X-ray spectra and polarization from accreting black holes: Polarization of the thermal emission

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Abstract. Multicolour black-body emission from the accretion disc around the black hole can be polarized on its way through the atmosphere above the accretion disc. We model this effect by assuming Kerr metric for the black hole, a standard thin disc for the accretion flow and Thomson scattering in the atmosphere. We compute the expected polarization degree and the angle as they can be measured for different inclinations of the observer, optical thickness of the atmosphere and different values of the black hole spin. All relativistic effects near a compact centre are taken into account.

1. Assumptions of the model
We assume a Keplerian geometrically thin and optically thick accretion disc around the Schwarzschild or extreme Kerr black hole. At each radius the disc emits the black body emission whose temperature is given by the Novikov-Thorne expression \[^{[1]}\] for an outer part of the disc. We suppose that there is zero torque at the inner edge of the disc and the disc reaches only down to the innermost stable circular orbit.

The photons are scattered in the atmosphere of the disc and thus the observed radiation can be polarized. We assume multiple Thomson scattering in the semi-infinite atmosphere with different opacities. We compute it by Monte Carlo simulations \[^{[2]}\] for finite opacities and we use Chandrasekhar’s formula for infinite opacity \[^{[3]}\]. The effect of hardening of the energy spectrum due to Comptonization is modeled by the hardening factor that increases the effective temperature \[^{[4]}\].

Once the photons leave the atmosphere the polarization vector can be rotated due to strong gravity of the central black hole. The emission is amplified by the transfer function \[^{[5]}\] and the energy of photons is shifted by the gravitational and Doppler effects. We assume that scattering occurs only close above the disc and we use the transfer function computed for the equatorial plane \[^{[6]}\].

In all computations we assumed the mass of the central black hole \(M_\bullet = 3M_\odot\), the accretion rate \(\dot{M} = 10^{-9}M_\odot\text{yr}^{-1}\) and the hardening factor \(f = 1.7\).
The local polarization is induced by Thomson scattering (see the left panel in Fig. 1) and it is defined in the local frame co-moving with the Keplerian disc. Due to the aberration the polarization angle for each photon is different at infinity even in the Schwarzschild space-time. In Kerr case the rotation of polarization vector because of the gravitational dragging is added. The dependence of the change of the polarization angle on the position of the emission from the disc is shown in Fig. 2. It can be seen that farther away from the black hole this change is not too large. Therefore the depolarizing effect of the integration over this part of the disc will be relatively small. On the other hand below the critical point, where the light is emitted perpendicularly to the disc, the change of the polarization angle can acquire any value. Thus the depolarizing effect of this region can be quite large. Therefore for the overall polarization measured at infinity it is important if this critical point is above or below the marginally stable orbit. It is clear that the depolarizing region will be smaller for lower spin of the black hole. Note also that the area of depolarizing region is larger for lower inclinations of the observer (the critical point moves farther away from the black hole).

3. Polarization at infinity
The dependence of the local polarization on the emission angle for different opacities of the disc’s atmosphere is shown in the left panel in Fig. 1. In the right panel of the same figure we show the multicolour black-body flux at infinity integrated over the whole disc. As expected, the normalization of the flux scales with the cosine of the inclination angle. The disc has higher temperature and reaches closer to the centre for the extreme Kerr black hole therefore the flux reaches higher energies and has higher normalization in this case.

The energy dependence of the polarization degree and angle at infinity is shown in Fig. 3. The character of the polarization at lower energies is given mainly by the emission originating far away from the black hole. The polarization degree and angle are equal to the local ones for the emission angle equal to the inclination of the observer (compare with the left panel in Fig. 1).
Figure 2. Contour graphs of the change of the polarization angle for Schwarzschild (left) and extreme Kerr (right) black hole. The observer inclination is $\theta_o = 30^\circ, 60^\circ$ and $85^\circ$ (top to bottom). The observer is located to the top of the pictures. The innermost stable circular orbit is shown for the Schwarzschild case. The critical point, where the photons are emitted perpendicularly to the disc, is shown by a cross. The black hole rotates counter-clockwise in the Kerr case. The graphs are represented in the coordinates $x = r \cos \varphi$, $y = r \sin \varphi$ in the equatorial plane where $r$ and $\varphi$ are Boyer-Lindquist coordinates.
Figure 3. The energy dependence of the polarization degree (left) and polarization angle (right) at infinity for different opacities of the atmosphere $\tau = \infty, 2.0, 1.0, 0.5$ (from top to bottom), in the case of the Schwarzschild (dashed lines) and extreme Kerr (solid lines) black holes and observer inclinations of $30^\circ$, $60^\circ$ and $85^\circ$. A polarization angle of $0^\circ$ represents the direction aligned with the projected symmetry axis of the disc.
Figure 4. The dependence of the polarization degree (left) and polarization angle (right) at infinity on cosine of the observer’s inclination for different opacities of the atmosphere $\tau = \infty, 2.0, 1.0, 0.5$ (from top to bottom), in the case of the Schwarzschild (dashed lines), extreme Kerr (solid lines) and highly rotating Kerr (dash-dotted lines) black holes. A polarization angle of $0^\circ$ represents the direction aligned with the projected symmetry axis of the disc.
In most cases, the polarization is highest for these energies. For high energies (above 10 keV), the polarization degree increases. The polarization here is influenced mainly by that region of the disc, where the transfer function is the largest and the temperature is the highest. This area is not very large and thus the span of the change of the polarization angle is small. Therefore the depolarizing effect is not very large. Note, however, that for the same reason (small area) the flux for this interval of energy is also very small (see the right panel in Fig. 1).

The dependence of the polarization degree and angle on the inclination of the observer is shown in Fig. 4. Both quantities are integrated over the whole energy range (0.01–100 keV). The polarization degree in most cases increases with the inclination angle of the observer. The polarization angle does not change much with the observer’s inclination, mainly for lower inclinations. However its value depends on the spin of the black hole.

4. Conclusions
We have investigated the GR and Doppler effects on the polarization properties of the thermal radiation emitted by an accretion disc around a stellar mass black hole. The polarization at infinity is changed from its local value due to strong gravity effects and fast orbital motion of the disc close to the central black hole. The difference is particularly dramatic especially in the region below the critical point, where the polarization angle swings over the entire range of 180 degrees.

The continuous variation of the polarization angle with energy is a clear signature of the GR effects. The most interesting interval of energy is between 1 and 10 keV. Below this energy range the emission comes from far away from the disc centre, above this energy interval the flux rapidly decreases. Note, however, that for different maximum temperatures of the disc this energy interval can change. The maximum disc temperature depends on several parameters of the model — the black hole mass, black hole spin, accretion rate and hardening factor.

The polarization degree is the highest for the lowest studied opacity of the disc’s atmosphere and in most cases it grows with the observer’s inclination. The polarization angle does not change much with the inclination of the observer apart from the highest inclinations. Instead, it depends quite strongly on the spin of the central black hole.

Finally, we would like to point out that the effects of strong gravity on the polarization state of emerging radiation will be measurable by the next missions with an X-ray polarimeter based on the Gas Pixel Detector as was investigated in our recent paper [7].

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