Black Holes from Stars to Galaxies – Across the Range of Masses
Proceedings IAU Symposium No. 238, 2006
V. Karas & G. Matt, eds.

doi:10.1017/S1743921307005558

Intensity and polarization light-curves from radiatively-driven clouds

Jiří Horák and Vladimír Karas

Astronomical Institute, Academy of Sciences, Boční II, CZ-140 31 Prague, Czech Republic
email: horak@astro.cas.cz, vladimir.karas@cuni.cz

Abstract. We study linear polarization from scattering of light on a cloud of relativistic electrons. We assume that the cloud is hovering above an accretion disc, or it is in an accelerated motion under the combined influence of the radiation and gravitational fields near an accreting black hole. At first we derive simple and general analytical formulae for the Stokes parameters. These formulae are then used in calculations of the temporal evolution of the observed signal.

We find that higher-order images can significantly enhance the observed flux. Possible targets where the effect should be searched are accreting super-massive black holes and Galactic microquasars exhibiting episodic accretion/ejection events.

Keywords. Polarization – Thomson scattering – radiative acceleration – gravitational lensing

1. 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. We adopt the first-scattering approximation and we restrict the cloud motion to the symmetry axis. 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 indirect photons contribute most intensely to the total signal if the cloud moves toward the black hole and the observer inclination i is small.

2. Local intensity and polarization

The electron distribution is considered isotropic in the cloud comoving frame. We derived simple formulae for the non-vanishing 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 $\mathcal{A} \equiv \frac{4}{3}\langle\gamma_{\mathrm{e}}^2\beta_{\mathrm{e}}^2\rangle$ and $\mathcal{B} \equiv 1-\langle\ln[\gamma_{\mathrm{e}}(1+\beta_{\mathrm{e}})]/(\beta_{\mathrm{e}}\gamma_{\mathrm{e}}^2)\rangle$. A is a constant factor proportional to the cloud optical depth; β_{e} and γ_{e} are electron individual velocity and the Lorentz factor; $\langle\ldots\rangle$ denotes the averaging over the particle distribution in the cloud comoving frame. The fourth Stokes parameter, V, vanishes (linear polarization). The Stokes parameters are evaluated in the polarization frame comoving with the cloud, whose one basis vector is pointed along the direction of the scattered radiation and the two other basis vectors lie in the perpendicular observation plane. The incident unpolarized radiation comes into the formulae as components of the stress-energy tensor $T^{\alpha\beta}$ with respect to this reference frame.

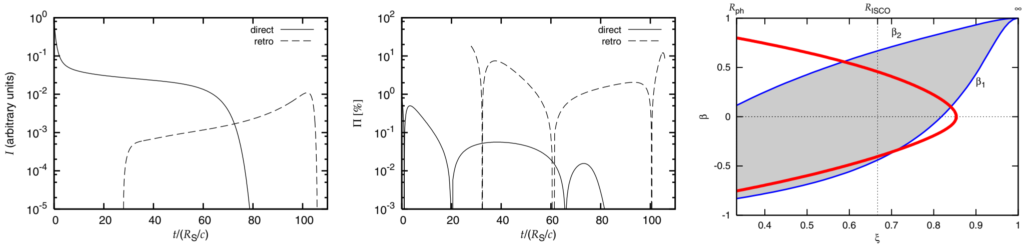

Figure 1. Examples of intensity (left panel) and polarization (middle panel) lightcurves. Contributions of the retro-lensing images have been summed together and plotted (by a dashed line); they are clearly distinguished from the signal produced by the direct-image photons (solid line). Polarization vanishes at the moment when the cloud crosses one of the critical velocities $\beta_1(\xi)$, $\beta_2(\xi)$, where $x \equiv 1 - R_{\rm S}/r$ is dimensionless radius. In both cases the view angle was $i = 5$ deg from the symmetry axis. Regions of different polarization are shown together with the velocity curve $\beta(\xi)$ (red curve; see the right panel).

The total four-force acting on the cloud is a superposition of the radiation and inertial terms. We solved the equation of motion in the spacetime of a static black hole (Schwarzschild radius $R_{\rm S} \equiv 2GM_{\bullet}/c^2$). The radiation field influences both components of the model – the bulk motion of the cloud as well as the electron distribution of the cloud. For polarization we obtain two critical velocities at which the polarization vector changes its orientation between transversal and longitudinal one. Similar effect of polarization direction changing with velocity of the scattering medium was studied by Beloborodov (1998) for the model of a wind from the disc. Below, by solving the equations of motion, we find how the observed polarization depends on time.

3. 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 single round about the black hole by the angle $2\pi \pm i$. The effect is usually small but for small inclinations the images take the form of Einstein arcs and may be quite significant (the flux level is up to several percent of the total signal). 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.

4. Conclusions

Our calculation is self-consistent in the sense that the motion of the blob and of photons is connected with the resulting polarization properties of the emerging signal. We concentrated ourselves on gravitational effects and compared the polarization magnitudes of direct and retrolensing images. We have estimated the mutual delay between the signal peaks formed by photons of different orders. The delay is characteristic to the effect and has a value proportional to the black hole mass.

We thank the Grant Agency of the Academy of Sciences (ref. 300030510) for support.

References

Beloborodov, A. M. 1998, ApJ, 496, L105
Horák, J. & Karas, V. 2006a, MNRAS, 365, 813
Horák, J. & Karas, V. 2006b, PASJ, 58, 204