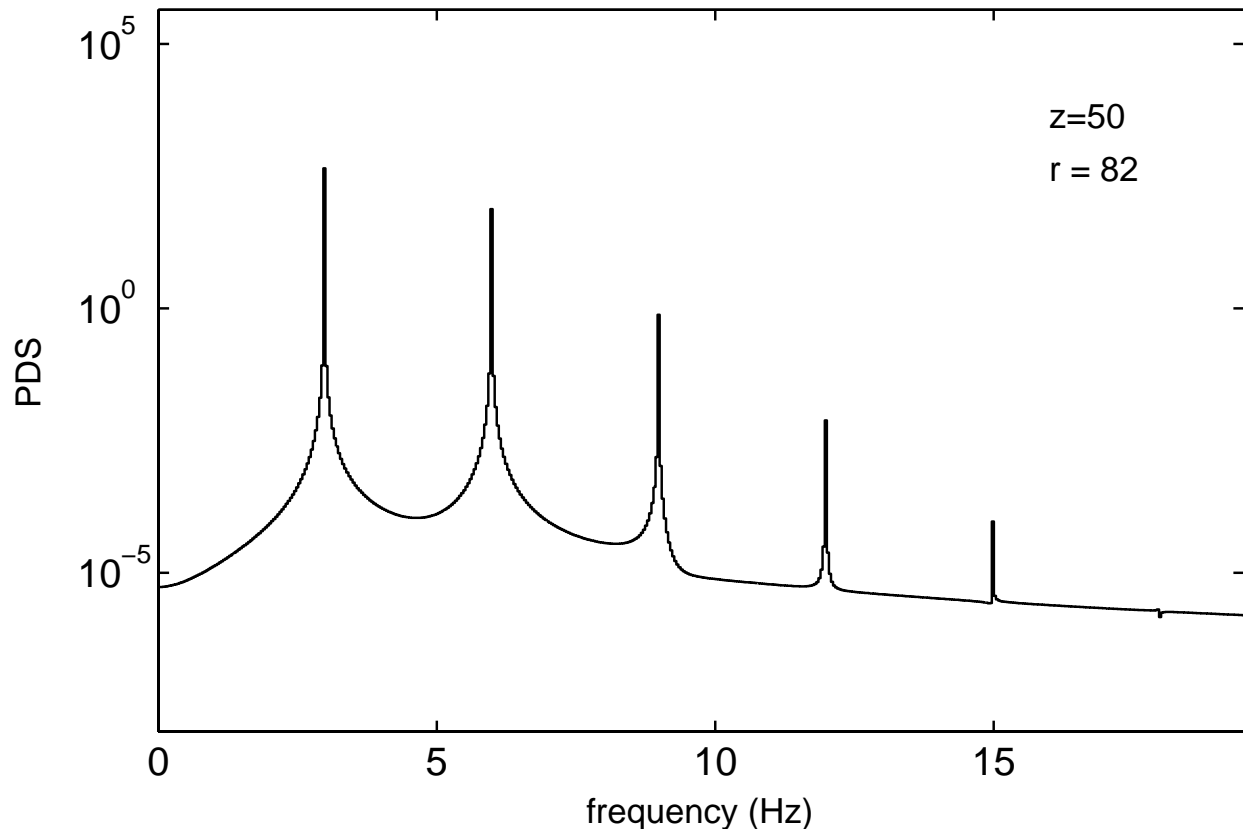


Fig. 2.— Power density spectrum of the function $1 + \cos^2 \Theta'(t(t_{obs}))$ which describes the scattered component of the observed flux [cfr.eqn.(3)]. The strong non-linear dependence of this function on t_{obs} leads to the simultaneous formation of a forest of sub-harmonics (see text for details).

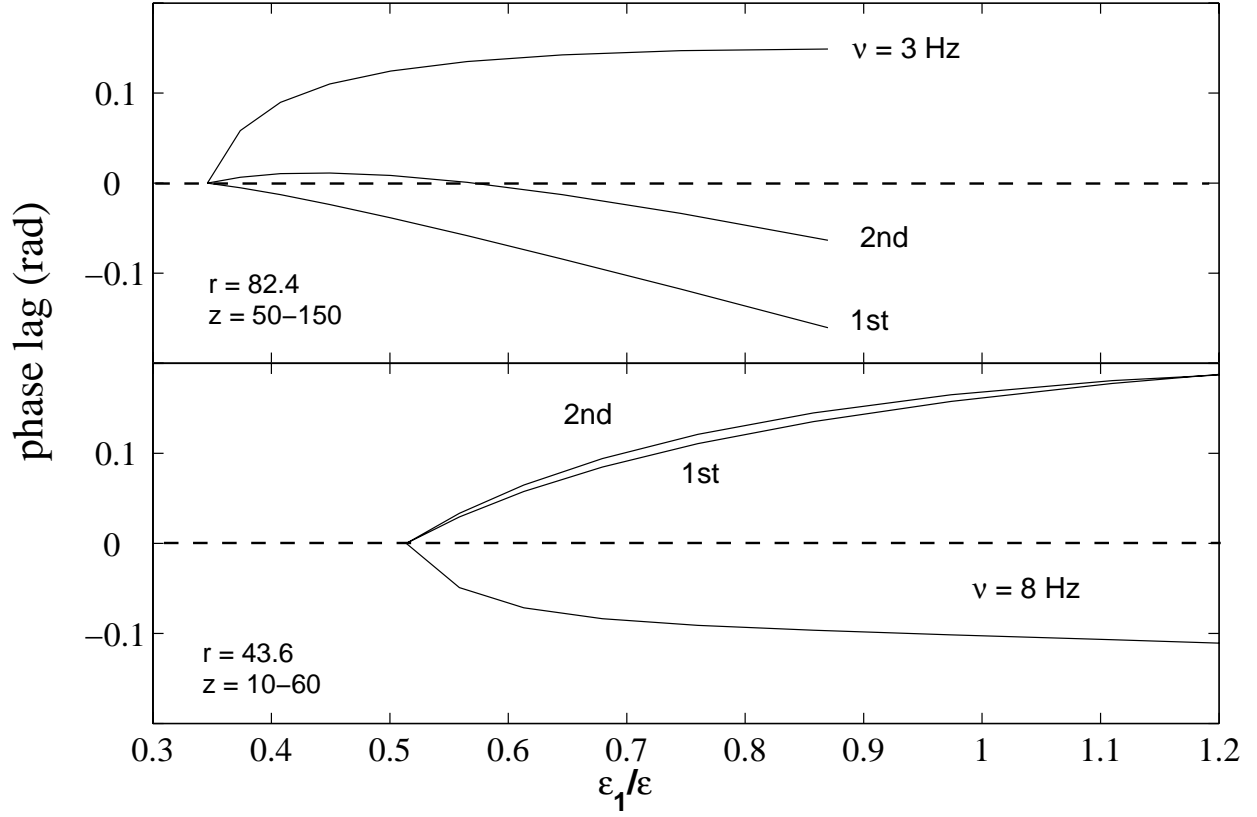


Fig. 3.— Phase lag vs. energy for the fundamental and the first two harmonics for two different distances r of the source from the axis. Phase lags are normalized to those of the lowest energy. Both r and z are in units of r_g .

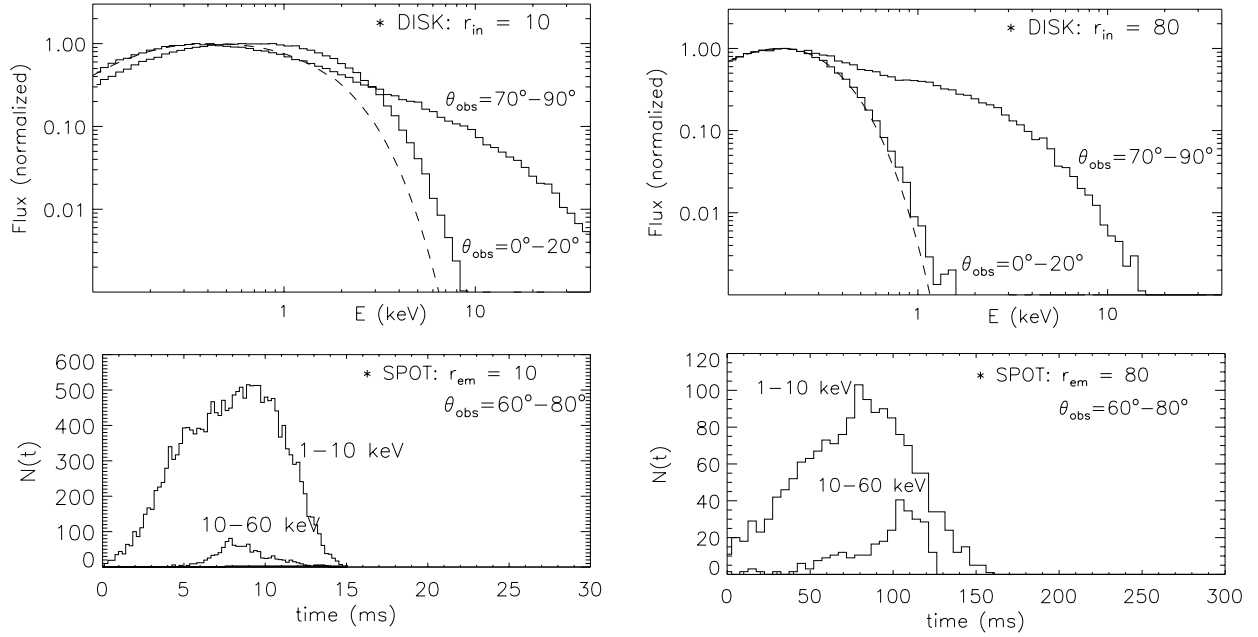


Fig. 4.— Results of our Monte Carlo simulation. Top panels: energy spectrum of the radiation emitted by a standard disk (left) and by a truncated disk (right). The radiation is partly Comptonized by the jet and forms an exponentially decreasing hard tail whose extension depends on the angle of observation. With the choice of the model parameters quoted in the figures, the spectral form is similar to an "intermediate case". However, larger Lorentz factor and/or a higher mass loss rate of the jet can lead to even more extended hard tails. Bottom Panels: the figures show the differences in the arrival time of the reprocessed radiation emitted by a localized thermal source and observed at large inclination angle.