X-ray spectra and polarization from accreting black holes

Polarization of the thermal emission

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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 Rayleigh 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.

Assumptions of the model

We assume Keplerian geometrically thin and optically thick disc around the Schwarzschild or extreme Kerr black holes. At each radius the disc emits the black body emission whose temperature is given by the Novikov-Thorne expression (Novikov & Thorne 1973) for the 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 Rayleigh scattering in the semi-infinite atmosphere with different opacities. We compute it by Monte Carlo simulations for finite opacities and we use Chandrasekhar's formula for infinite opacity (Chandrasekhar 1960). The effect of hardening of the energy of photons due to scattering is modeled by the hardening factor that increases the effective temperature (Shimura & Takahara 1995).

After 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 (Cunningham 1976, Dovčiak 2004) 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.

In all computations we assumed the mass of the central black hole $M_\bullet = 3M_\odot$, the accretion rate $\dot{M} = 10^{-9}M_\odot/y$ and the hardening factor $f = 1.7$.

Change of the polarization angle

The local polarization induced by Rayleigh scattering (see the left panel in Fig. 2) 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. 1. 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).

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. 2. 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 disc for the extreme Kerr black hole therefore the flux reaches higher energies and has higher normalization in this case.

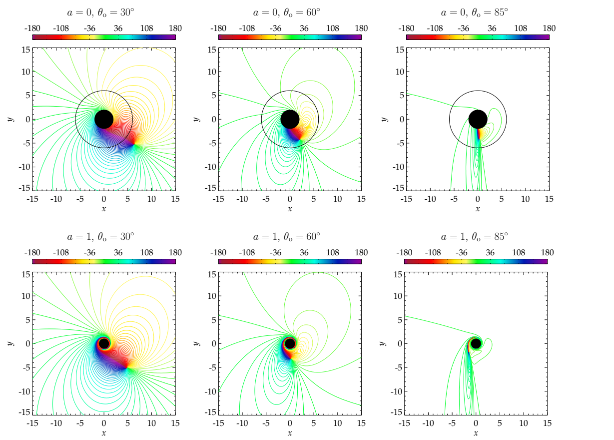

Fig. 1:
Contour graphs of the change of the polarization angle for Schwarzschild (top) and extreme Kerr (bottom) black hole and observer inclinations of 30°, 60° and 85° (left to right). The observer is located to the top of the pictures. The ISCO is shown for the Schwarzschild case. The black hole rotates counter-clockwise in the Kerr case.

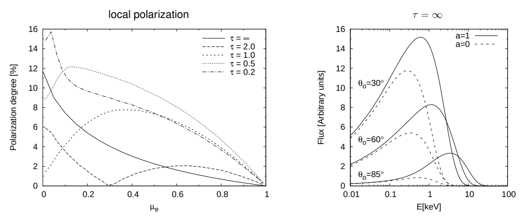

Fig. 2:
Left: The dependence of the local polarization degree on the cosine of the emission angle. Curves for different opacities τ are shown. The results for $\tau \gtrsim 5$ do not differ much from the case $\tau = \infty$.
Right: The multicolour black body spectra for the extreme Kerr (solid line) and Schwarzschild (dashed line) black hole for the three observer inclinations of 30°, 60° and 85° and for the atmosphere with opacity $\tau = \infty$.

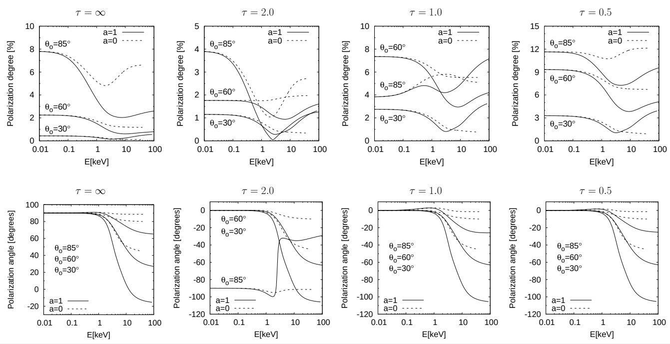

Fig. 3:
The energy dependence of the polarization degree (top) and polarization angle (bottom) as the observer at infinity would measure them for different opacities of the atmosphere $\tau = \infty, 2.0, 1.0, 0.5$ (from left to right), in the case of the Schwarzschild (dashed lines) and extreme Kerr (solid lines) black holes and observer inclinations of 30°, 60° and 85°.

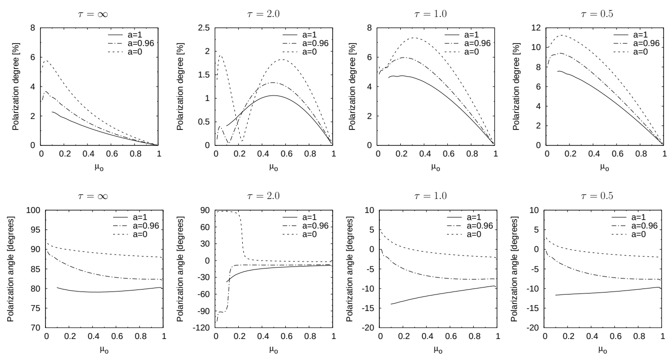

Fig. 4:
The dependence of the polarization degree (top) and polarization angle (bottom) at infinity on cosine of the observer's inclination for different opacities of the atmosphere $\tau = \infty, 2.0, 1.0, 0.5$ (from left to right), in the case of the Schwarzschild (dashed lines) and Kerr (dash-dotted and solid lines) black holes. The polarization is integrated in the whole energy range.

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. 2). In most cases, the polarization is highest for these energies.

For high energies (above 10keV), 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. 2).

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.

Conclusions

The polarization at infinity is changed from its local value due to depolarizing effect induced by strong gravity and fast orbital motion of the disc close to the central black hole, in the region below the critical point.

The most interesting interval of energy is at about or slightly below 1 keV up to 10 keV. Below this energy region the emission comes from far away from the centre, above this region the flux rapidly decreases. Note, however, that for different parameters of the model (black hole mass, accretion rate and hardening factor) the value of the upper boundary of the interesting energy interval will change.

The polarization degree is higher for the higher observer inclination and for the lower opacity of the disc's atmosphere.

The polarization angle does not change much with the inclination of the observer for lower inclinations. However, it depends on the spin of the central black hole.

References

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