Effects of retro-lensing light curves near a black hole

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Abstract

We study the model light-curves from radiatively-driven clouds near an accreting black hole. Taking into account the multiple images due to strong gravitational lensing, we find that sharp spikes can significantly enhance the observed flux.

We also consider the polarization properties. The retro-lensed photons give rise to peaks in the observed signal occurring with a characteristic mutual time lag after the direct-image photons. Duration of these features is very short and it is a signature of the photon orbit.

Model

We consider a cloud of particles moving through the radiation field of a standard thin accretion disc. Primary photons from the disc are scattered by electrons in the cloud, they are beamed in the direction of the cloud motion, and polarized by Thomson mechanism.

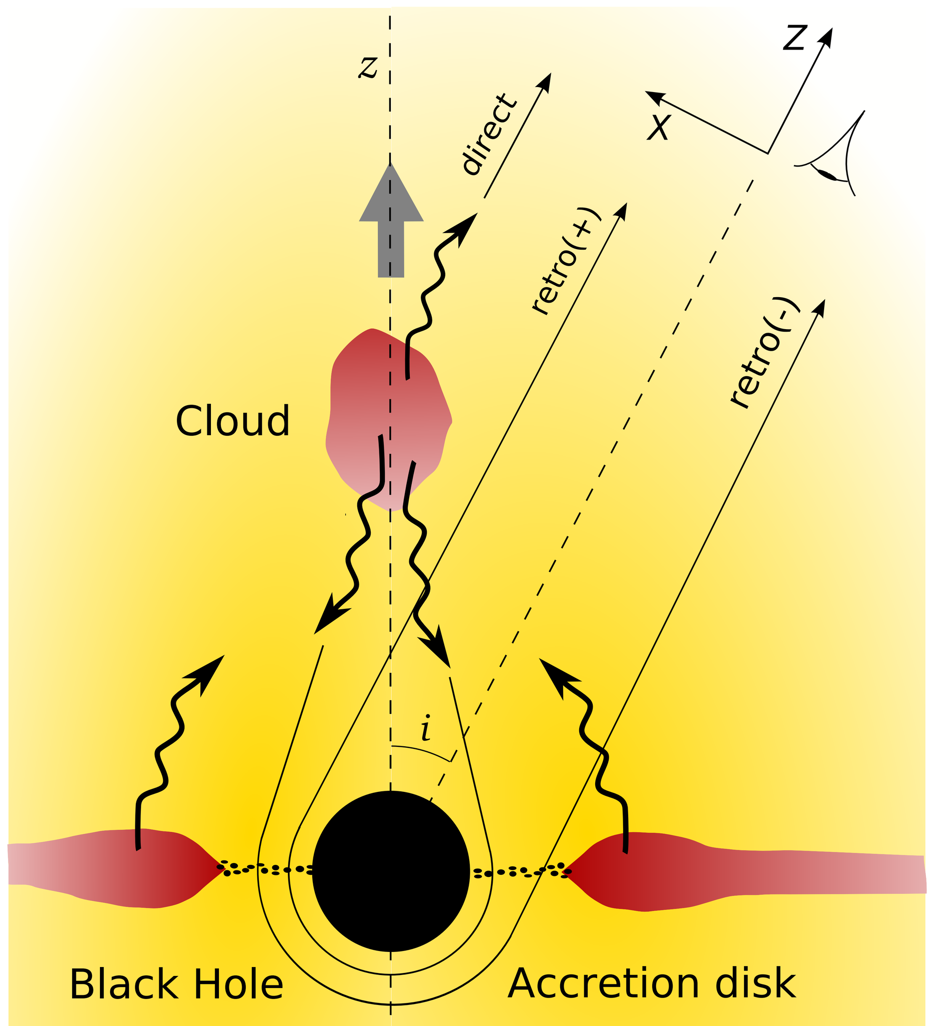

Fig. 1. Geometry of the model. An accretion disk is the source of primary unpolarized light, which is then Thomson scattered on a cloud. The cloud moves in the radiation field of the disk that acts on the cloud together with gravity of the central black hole. The light rays of primary and scattered photons are also influenced. Direct and indirect (retro-lensed) light rays exhibit different degree of linear polarization and they experience different amplification and the Doppler boosting. The observed lightcurve is produced by the rays reaching an observer at view angle i far from the centre, along Z-direction.

Light intensity and polarization

The electron distribution is considered isotropic in the cloud comoving frame. We derived simple formulae for frequency-integrated Stokes parameters I, Q and U of the scattered radiation (Horák & Karas 2006a,b):

$$I = A\left[(1+\mathcal{A})\left(T^{tt}+T^{ZZ}\right)+\mathcal{B}\left(T^{tt}-3T^{ZZ}\right)-2\mathcal{A}T^{tZ}\right],$$

$$Q = A\left(T^{YY}-T^{XX}\right), \qquad U = -2\,A\,T^{XY},$$

where

$$\mathcal{A} \equiv \tfrac{4}{3}\left\langle\gamma_{\rm e}^2\beta_{\rm e}^2\right\rangle,$$

$$\mathcal{B} \equiv 1-\left\langle\frac{\ln[\gamma_{\rm e}(1+\beta_{\rm e})]}{\beta_{\rm e}\gamma_{\rm e}^2}\right\rangle;$$

$\beta_{\rm e}$, $\gamma_{\rm e}$ are velocity and the Lorentz factor corresponding to an individual electron, while the angle brackets denote the averaging over the particle distribution in the cloud comoving frame.

The Stokes parameters are evaluated in the polarization frame comoving with the cloud; one basis vector is pointed along the direction of the scattered radiation and the other two basis vectors are perpendicular to it. The incident unpolarized radiation comes into the formulae as components of the stress-energy tensor $T^{\alpha\beta}$. The fourth Stokes parameter V vanishes, as the resulting polarization is linear.

Motion of the cloud

The total four-force f^{α} acting on the cloud is a superposition of the radiation and inertial terms. The cloud motion is solved in the spacetime of Schwarzschild black hole (radius $r_{\rm s}$). The radiation field influences the bulk motion of the cloud as well as the local electron distribution in the cloud frame. We find two critical velocities at which the polarization vector changes its orientation between transversal and longitudinal one.

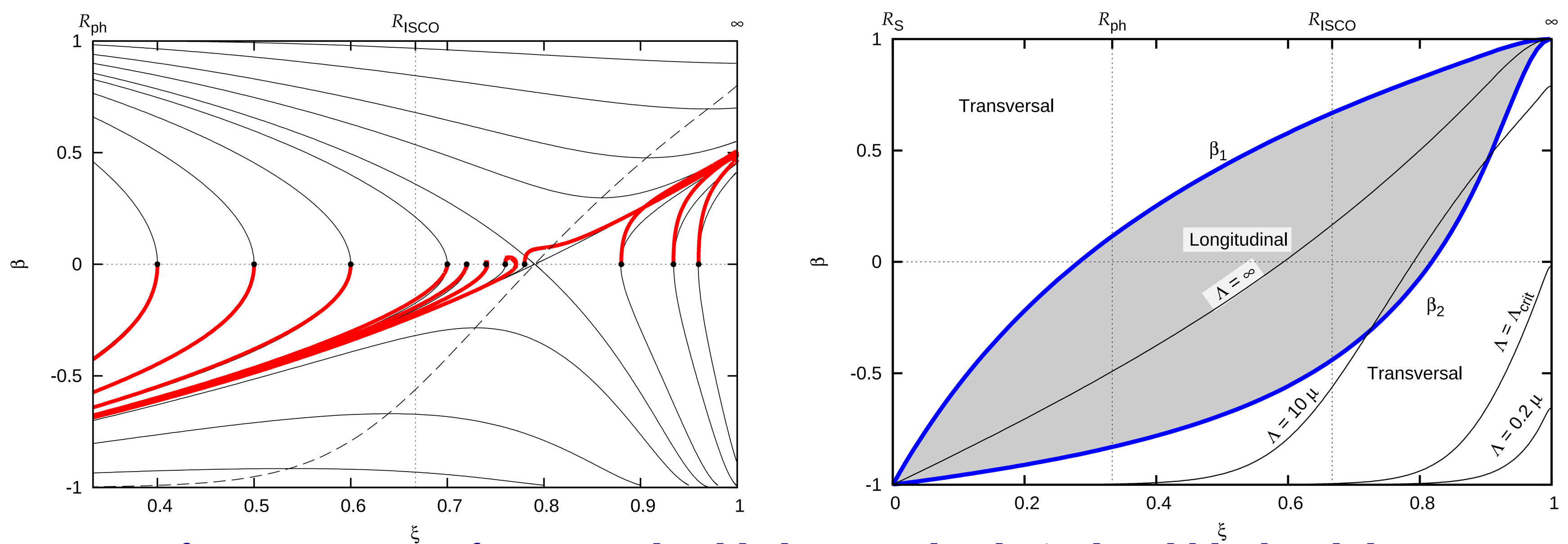

Fig. 2. Left: Trajectories of warm and cold electron clouds (red and black solid curves, respectively) in the plane of height ($\xi \equiv 1 - r/r_{\rm s}$) vs. bulk velocity. Right: critical velocities of the cloud motion, $\beta_1(\xi)$ and $\beta_2(\xi)$, at which the observed polarization changes its orientation. At saturation velocities the radiation and gravitational accelerations cancel each other.

Retro-lensing lightcurves and polarization

When determining the temporal evolution of observed intensity and polarization we consider the first three images of the observed radiation – the direct one and two retro-lensed images. The latter are formed by rays making a round about the black hole by the angle $2\pi \pm i$. For small inclination angles these images take the form of Einstein arcs. The retro-lensed photons give rise to peaks in the observed signal occurring with a characteristic mutual time lag after the direct-image photons. Duration of these features is very short and comparable to the light crossing time.

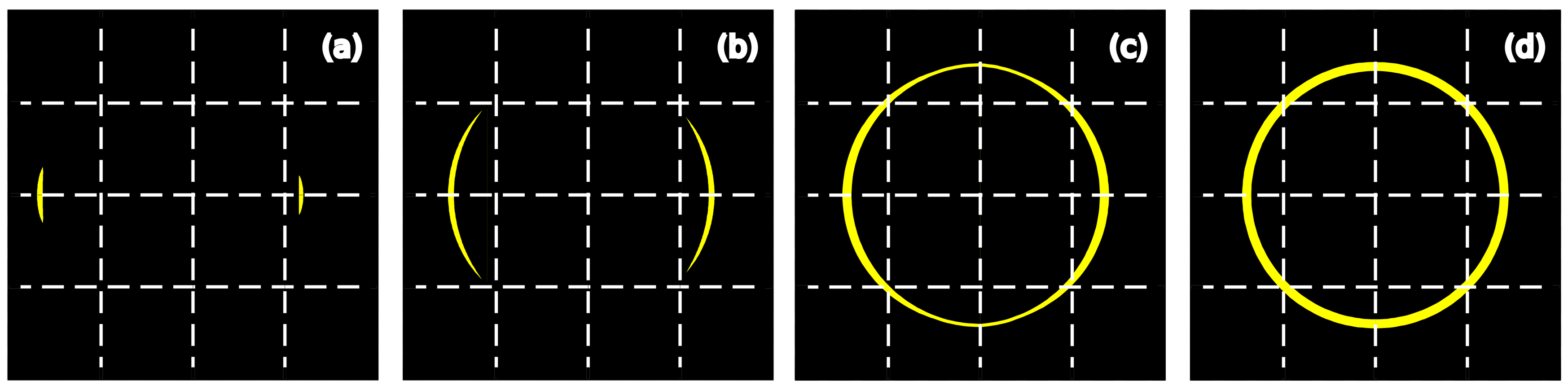

Fig. 3. The Einstein arcs appear in the observer plane when the inclination i of the source becomes comparable to its angular size. The observed polarization is then reduced significantly.

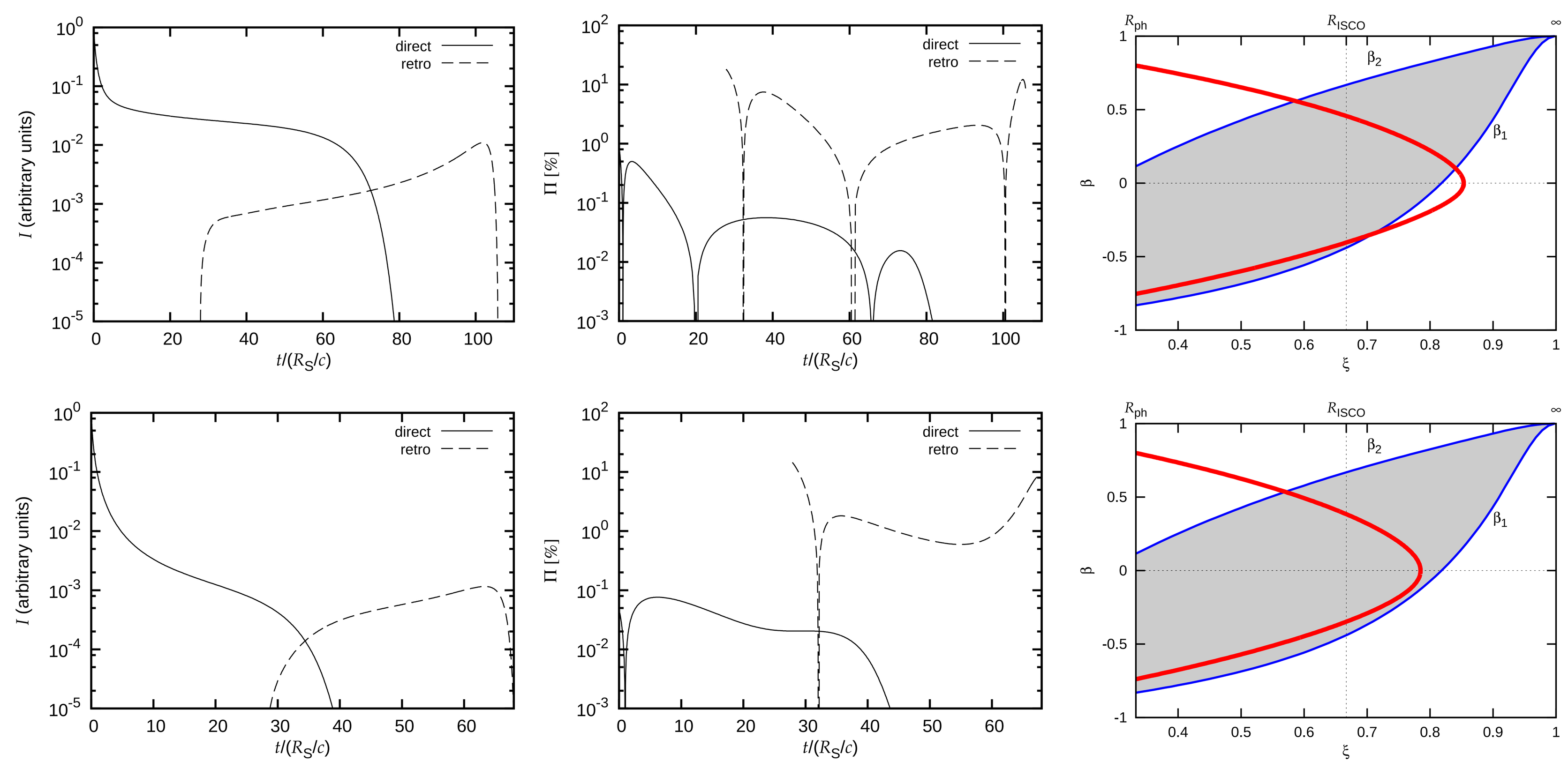

Fig. 4. A comparison between two typical cases with the identical initial conditions except for the cloud temperature: a cold cloud (upper panels, versus a warm cloud (lower panels, the electron Lorentz factor is 3 at start). Examples are shown of intensity (left panels) and polarization (middle panels) lightcurves. Contributions of the retro-lensing images have been summed together (dashed line); they are clearly distinguished from the signal produced by the direct-image photons (solid line). Polarization vanishes at the moment when the cloud crosses one of the curves $\beta_1(\xi)$, $\beta_2(\xi)$. The view angle was $i = 5$ deg in both cases.

Conclusions

Our calculation is self-consistent in the sense that the motion of the blob and of photons, and the resulting polarization are mutually connected. We concentrated ourselves on gravitational effects and compared the predicted flux intensities and the polarization magnitudes of direct and retrolensing images. We have noticed the mutual delay between the signal peaks formed by photons of different orders. The time delay of the order of light circle time near the photon orbit. It is characteristic to the effect and has a value proportional to the black hole mass.

References

[1] Horák J., Karas V., 2006a, MNRAS 365, 813

[2] Horák J., Karas V., 2006b, PASJ, 58, 204

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