X-ray spectra and polarization from accreting black holes

Polarization from an orbiting spot

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The polarization from a spot orbiting around Schwarzschild and extreme Kerr black holes is studied. We assume different models of local polarization. Firstly, as a toy model we set local polarization vector either normal to the disc plane, or we assume strictly azimuthal direction. Then we examine more realistic situation with a spot arising due to the emission from the primary source above the disc. We employ either Rayleigh single scattering or Compton multiple scattering approximations. Overall flux, degree and angle of polarization integrated over the whole orbit as well as their time dependence during the spot revolution are examined as functions of the observer’s inclination angle and black hole angular momentum. The gravitational and Doppler shifts, lensing effect as well as time delays are taken into account.

Introduction

Even when clearly observed, relativistic lines behave differently than previously expected. The best example is the lack of correlation between line and continuum emission in MCG–6-30-15 (Fabian et al. 2002). This does not necessarily mean that the iron line is not produced in the innermost regions of accretion discs (Miniutti et al. 2003). Polarimetric studies could be very useful to discriminate between different geometries and physical states of accreting sources in strong gravity regime. Here we examine consequences of a specific model of an illuminated accretion disc (Dovčiak et al. 2004).

Model

We assume Keplerian geometrically thin and optically thick disc around the Schwarzschild or extreme Kerr black holes. The spot is two-dimensional and it rotates together with the disc. We assume the spot does not change its shape during its orbit. Only the zero order photons have been taken into account here. Only the emission from the spot is considered; the decrease of polarization degree due to the disc and corona emission is not accounted for.

We apply four different models of local polarization. In the first two models the local emission is totally polarized either in the direction normal to the disc or in the azimuthal direction. In the case of partial local polarization the observed one will decrease proportionally. The explicit form of the local Stokes parameters for these two configurations are:

Normal polarization:

$$\begin{aligned} I(E) &= E^{-\Gamma}\,\mathrm{e}^{-\gamma d^2} \\ Q(E) &= I(E) \\ U(E) &= 0 \\ V(E) &= 0 \end{aligned}$$

Azimuthal polarization:

$$\begin{aligned} I(E) &= E^{-\Gamma}\,\mathrm{e}^{-\gamma d^2} \\ Q(E) &= -I(E)\cos\{2\arctan[\tan(\Phi_\mathrm{e})\mu_\mathrm{e}]\} \\ U(E) &= I(E)\sin\{2\arctan[\tan(\Phi_\mathrm{e})\mu_\mathrm{e}]\} \\ V(E) &= 0 \end{aligned}$$

Here, Γ is an intensity powerlaw index, γ characterizes the size of the spot, d is a distance from the spot centre — thus the intensity decreases Gaussian-like with the distance from the spot centre. The main difference between the two configurations is that the local polarization depends on azimuthal emission angle Φ_e and cosine of the emission angle μ_e in the azimuthal case.

The other two models of local polarization describe a more realistic situation: the spot is considered a part of the disc illuminated from a flare (considered to be a point source) above it and moving with Keplerian velocity. The photons from the primary source (the flare) are scattered in the disc. Some of them are eventually reflected in the direction to the observer. The scattering is handled in two different approximations — Rayleigh single scattering and Compton multiple scattering approximations. The explicit form of the local Stokes parameters in these cases are:

Rayleigh scattering:

$$\begin{aligned} I(E) &= (I_\mathrm{l}+I_\mathrm{r})\,N(E) \\ Q(E) &= (I_\mathrm{l}-I_\mathrm{r})\,N(E) \\ U(E) &= U_\mathrm{c}\,N(E) \\ V(E) &= 0 \\ N(E) &= \frac{h}{\sqrt{h^2+d^2}^{\,3}}\,E^{-\Gamma} \end{aligned}$$

Compton scattering:

$$\begin{aligned} I(E) &= \frac{I_\mathrm{l}+I_\mathrm{r}}{\langle I_\mathrm{l}+I_\mathrm{r}\rangle}\,N(E) \\ Q(E) &= \frac{I_\mathrm{l}-I_\mathrm{r}}{\langle I_\mathrm{l}+I_\mathrm{r}\rangle}\,N(E) \\ U(E) &= \frac{U}{\langle I_\mathrm{l}+I_\mathrm{r}\rangle}\,N(E) \\ V(E) &= 0 \\ N(E) &= \frac{h}{\sqrt{h^2+d^2}^{\,3}}\,f(E;\mu_\mathrm{i},\mu_\mathrm{e}) \end{aligned}$$

The functions I_l, I_r and U_c are derived for Rayleigh single scattering, see eq. (X.172) in Chandrasekhar (1960). They depend on azimuthal emission angle Φ_e and cosine of the emission angle μ_e in quite a complicated way, moreover, they depend on the incident azimuthal angle and cosine of the incident angle as well (the last two change throughout the spot). We assume that the primary source emits powerlaw radiation with index Γ, the factor in expression for $N(E)$ is due to different illumination of different “rings” forming the spot (h is height of the flare and d is distance from the centre of the spot).

In the Compton scattering approximation we used the combination of Rayleigh single scattering together with Compton multiple scattering. The function $f(E;\mu_\mathrm{i},\mu_\mathrm{e})$ is proportional to the reflected intensity if the disc is illuminated by a powerlaw. The disc is assumed to be neutral and also the photoabsorption is taken into account, for details see Matt et al. (1991). Unfortunately, this function was averaged over azimuthal angles. To reestablish this dependence we used the Rayleigh single scattering formulae. The symbol $\langle\ \rangle$ means averaging over the azimuthal angles.

Results

The results of our computations are presented on Figs. 1–4. The polarization degree (Fig. 1) decreases in all models mainly in that part of the orbit where the spot moves close to the region where the photons that reach the observer are emitted perpendicularly to the disc. The polarization angle (Fig. 2) changes rapidly in this part of the orbit. The decrease in observed polarization degree for azimuthal local polarization happens also in those parts of the orbit where the local polarization vector points approximately in the direction of photon’s motion. The polarization has more complicated behaviour for the more realistic models. One of the most interesting features is the peak in polarization degree for the extreme Kerr black hole for large inclinations. It is due to the lensing effect when the emission with a particular polarization angle is enhanced. This is not visible for the Schwarzschild case because the spot is orbiting farther away from the centre.

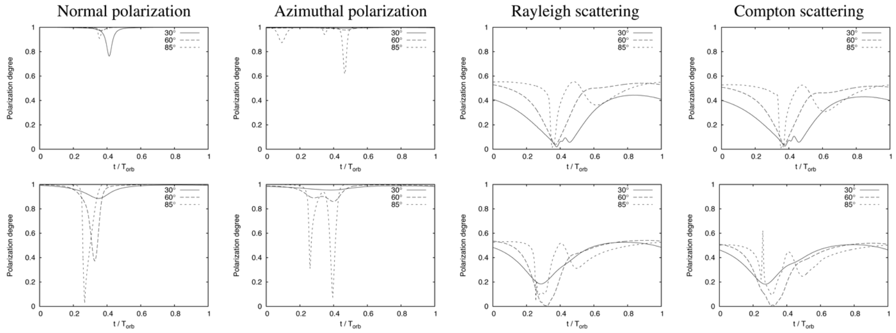

Fig. 1:
The time dependence of the polarization degree from a polarized orbiting spot in four different configurations of the local polarization vector — perpendicular to the disc, azimuthal, Rayleigh single scattering and Compton scattering approximations (from left to right) for Schwarzschild and extreme Kerr black holes (from up to bottom) and for three observer’s inclination angles ($30°, 60°$ and $85°$) as measured by an observer at infinity. Only the polarization from the spot itself is considered, the contributions of (un)polarized disc and corona emission is neglected in these simulations. The spot is located at $r_\mathrm{s}=7$ for Schwarzschild and $r_\mathrm{s}=3$ for extreme Kerr black hole. The radius of the spot is approximately $\delta r = 0.87$

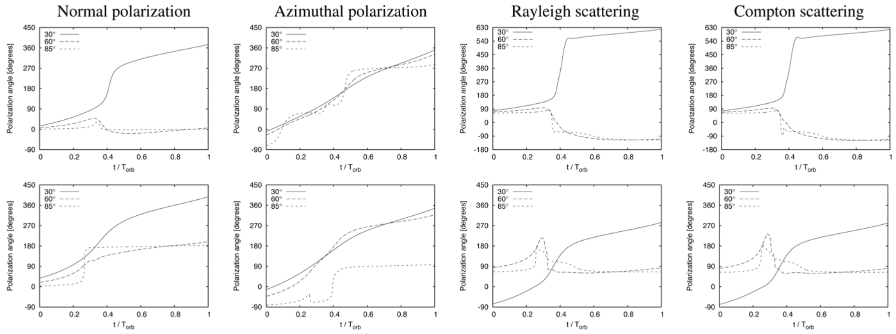

Fig. 2:
Same as in Fig. 1 but for the observed polarization angle.

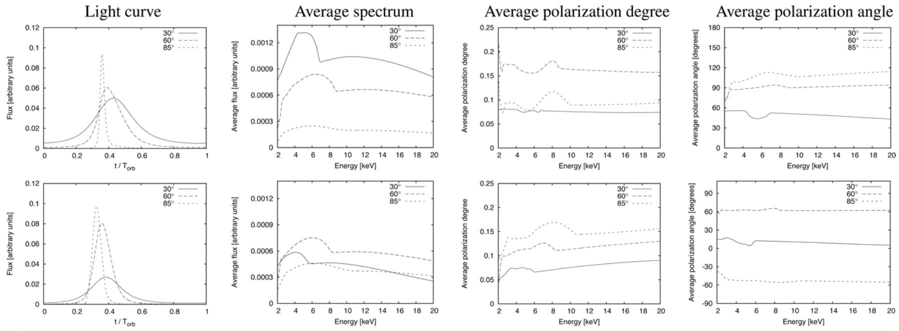

Fig. 3:
The light curve and average spectra, average polarization degree and average polarization angle for an orbiting spot in Compton scattering approximation of the local Stokes parameters for the Schwarzschild (upper row) and extreme Kerr (bottom row) black holes. The average is taken for one whole orbit. Other parameters are the same as in Fig. 1.

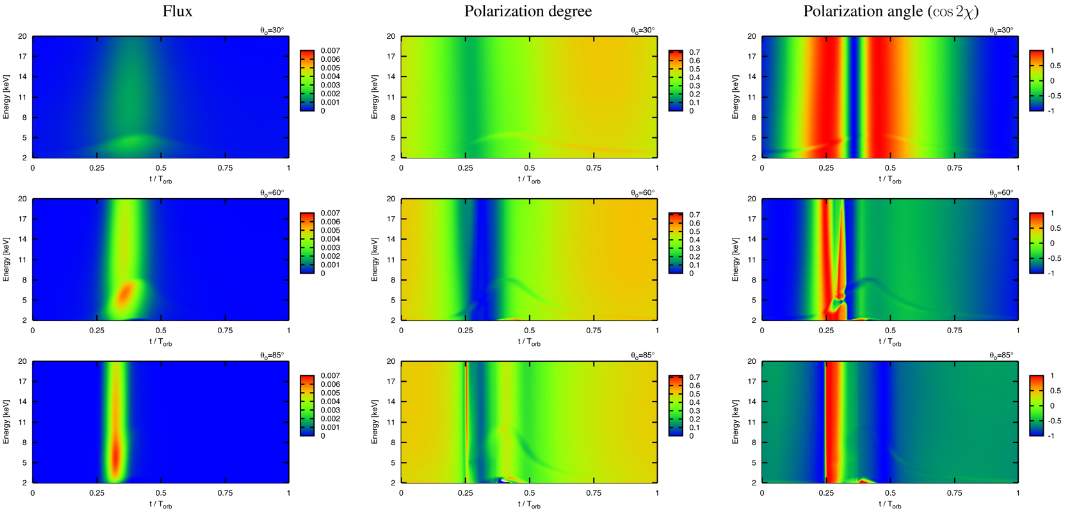

Fig. 4:
Dynamical spectrum, polarization degree and polarization angle (from left to right) of an orbiting spot for an extreme Kerr black hole for three different observer’s inclination angles $\theta_\mathrm{o} = 30°, 60°$ and $85°$ (from up to bottom) in Compton scattering approximation of the local Stokes parameters. Other parameters are the same as in Fig. 1.

The energy dependence of polarization (Fig. 3 and 4) is interesting only for the Compton scattering approximation model where the Iron edge is visible not only in the flux but also in the polarization degree and angle. In other models the energy flux is a simple powerlaw and polarization degree and angle does not depend on the energy.

Conclusions

The idea of using polarimetry to gain additional information about compact objects is not a new one: it was proposed by Rees (1975) that polarized X-rays are of high relevance. Pozdnyakov et al. (1979) studied spectral profiles of iron X-ray lines resulting from multiple Compton scattering. Temporal variations of polarization were also discussed, in particular the case of orbiting spots near a black hole (Connors et al. 1980). Strong gravity effects can be revealed as the direction of polarization vector is changed upon light propagation near a black hole. This may be relevant not only for the inner regions of AGN, for which we assumed X-ray reflection as the mechanism producing spectral a polarimetric features, but also for radiation coming from individual blobs of gas orbiting near the Galaxy Center where SSC mechanism likely operates.

References

[1] Chandrasekhar S., 1960,*Radiative transfer* (New York: Dover)
[2] Connors P. A., Piran T., Stark R. F., 1980, ApJ, 235, 224
[3] Dovčiak M., Karas V., Matt, G. 2004, MNRAS, 355, 1005
[4] Fabian A. C., Iwasawa K., Reynolds C. S., Young A. J., 2000, PASP, 112, 1145
[5] Matt G., Perola G. C. and Piro L. 1991, A&A, 247, 25
[6] Miniutti G., Fabian A. C., Goyder R., Lasenby A. N., 2003, MNRAS, 344, L22
[7] Pozdnyakov L. A., Sobol I. M., Sunyaev R. A., 1979, A&A, 75, 214
[8] Rees M. J., 1975, MNRAS, 171, 457