Polarization signatures of strong gravity in AGN accretion discs

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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 observer’s inclination angle, of the height of the primary source and of the inner radius of the disc emitting region. It is shown that polarimetry can provide essential information on the properties of black holes sources, and it is argued that time variation of the polarization angle is a strong signature of general relativity effects. The expected polarization degree and angle should be detectable by new generation polarimeters, like the one planned for the Xeus mission.

Key words: galaxies: nuclei – X-rays: galaxies – polarization – relativity

1 INTRODUCTION
Accretion discs in central regions of active galactic nuclei (AGN) are subject to strong external illumination originating from some kind of corona and giving rise to specific spectral features in the X-ray band, namely a Compton Reflection component and fluorescent emission lines, the most prominent of them being that of iron. It has been shown that the shape of the intrinsic spectra must be further modified by the strong gravitational field of the central mass, and so X-ray spectroscopy could allow us to explore the innermost regions of accretion flows near super-massive black holes (for recent reviews, see Fabian et al. 2000; Reynolds & Nowak 2003). Similar mechanisms operate also in some Galactic black hole candidates.

However, a rather surprising result from recent XMM-Newton observation is that relativistic iron lines are not as common as previously believed (Bianchi et al. 2004 and references therein). This does not necessarily mean that the iron line is not produced in the innermost regions of accretion discs. The situation is likely more complex than in simple, steady scenarios, and indeed some evidence for the line emission arising from orbiting spots is present in the time-resolved spectra of a few AGN (e.g., Dovčiak et al. 2004a, and references therein). Even when clearly observed, relativistic lines behave differently than expected. The best example is the puzzling lack of correlation between line and continuum emission in MCG–6-30-15 (Fabian et al. 2002), unexpected because the very broad line profile clearly indicates that the line originates in the innermost regions of the accretion disc, hence very close to the illuminating source. Miniutti et al. (2003, 2004) have proposed a solution to this problem in terms of the source moving along the black hole rotation axis or very close to it.

In this paper we demonstrate that polarimetric studies could be very useful to discriminate between different geometries and physical states of accreting sources in strong gravity regime. The idea of using polarimetry to gain additional information about 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, Sobol & Sunyaev (1979) studied spectral profiles of iron X-ray lines that result from multiple Compton scattering. Laor et al. (1990) studied the polarization of a thin accretion disc around a rotating black hole within the framework of general relativity, using an improved radiative transfer computations. Later on, various influences affecting polarization (due to magnetic fields, absorption as well as strong gravity) were examined for black hole accretion discs (Ágol & Blaes 1996; Ogura, Ohno & Kojima 2000). Temporal variations of polarization were also discussed, in particular the case of orbiting spots near a black hole (Connors, Piran & Stark 1980; Bao, Wiita & Hadrava 1996). Here we examine consequences of a specific model of an illuminated accretion disc. 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 gravitational field, providing additional information on its structure. In this paper we calculate the observed polarization of the reflected radiation assuming the lamp-post model (Martocchia & Matt 1996; Petrucci & Henri 1997; Ghisellini et al. 2004). We assume a rotating (Kerr) black hole as the only source of the gravitational field, having a common symmetry axis with an accretion disc.

In the next section, by employing Monte-Carlo computations (Matt, Perola & Piro 1991; Matt 1993) we will find the intrinsic emissivity of an illuminated disc. Then we will integrate contributions to the total signal across the disc emitting region and, using a general relativistic ray-tracing technique (Dovčiak et al. 2004b, 2004c), we derive the Stokes parameters as measured by a distant observer. We will present the polarization properties of scattered light as a function of 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 $\theta_0$ of the observer. The conclusion will be that the X-ray polarimetry can be very useful to help discriminating between models and determining their parameters.

2 POLARIZATION OF REFLECTED LIGHT IN THE STRONG GRAVITY REGIME

2.1 An irradiated disc near a black hole

The local emissivity of radiation reflected at a given point of the disc is assumed to be proportional to the incident illumination by the primary power-law continuum. The primary source of the lamp-post model is located at height $h$ above the black hole, and so we first need to integrate light rays from the source down to the disc. The disc is assumed to be stationary and we restrict ourselves to the time-averaged analysis, assuming processes that vary in a much slower pace than the light-crossing time at the corresponding radius.

An incident photon strikes the disc at a certain point $P(r, \varphi)$ in equatorial plane $\theta = \pi/2$ (i.e. $z = 0$). Four-momentum of an incident photon is

$$p_i^t = 1 + 2r^{-1} + 4\Delta^{-1},$$

$$p_i^r = R_\sigma \left[(r^2 + a^2)^2 - \Delta r^{-2} (a^2 + q_0^2)\right]^{1/2},$$

$$p_i^\varphi = q_0 r^{-2},$$

$$p_i^\theta = 2a r^{-1} \Delta^{-1},$$

where $q_0^2 \equiv \sin^2\theta_0 (h^2 + a^2) \Delta p^{-1} - a^2$ is Carter’s constant of motion, $\Delta(r) \equiv r^2 - 2r + a^2$, $\Delta_\parallel \equiv \Delta(h)$, and $R_\sigma$ is the sign of $p_\mu$. Usual notation is employed for Kerr metric functions in Boyer-Lindquist coordinates (e.g. Kato, Fukue & Mineshige 1998). All quantities are made dimensionless by $GM/c^2$. The disc is defined by $r_{in} \leq r \leq r_{out}$. We also denoted $\theta_0$ to be the local angle of emission under which photon emerges in the source rest frame ($\theta_0 = 0$ corresponds to a photon heading downwards to the disc, while $\theta_0 = 180^\circ$ is for upward direction). Afine parametrization has been employed in such a way that conserved energy of an incident photon is $-p_{it} = -p_{ri} = 1$ and its conserved angular momentum vanishes, i.e. $I^\varphi = 0$. The assumed range of key parameters is $0 \leq a \leq 1$, $0 \leq \theta_0 \leq 90^\circ$ (in this paper we show results for a rapidly rotating black hole, $a \to 1$, and we use $5^\circ$ resolution in $\theta_0$).

The following considerations are necessary in order to derive the observed spectrum and polarization. First, the gravitational and Doppler-induced shift of energy of the primary photons impinging on the disc is

$$g_0 = \frac{E_0}{E_p} = \frac{p_{i\mu} U_\mu}{p_{p\mu} U_{p\mu}} = \frac{p_{i\mu} U_\mu}{U_p^2},$$

where $E_p$ and $E_i$ denote the photon energy at the point of emission from the primary source and at the point of incidence on the disc, respectively. $U_\mu$ is Keplerian four-velocity of the disc medium and $U_p^\mu$ is four-velocity of the primary source. The only non-zero component of the latter quantity is $U_p^\varphi = \sqrt{(h^2 + a^2) \Delta p}$.\n
Cosine of local incidence angle is

$$\mu_i = \left| \cos \delta_i \right| = \frac{p_{i\alpha} n^\alpha}{p_{i\mu} U_\mu},$$

where $n^\alpha = -e^{\alpha}_0(0, 0, -r^{-1}, 0)$ denotes normal direction to the disc in the co-moving frame of the disc medium. For explicit definition of the local tetrad $e^{\alpha}_0$ and further details, see Dovčiak et al. (2004b).

The reflection component has been computed by a Monte-Carlo code (Matt 1993). The number of reflected photons is proportional to the incident flux $N_p^i(E_p)$ arriving from the primary source,

$$N_p^i(E_p) = N_p^i(E_p) \frac{d\Omega_\sigma}{dS_\sigma},$$

where $N_p^i(E_p) = N_\sigma E_p^{-1}$ represents an isotropic and steady power-law primary emission that is emitted into solid angle $d\Omega$, and eventually illuminates the local area element $dS_\sigma$ on the disc. The ratio $d\Omega_\sigma/dS_\sigma$ is

$$d\Omega_\sigma = \frac{d\Omega_\sigma}{dS} \frac{dS}{dS_\sigma} = \sin \theta_0 d\theta_0 \frac{d\Omega}{d\Omega_\sigma} \frac{dS}{dS_\sigma},$$

where $d\Omega = r^{-2} (p_i^\theta)^{-1} dS_\perp$ is the element of coordinate area corresponding to proper area $dS_\perp$ perpendicular to the incident ray. The proper area projected onto the disc is

$$dS_\sigma = \frac{U_p^\varphi}{U_p^t} g_0 dS_\perp.$$

Only direct photon rays are considered in the present computations, indirect image photons being known to produce merely a marginal correction to the total signal under usual circumstances, i.e., a moderate inclination angle of the source. This is because luminosity of the successive images of the same source decreases exponentially with the order of the corresponding image (e.g. Luminet 1979). The contribution of indirect photons may be important only in case of a highly inclined (edge-on) disc system, in which case caustics play a role (Bao et al. 1994; Rauch & Blandford 1994).

It follows from equations (7)–(9) that the incident spectrum of the disc conforms to a power-law profile in energy with the same photon index $\Gamma$ as the original primary emission, i.e. $N_p^i(E) = N_\sigma E^{-\Gamma}$ with the normalization factor

$$N_\sigma = N_\sigma g_0^{-1} \left(1 - \frac{2h}{h^2 + a^2}\right)^{1/2} \frac{\sin \theta_0 d\theta_0}{r dr}.$$
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2.2 Gravity induced changes of polarization

The assumption of a geometrically thin accretion disc near a rotating black hole defines geometry of the system and metric of the space-time. The intrinsic polarization of emerging light can be then computed locally, assuming a plane-parallel scattering layer. This problem was studied extensively in various approximations (Chandrasekhar 1960; Sunyaev & Titarchuk 1985). Here we adopt the approach of Matt (1993) and we refer the reader to recent papers (Dovčiak et al. 2004b, c) for more details on the treatment of polarized light in strong gravitational fields.

Four Stokes parameters, $I_{\nu}$, $Q_{\nu}$, $U_{\nu}$ and $V_{\nu}$, entirely describe polarization properties of the scattered light. Hereafter we will distinguish the quantities that are determined
locally at the point of emission on the disc surface (denoted by index ‘loc’) and those relevant to a distant observer (index ‘o’). We introduce specific Stokes parameters,

\[
\begin{align*}
\hat{i}_\nu &= \frac{I_\nu}{E}, & q_\nu &= \frac{Q_\nu}{E}, & u_\nu &= \frac{U_\nu}{E}, & v_\nu &= \frac{V_\nu}{E},
\end{align*}
\]

and then specific Stokes parameters per energy bin, i.e. \(\Delta i_\nu, \Delta q_\nu, \Delta u_\nu\) and \(\Delta v_\nu\). The latter quantities are directly measurable, specifying the fluxes of photons with a given polarization. We can write

\[
\begin{align*}
\Delta i_o(E, \Delta E) &= N_0 \int dS \int dE_{\text{loc}} i_{\text{loc}}(E_{\text{loc}}) F, \\
\Delta q_o(E, \Delta E) &= N_0 \int dS \int dE_{\text{loc}} [q_{\text{loc}}(E_{\text{loc}}) \cos 2\Psi - u_{\text{loc}}(E_{\text{loc}}) \sin 2\Psi] F, \\
\Delta u_o(E, \Delta E) &= N_0 \int dS \int dE_{\text{loc}} [q_{\text{loc}}(E_{\text{loc}}) \sin 2\Psi + u_{\text{loc}}(E_{\text{loc}}) \cos 2\Psi] F, \\
\Delta v_o(E, \Delta E) &= N_0 \int dS \int dE_{\text{loc}} v_{\text{loc}}(E_{\text{loc}}) F.
\end{align*}
\]

Here, \(F \equiv F(r, \varphi) = g^2 l \mu e r\) is the transfer function, \(g^2\) being the total energy shift between observed and emitted photons, \(l\) the lensing effect, \(\mu\) the cosine of the emission angle, and \(\Psi\) the angle by which a vector rotates while it is parallally transported along the light geodesic. One can refer to \(\Psi\) as the gravity-induced change of polarization angle, because polarization vector is parallally transported along the light ray. The integration domain covers the X-rays emitting surface of the disc, \(r_{\text{in}} \leq r \leq r_{\text{out}}\). Notice that the local specific Stokes parameters may depend on \(r, \varphi\) and \(\mu\), which we do not state explicitly in eqs. (11–15) for simplicity but we take this dependency into account when integrating contributions to the observed values.

A complementary way of characterizing polarization is in terms of degree of polarization \(P_\circ\) and by two polarization angles \(\chi_\circ\) and \(\xi_\circ\):

\[
\begin{align*}
P_\circ &= \sqrt{q^2_\circ + u^2_\circ + v^2_\circ} / i_\circ, \\
\tan 2\chi_\circ &= u_\circ / q_\circ, \\
\sin 2\xi_\circ &= v_\circ / \sqrt{q^2_\circ + u^2_\circ + v^2_\circ}.
\end{align*}
\]

Unpolarized primary radiation was assumed and the approximation of single Rayleigh scattering was adopted in our examples hereby. The angular dependence of the local Stokes parameters is therefore given by eqs. (1.147) and (X.172) in Chandrasekhar (1960). See Matt (1993) and Dovčiak et al. (2004b) for discussion of the adopted approximation in the present context. The angle \(\xi_\circ\) characterizes the circular polarization and it vanishes in our case.

An explicit formula can be given for the angle \(\Phi_1\) between the projection of three-momentum of an incident photon (in the local rest-frame co-moving with the disc) and the radial vector,

\[
\Phi_1 = -R^1_o \arccos \left( \frac{-1}{\sqrt{1 - p_{\alpha}^2}} \frac{p_{\alpha} c_{\alpha}^2}{p_{\mu} U^\mu} \right) + \frac{\pi}{2},
\]

where \(R^1_o\) is positive for incident photons travelling outwards \((p^\mu_\parallel > 0)\) and it is negative in case of inward direction \((p^\mu_\parallel < 0)\). The \(\varphi\)-component of the local tetrad is \(c_{(\varphi)\alpha} = \sqrt{(-U^\varphi, 0, 0, U^\varphi)}\). Equation (19) appears in evaluation of local Stokes parameters (Chandrasekhar 1960).

Polarization of scattered light is shown in Figure 4 where we plot the polarization degree and the change of polarization angle as functions of \(h\) (we used a 14 points grid with \(h \leq 100\)). Notice that in the Newtonian case only polarization angles of 0° or 90° would be expected for symmetry reasons. The two panels in the figure correspond to different locations of the inner disc edge: \(r_{\text{in}} = 6\) and \(r_{\text{in}} = 1.20\), respectively. The curves are strongly sensitive to \(r_{\text{in}}\) and \(h\), while the dependence on \(r_{\text{out}}\) is weak for a large disc (here \(r_{\text{out}} = 400\)). Sensitivity to \(r_{\text{in}}\) is particularly appealing if one remembers practical difficulties in estimating \(r_{\text{in}}\) by fitting spectra. The effect is clearly visible even for \(h \sim 20\). Graphs corresponding to \(r_{\text{in}} = 6\) and \(a = 0.999\), resemble, in essence quite closely, the non-rotating case \((a = 0)\) because dragging effects are most prominent near horizon.

Figure 4 shows the polarization degree and angle as functions of the observer’s inclination. Again, by comparing the two cases of different \(r_{\text{in}}\) one can appreciate how sensitive polarization is to details of the flow near the inner disc boundary. Furthermore, it is worth noticing that the polarization degree has a local maximum for moderate inclination angles \((\mu_\circ \sim 0.9)\). This peak occurs mainly due to interplay between the intrinsic polarization on the disc and special-relativistic aberration of the outgoing photons, while general relativistic effects are shaping details of the profile.

The above-described polarization features are representative of the scattering mechanism and the gravitational field structure acting on reflected photons. However, in order to compute directly observable characteristics one has to combine the primary continuum with the reflected component. Polarization degree of the resulting signal depends on mutual proportion of the two components and also on the energy range of observation. In Figure 4 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 dilution of primary light by factor \(~g_h^2(h, \theta_3) I_h(h, \theta_3)\), where \(g_h = \sqrt{1 - 2h/(a^2 + h^2)}\) is the redshift of primary photons reaching directly the observer. The whole term is a combination of special-relativistic transformation and general-relativity light bending (factor \(I_h\) is order of unity and can be safely ignored here; cf. Dovčiak et al. 2004b). 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 influence as long as primary light is itself unpolarized.

3 CONCLUSIONS

We examined the polarimetric properties of X-ray illuminated accretion discs in the lamp-post model. We found that observed values of Stokes parameters are expected to be rather sensitive of the model parameters. The adopted approach provides additional information with respect to traditional spectroscopy, and so it has a 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. Our calcula-
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Figure 3. Net polarization degree of the total (primary plus reflected) signal as a function of height $h$ (left panel) and a function of $\mu_o$ (right panel). In each panel, curves are parametrized by the corresponding energy range.

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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 degree of the order of one percent in bright AGN, making polarimetry, along with timing and spectroscopy, a tool for exploring the properties of the accretion flows in the vicinity of black holes.

tions are complementary to those of Laor et al. (1990), where the general relativity induced change of polarization angle and degree were computed for the disc thermal emission.

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. Complete time-resolved analysis (including all consequences of the light travel time in curved space-time) is beyond the scope of this paper and we defer it to future work, assuming here that the primary source varies on a time-scale longer than the light-crossing time in the system. This is a well-substantiated assumption also from a practical point of view, since feasible techniques will anyway require sufficient integration time (i.e. of the order of several ksec). Here, suffice it to note that a variation of $h$ implies a variation of the observed polarization angle of the reflected radiation. Although the change of polarization angle and the degree of polarization are sensitive to general relativity effects, to certain degree they depend also on other assumptions about the source geometry and local physics of the source. However, it should be obvious that time-resolved polarimetry can set constraints on the models that are substantially more stringent than what can be achieved by pure spectroscopy.

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