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Polarization of radiation from AGN accretion discs – the lamp-post model

Michal Dovčiak[1], Vladimír Karas[2], Giorgio Matt[3] and Andrea Martocchia[4]

[1]Astronomical Institute, Czech Academy of Sciences, Boční II 1401, CZ-141 31 Praha 4, Czech Republic
[2]Charles University in Prague, Faculty of Mathematics and Physics, V Holešovičkách 2, Praha, Czech Republic
[3]Dipartimento di Fisica, Università degli Studi "Roma Tre," I-00146 Roma, Italy
[4]UPS/Centre d'Etude Spatiale des Rayonnements, Toulouse, France

ABSTRACT
The effects of strong gravity on the polarization of the Compton reflection from an X-ray illuminated accretion disc are studied. The gravitational field of a rotating black hole influences Stokes parameters of the radiation along the propagation to a distant observer. Assuming the lamp-post model, the degree and the angle of polarization are examined as functions of the energy, observer's inclination angle, height of the primary source and inner radius of the disc emitting region.

1 INTRODUCTION

In this contribution we show that polarimetric studies in the X-ray domain could provide additional information about accretion discs in a strong gravity regime, which may be essential to discriminate between different possible geometries of the source. The idea of using polarimetry to gain additional information about accreting compact objects is not a new one. In this context 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 that result from multiple Compton scattering. Later on, various processes affecting polarization (due to magnetic fields, absorption as well as strong gravity) were examined for black-hole accretion discs (Agol and Blaes, 1996). Temporal variations of polarization were also discussed, in particular the case of orbiting spots near a black hole (Connors et al., 1980; Bao et al., 1996). With the promise of new polarimetric detectors (Costa et al., 2001), quantitative examination of specific models becomes timely.

Since the reflecting medium has a disc-like geometry, a substantial amount of linear polarization is expected in the resulting spectrum because of Compton scattering. Polarization properties of the disc emission are modified by the photon propagation in a gravitational field, providing additional information on its structure. Here we calculate the observed polarization of the reflected radiation assuming the lamp-post model for the stationary power-law illuminating source (Martocchia and Matt, 1996; Petrucci and Henri, 1997).

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2 ASSUMPTIONS

We assume a rotating (Kerr) black hole as the only source of the gravitational field, having a common symmetry axis with an accretion disc. The disc is also assumed to be stationary and we restrict ourselves to the time-averaged analysis. In other words, we examine processes that vary at a much slower pace than the light-crossing time at the corresponding radius. Intrinsic polarization of the emerging light can be computed locally, assuming a plane-parallel scattering layer which is illuminated by light radiated from the primary source. This problem was studied extensively in various approximations (e.g., Chandrasekhar, 1960; Sunyaev and Titarchuk, 1985). Here we employ the Monte Carlo computations (Matt et al., 1991; Matt, 1993) to determine the intrinsic emissivity of an illuminated disc. The exact form of the local Stokes parameters can be found in (Dovčiak et al., 2004a, section describing the kyl1cr model). We integrate contributions to the total signal across the disc emitting region using a general relativistic ray-tracing technique described in (Dovčiak, 2004; Dovčiak et al., 2004a) and we compute the polarization angle and degree as measured by a distant observer. We show the polarization properties of scattered light as a function of energy and model parameters, namely, the height $z = h$ of the primary source on the symmetry axis, the dimensionless angular momentum a of the black hole, and the viewing angle $\theta_{\rm o}$ of the observer.

3 RESULTS

In the first set of figures (Figs 1 and 2) we show the energy dependence of the polarization angle and degree due to reflected and reflected-plus-direct radiation for different inclination angles and different heights of the primary source. One can see that the polarization of reflected radiation can be as high as thirty percent or even more for small inclinations and small heights. Polarization of the reflected radiation does not depend on energy very much except for the region close to the iron edge at approximately 7.2 keV, where it either decreases for small inclinations or increases for large ones.

In order to compute observable characteristics one has to combine the primary power-law continuum with the reflected component. The polarization degree of the resulting signal depends on the mutual proportion of the two components and also on the energy range in which the signal is integrated. The net degree of polarization increases with energy (see bottom panels in Figs 1 and 2) due to the fact that the intensity of radiation from the primary source decreases exponentially, the intensity of the reflected radiation increases with energy (in the energy range 3–15 keV) and the polarization of the reflected light alone is more or less constant. In our computations we assumed that the irradiating source emits isotropically and its light is affected only by gravitational redshift and lensing, according to the source location at $z = h$ on axis. This results in a dilution of primary light by factor $\sim g_{\rm h}^2(h, \theta_{\rm o})\, l_{\rm h}(h, \theta_{\rm o})$, where $g_{\rm h} = [1 - 2h/(a^2 + h^2)]^{1/2}$ is the redshift of primary photons reaching directly the observer, $l_{\rm h}$ is the corresponding lensing factor. Here, the redshift is the dominant relativistic term, while lensing of primary photons is a few percent at most and it can be safely ignored. Anisotropy of primary radiation may further attenuate or amplify the polarization degree of the final signal, while the polarization angle is rather independent of this effect as long as the primary light is itself unpolarized.

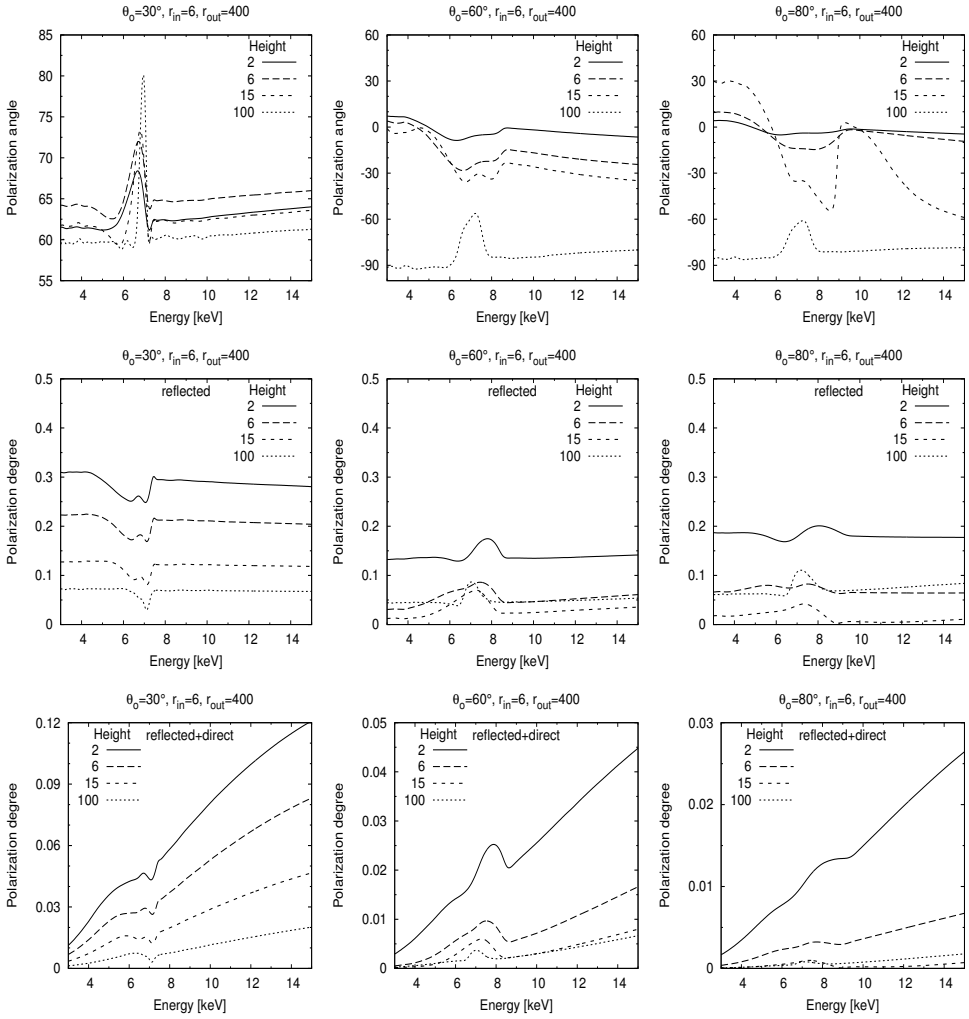

Figure 1. Energy dependence of polarization angle (top panels) and polarization degree (middle panels) due to reflected radiation for different observer's inclination angles ($\theta_o = 30°, 60°$ and $80°$) and for different heights of the primary source ($h = 2, 6, 15$ and 100). Polarization degree for reflected-plus-direct radiation is also plotted (bottom panels). The emission comes from a disc within $r_{in} = 6$ and $r_{out} = 400$. Isotropic primary radiation with photon index $\Gamma = 2$ and angular momentum of the central black hole $a = 0.9987$ were assumed.

The polarization of scattered light is also shown in Fig. 3, where we plot the polarization degree and the change of the polarization angle as functions of h. Notice that in the Newtonian case only polarization angles of 0° or 90° would be expected for reasons of symmetry. The two panels in the figure correspond to different locations of the inner disc edge: $r_{in} = 6$ and $r_{in} = 1.20$, respectively. The curves are strongly sensitive to r_{in} and h,

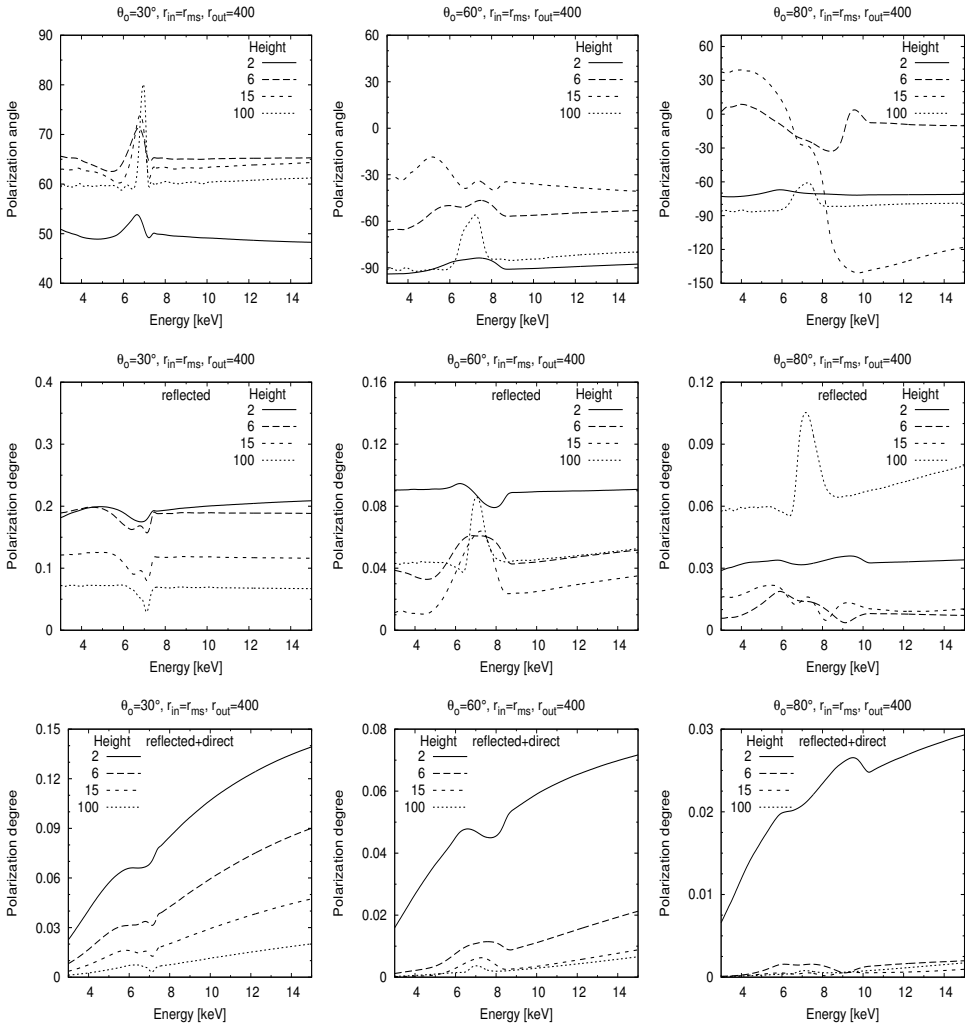

Figure 2. Same as in the previous Fig. 1 but for disc starting at $r_{\rm in} = 1.20$.

while the dependence on $r_{\rm out}$ is weak for a large disc (here $r_{\rm out} = 400$). Sensitivity to $r_{\rm in}$ is particularly appealing if one remembers the practical difficulties in estimating $r_{\rm in}$ by fitting spectra. The effect is clearly visible up to $h \sim 10$ for polarization degree and even higher for polarization angle (for larger inclination angles of the observer). Graphs corresponding to $r_{\rm in} = 6$ and $a = 0.9987$, resemble, in essence quite closely, the non-rotating case ($a = 0$) because dragging effects are most prominent near the horizon.

Figure 4 shows the polarization degree and angle as functions of the observer's inclination. Again, by comparing the two cases of different $r_{\rm in}$ one can clearly recognize that the polarization is sensitive to details of the flow near the inner disc boundary.

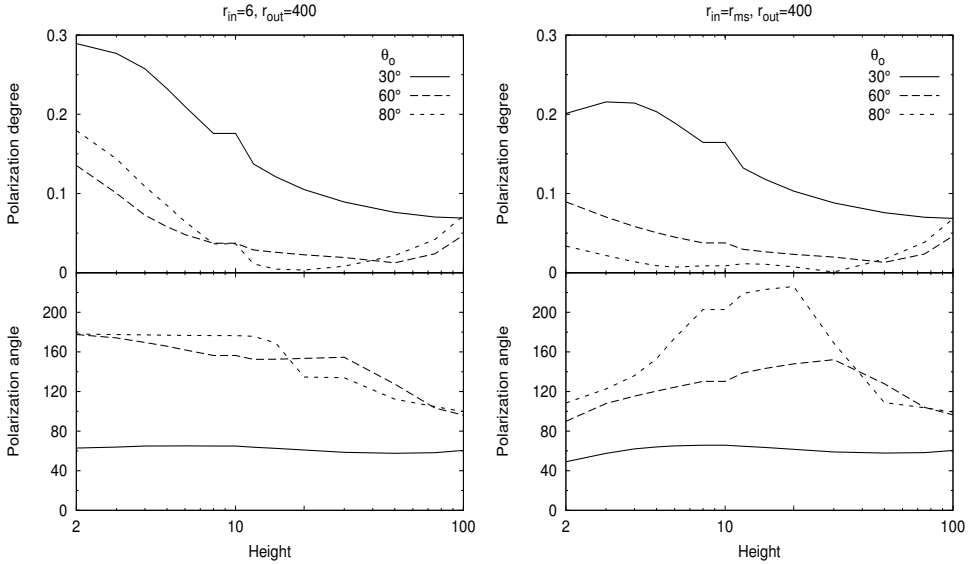

Figure 3. Polarization degree and angle due to reflected radiation integrated over the whole surface of the disc and propagated to the point of observation. Dependence on height h is plotted. *Left panel:* $r_{\rm in} = 6$. *Right panel:* $r_{\rm in} = 1.20$. In both the panels the energy range was assumed 9–12 keV, the photon index of incident radiation $\Gamma = 2$, the angular momentum $a = 0.9987$. The figure is taken from (Dovčiak et al., 2004b).

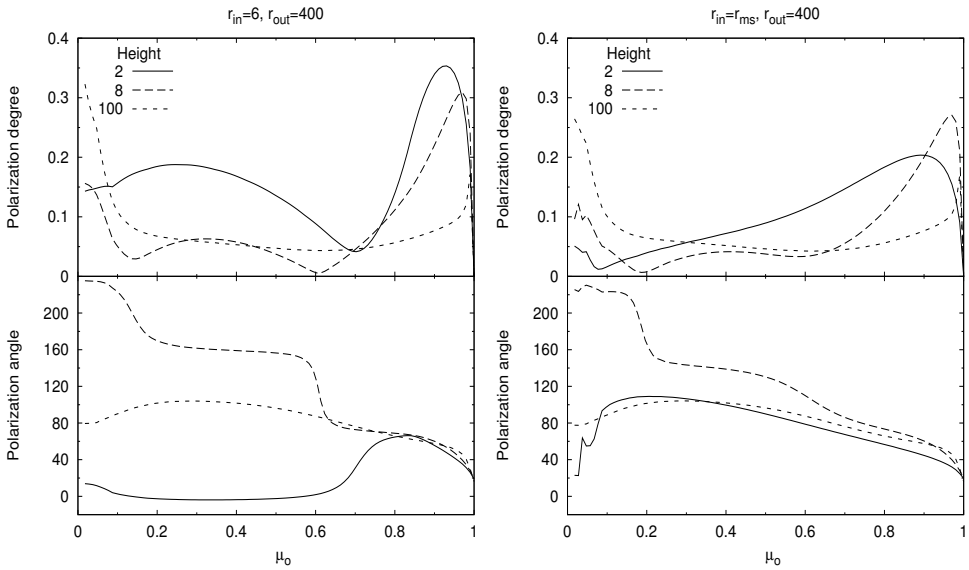

Figure 4. Polarization degree and angle as functions of $\mu_{\rm o}$ (cosine of observer inclination, $\mu_{\rm o} = 0$ corresponds to the edge-on view of the disc). The same model is shown as in the previous Fig. 3. The figure is similar to Fig. 2 in (Dovčiak et al., 2004b) but computed with higher resolution.

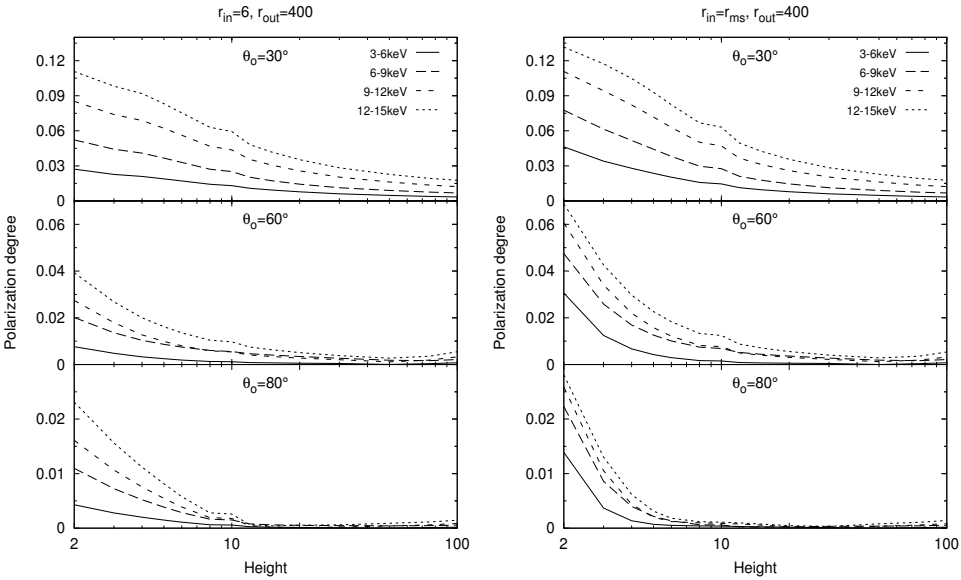

Figure 5. Net polarization degree of the total (primary plus reflected) signal as a function of h. *Left panel:* $r_{\rm in} = 6$. *Right panel:* $r_{\rm in} = 1.20$.

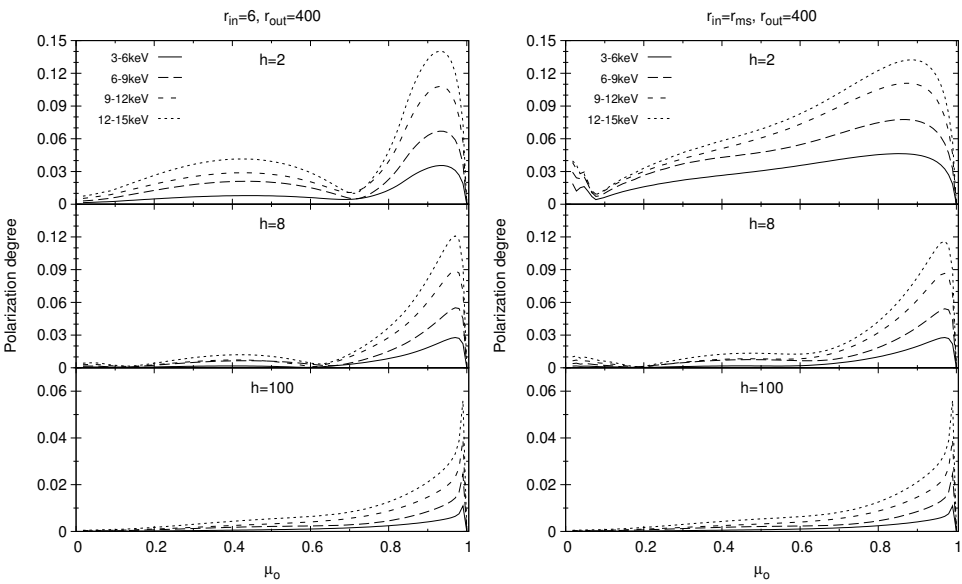

Figure 6. Net polarization degree of the total (primary plus reflected) signal as a function of $\mu_{\rm o}$. The same model is shown as in the previous Fig. 5.

The dependence of the polarization degree of overall radiation (primary plus reflected) on the height of the primary source and the observer inclination in different energy ranges is shown in Figs 5 and 6.

4 CONCLUSIONS

We examined the polarimetric properties of X-ray illuminated accretion discs in the lamp-post model. From the figures shown it is clear that observed values of polarization angle and degree are rather sensitive to the model parameters. The adopted approach provides additional information with respect to traditional X-ray spectroscopy and so it has great potential for discriminating between different models. It offers an improved way of measuring rotation of the black hole because the radiation properties of the inner disc region most likely reflect the value of the black-hole angular momentum. One should stress here, that firstly, the estimation of the black hole spin in spectroscopy is usually based on assuming that the innermost line- or continuum-emitting orbit coincides with the innermost stable orbit, and secondly, there are always several unknown variables at play. Therefore it would be better to get the value of the inner edge of the disc and the spin of the black hole on the base of both the spectroscopy and polarimetry.

While our calculations have been performed assuming a stationary situation, in reality it is likely that the height of the illuminating source changes with time, and indeed such variations have been invoked by Miniutti et al. (2003) to explain the primary and reflected variability patterns of MCG-6-30-15. A complete time-resolved analysis (including all consequences of the light travel time in curved space-time) is beyond the scope of this contribution and we defer it to future work, assuming that the primary source varies on a time-scale longer than light-crossing time in the system. This is also a well-substantiated assumption from a practical point of view, since feasible techniques will anyway require sufficient integration time (i.e., order of several ksec). Once full temporal resolution is possible, the analysis described above can be readily extended. Here, it suffices to note that a variation of h implies a variation of the observed polarization angle of the reflected radiation. As it is hard to imagine a physical and/or geometrical effect giving rise to the same effect, time variability of the polarization angle can be considered (independently of the details) a very strong signature of strong-field general relativity effects at work.

New generation photoelectric polarimeters (Costa et al., 2001) in the focal plane of large area optics (such as those foreseen for *Xeus*) can probe polarization degrees of the order of one percent in bright AGNs, making polarimetry, along with timing and spectroscopy, a tool for exploring the properties of the accretion flows in the vicinity of black holes.

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