Polarization of AGN accretion discs in lamp-post model with strong gravity in Compton scattering approximation

M. Dovčiak[1] V. Karas[1,2] G. Matt[3]

[1] Astronomical Institute
Academy of Sciences of the Czech Republic

[2] Faculty of Mathematics and Physics
Charles University Prague

[3] Dipartimento di Fisica
Università degli Studi "Roma Tre"

Radiative (magneto)hydrodynamical seminar
2nd June 2005

Outline

Motivation

- X-ray observations of AGN and galactic BHs

Polarization in lamp-post model of the accreting black hole

- The lamp-post model
- Parallel transport of the polarization vector
- Definition and meaning of the Stokes parameters
- Local Stokes parameters in Compton scattering approximation
- Observed Stokes parameters and polarization

Results

- Observed polarization angle and degree

Summary

X-ray observations of AGN and galactic BHs

Observed photon flux often shows

- relativistically broadened Kα iron line
- narrow-line features in 5 – 6 keV range

Possible explanation

- emission from the accretion disc illuminated by X-rays emitted by the disc's corona
- emission from orbiting spots illuminated by flares

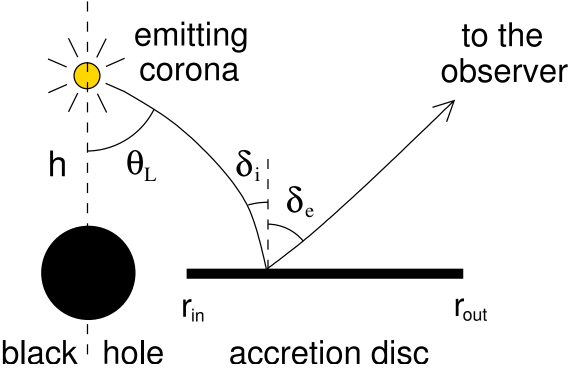
X-ray observations of AGN and galactic BHs

Measurement of the system properties

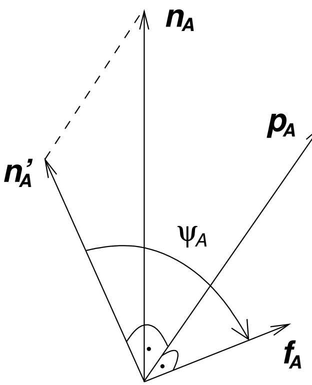
- black hole mass
- spin of the black hole
- inclination of the system
- emission region

Reflection of X-rays from the matter in the disc
$\longrightarrow$ polarization of the observed flux!

The lamp-post model

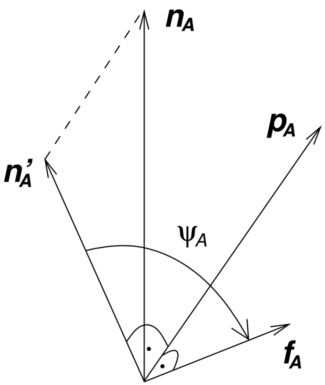


Definition of the change of the polarization angle



- p_A – 3-momentum of a photon
- n_A – normal to the disc
- n'_A – projection of n_A to the plane perpendicular to p_A,
- f_A – vector which is parallelly transported along the geodesic (as 4-vector)
- Ψ_A – angle between n'_A and f_A

Definition of the change of the polarization angle

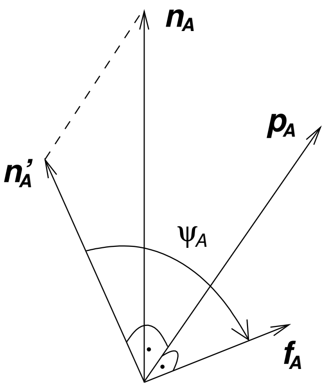


- p_A – 3-momentum of a photon
- n_A – normal to the disc
- n'_A – projection of n_A to the plane perpendicular to p_A,
- f_A – vector which is parallelly transported along the geodesic (as 4-vector)
- Ψ_A – angle between n'_A and f_A

All the quantities are evaluated

- at the disc with respect to the local rest frame co-moving with the disc for $A = 1$
- at infinity with respect to the stationary observer at the same light geodesic for $A = 2$

Definition of the change of the polarization angle



$$\Psi = \Psi_2 - \Psi_1$$

- p_A – 3-momentum of a photon
- n_A – normal to the disc
- n'_A – projection of n_A to the plane perpendicular to p_A,
- f_A – vector which is parallelly transported along the geodesic (as 4-vector)
- Ψ_A – angle between n'_A and f_A

All the quantities are evaluated

- at the disc with respect to the local rest frame co-moving with the disc for $A = 1$
- at infinity with respect to the stationary observer at the same light geodesic for $A = 2$

The change of the polarization angle

Connors & Stark 1977; Connors, Piran & Stark 1980:

$$\boxed{\tan\Psi = \frac{Y}{X}} \qquad \begin{aligned} X &= -(\alpha - a\sin\theta_o)\kappa_1 - \beta\kappa_2 \\ Y &= (\alpha - a\sin\theta_o)\kappa_2 - \beta\kappa_1 \end{aligned}$$

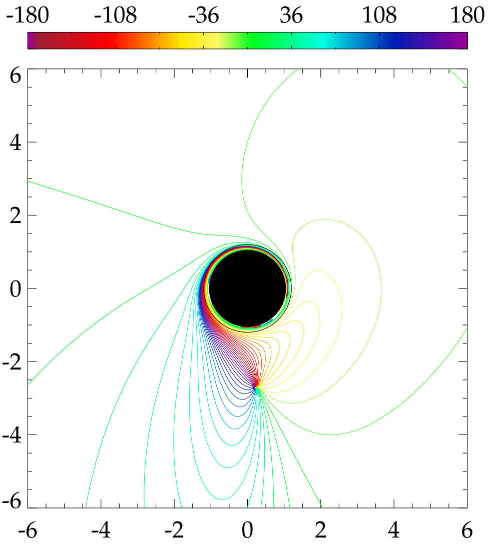
$\kappa_1,\ \kappa_2$ – components of the complex constant of motion κ_{pw} (see Walker & Penrose 1970)

$$\begin{aligned} \kappa_1 &= a\,r\,p_e^\theta f^t - r\,[a p_e^t - (r^2+a^2)\,p_e^\varphi]f^\theta - r(r^2+a^2)\,p_e^\theta f^\varphi \\ \kappa_2 &= -r\,p_e^r f^t + r\,[p_e^t - a p_e^\varphi]f^r + a\,r\,p_e^r f^\varphi \end{aligned}$$

f^μ corresponds to the 3-vector f_1 which is chosen in such a way that it is a unit vector parallel with n_1' (i.e. $\Psi_1 = 0$)

$$f^\mu = \frac{n^\mu - \mu_e\left(g\,p_e^\mu - U^\mu\right)}{\sqrt{1-\mu_e^2}}\,.$$

The change of the polarization angle



$a = 0.9987$

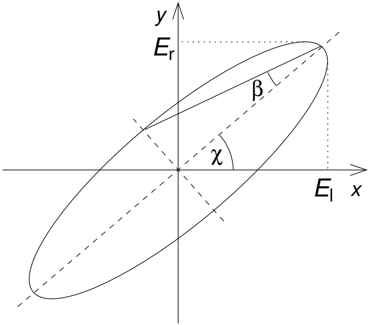
$r_{\mathrm{h}} = 1.05$

$r_{\mathrm{ms}} = 1.20$

$\theta_{\mathrm{o}} = 70^{\circ}$

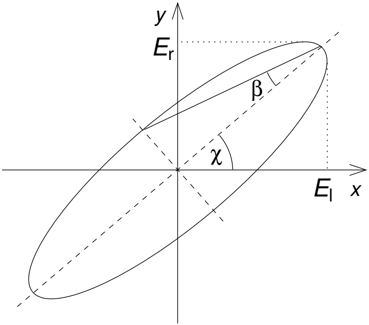
Definition of the Stokes parameters

$$
\begin{aligned}
E_{\mathrm{x}} &= E_{\mathrm{l}} \sin(\omega t - \varphi_{\mathrm{l}}) \\
E_{\mathrm{y}} &= E_{\mathrm{r}} \sin(\omega t - \varphi_{\mathrm{r}}) \\
\delta &= \varphi_{\mathrm{l}} - \varphi_{\mathrm{r}}
\end{aligned}
$$



Definition of the Stokes parameters

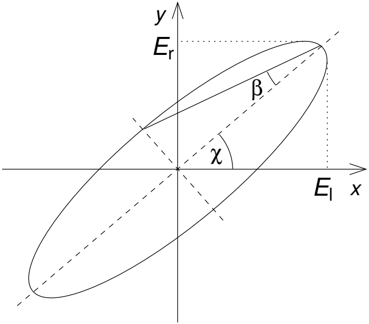
$$
\begin{aligned}
E_\mathrm{x} &= E_\mathrm{l} \sin(\omega t - \varphi_\mathrm{l}) \\
E_\mathrm{y} &= E_\mathrm{r} \sin(\omega t - \varphi_\mathrm{r}) \\
\delta &= \varphi_\mathrm{l} - \varphi_\mathrm{r}
\end{aligned}
$$



$$
\begin{aligned}
I &\equiv E_\mathrm{x}^2 + E_\mathrm{y}^2 = I_\mathrm{l} + I_\mathrm{r} \\
Q &\equiv E_\mathrm{x}^2 - E_\mathrm{y}^2 = I_\mathrm{l} - I_\mathrm{r} \\
&= I \cos 2\chi \cos 2\beta \\
U &\equiv 2E_\mathrm{x}E_\mathrm{y} \cos\delta \\
&= (I_\mathrm{l} - I_\mathrm{r}) \tan 2\chi \\
&= I \sin 2\chi \cos 2\beta \\
V &\equiv 2E_\mathrm{x}E_\mathrm{y} \sin\delta \\
&= (I_\mathrm{l} - I_\mathrm{r}) \frac{\tan 2\beta}{\cos 2\chi} \\
&= I \sin 2\beta
\end{aligned}
$$

Definition of the Stokes parameters

$$E_x = E_l \sin(\omega t - \varphi_l)$$
$$E_y = E_r \sin(\omega t - \varphi_r)$$
$$\delta = \varphi_l - \varphi_r$$



$$I \equiv \langle E_x^2 \rangle_t + \langle E_y^2 \rangle_t = I_l + I_r$$

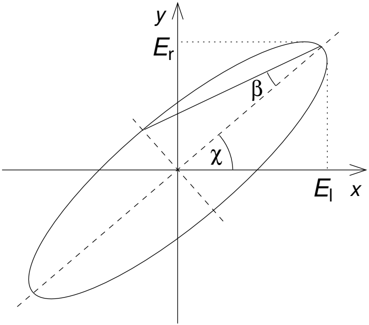
$$\begin{aligned} Q &\equiv \langle E_x^2 \rangle_t - \langle E_y^2 \rangle_t = I_l - I_r \\ &= PI \cos 2\chi \cos 2\beta \end{aligned}$$

$$\begin{aligned} U &\equiv \langle 2 E_x E_y \cos \delta \rangle_t \\ &= (I_l - I_r) \tan 2\chi \\ &= PI \sin 2\chi \cos 2\beta \end{aligned}$$

$$\begin{aligned} V &\equiv \langle 2 E_x E_y \sin \delta \rangle_t \\ &= (I_l - I_r) \frac{\tan 2\beta}{\cos 2\chi} \\ &= PI \sin 2\beta \end{aligned}$$

Definition of the Stokes parameters

$$
\begin{aligned}
E_x &= E_l \sin(\omega t - \varphi_l) \\
E_y &= E_r \sin(\omega t - \varphi_r) \\
\delta &= \varphi_l - \varphi_r
\end{aligned}
$$



$$
\begin{aligned}
I &\equiv \langle E_x^2 \rangle_t + \langle E_y^2 \rangle_t = I_l + I_r \\
Q &\equiv \langle E_x^2 \rangle_t - \langle E_y^2 \rangle_t = I_l - I_r \\
&= PI \cos 2\chi \cos 2\beta \\
U &\equiv \langle 2 E_x E_y \cos\delta \rangle_t \\
&= (I_l - I_r) \tan 2\chi \\
&= PI \sin 2\chi \cos 2\beta \\
V &\equiv \langle 2 E_x E_y \sin\delta \rangle_t \\
&= (I_l - I_r) \frac{\tan 2\beta}{\cos 2\chi} \\
&= PI \sin 2\beta
\end{aligned}
$$

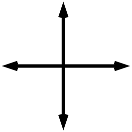
$$
P = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}, \quad \tan 2\chi = \frac{U}{Q}, \quad \sin 2\beta = \frac{V}{\sqrt{Q^2 + U^2 + V^2}}
$$

Meaning of the Stokes parameters

- linear polarization in the direction of x or y axes

  $P = 1, \quad \beta = 0, \quad \chi = 0 \quad \text{or} \quad \chi = \pi/2$

  $$\Rightarrow \quad \boxed{Q = \pm I, \quad U = 0, \quad V = 0}$$

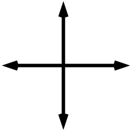


Meaning of the Stokes parameters

- linear polarization in the direction of x or y axes

  $P = 1, \quad \beta = 0, \quad \chi = 0 \quad \text{or} \quad \chi = \pi/2$

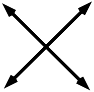
  $$\Rightarrow \quad \boxed{Q = \pm I, \quad U = 0, \quad V = 0}$$



- linear polarization in the direction forming an angle of $\pm 45^\circ$ with the x axis

  $P = 1, \quad \beta = 0, \quad \chi = \pm\pi/4$

  $$\Rightarrow \quad \boxed{Q = 0, \quad U = \pm I, \quad V = 0}$$

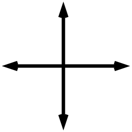


Meaning of the Stokes parameters

- linear polarization in the direction of x or y axes

  $P = 1, \quad \beta = 0, \quad \chi = 0 \quad \text{or} \quad \chi = \pi/2$

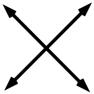
  $\Rightarrow \quad \boxed{Q = \pm I, \quad U = 0, \quad V = 0}$



- linear polarization in the direction forming an angle of $\pm 45^\circ$ with the x axis

  $P = 1, \quad \beta = 0, \quad \chi = \pm\pi/4$

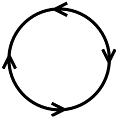
  $\Rightarrow \quad \boxed{Q = 0, \quad U = \pm I, \quad V = 0}$



- circular polarization (counter-clockwise or clockwise)

  $P = 1, \quad \beta = \pm\pi/4, \quad \chi \; - \;$ arbitrary

  $\Rightarrow \quad \boxed{Q = 0, \quad U = 0, \quad V = \pm I}$



Local Stokes parameters in Compton scattering approximation

$$I(E) = \frac{I_l^c + I_r^c}{\langle I_l^c + I_r^c \rangle} N(E)E \qquad Q(E) = \frac{I_l^c - I_r^c}{\langle I_l^c + I_r^c \rangle} N(E)E$$

$$U(E) = \frac{U^c}{\langle I_l + I_r \rangle} N(E)E \qquad V = 0$$

- I_l^c, I_r^c and U^c are Stokes coefficients for Rayleigh scattering in single scattering approximation (Chandrasekhar 1960)
- $N(E)$ is photon flux computed by Monte Carlo simulations of the multiple Compton scattering (Matt, Perola & Piro 1991)

Local Stokes parameters in Compton scattering approximation

$$
\begin{aligned}
I_l^c &= \mu_e^2(1+\mu_i^2) + 2(1-\mu_e^2)(1-\mu_i^2) \\
&\quad -4\mu_e\mu_i\sqrt{(1-\mu_e^2)(1-\mu_i^2)}\cos(\Phi_e-\Phi_i) \\
&\quad -\mu_e^2(1-\mu_i^2)\cos[2(\Phi_e-\Phi_i)]
\end{aligned}
$$

$$
I_r^c = 1+\mu_i^2+(1-\mu_i^2)\cos[2(\Phi_e-\Phi_i)]
$$

$$
\begin{aligned}
U^c &= -4\mu_i\sqrt{(1-\mu_e^2)(1-\mu_i^2)}\sin(\Phi_e-\Phi_i) \\
&\quad -2\mu_e(1-\mu_i^2)\sin[2(\Phi_e-\Phi_i)]
\end{aligned}
$$

Local Stokes parameters in Compton scattering approximation

$$
\begin{aligned}
I_{\mathrm{l}}^{\mathrm{c}} &= \mu_{\mathrm{e}}^2(1+\mu_{\mathrm{i}}^2)+2(1-\mu_{\mathrm{e}}^2)(1-\mu_{\mathrm{i}}^2) \\
&\quad -4\mu_{\mathrm{e}}\mu_{\mathrm{i}}\sqrt{(1-\mu_{\mathrm{e}}^2)(1-\mu_{\mathrm{i}}^2)}\cos(\Phi_{\mathrm{e}}-\Phi_{\mathrm{i}}) \\
&\quad -\mu_{\mathrm{e}}^2(1-\mu_{\mathrm{i}}^2)\cos[2(\Phi_{\mathrm{e}}-\Phi_{\mathrm{i}})]
\end{aligned}
$$

$$
I_{\mathrm{r}}^{\mathrm{c}} = 1+\mu_{\mathrm{i}}^2+(1-\mu_{\mathrm{i}}^2)\cos[2(\Phi_{\mathrm{e}}-\Phi_{\mathrm{i}})]
$$

$$
\begin{aligned}
U^{\mathrm{c}} &= -4\mu_{\mathrm{i}}\sqrt{(1-\mu_{\mathrm{e}}^2)(1-\mu_{\mathrm{i}}^2)}\sin(\Phi_{\mathrm{e}}-\Phi_{\mathrm{i}}) \\
&\quad -2\mu_{\mathrm{e}}(1-\mu_{\mathrm{i}}^2)\sin[2(\Phi_{\mathrm{e}}-\Phi_{\mathrm{i}})]
\end{aligned}
$$

$$
N(E) = g_{\mathrm{L}}^{\Gamma-1}\frac{\sin\theta_{\mathrm{L}}\,\mathrm{d}\theta_{\mathrm{L}}}{r\,\mathrm{d}r}\sqrt{1-\frac{2h}{h^2+a^2}}\,f(E;\mu_{\mathrm{i}},\mu_{\mathrm{e}})
$$

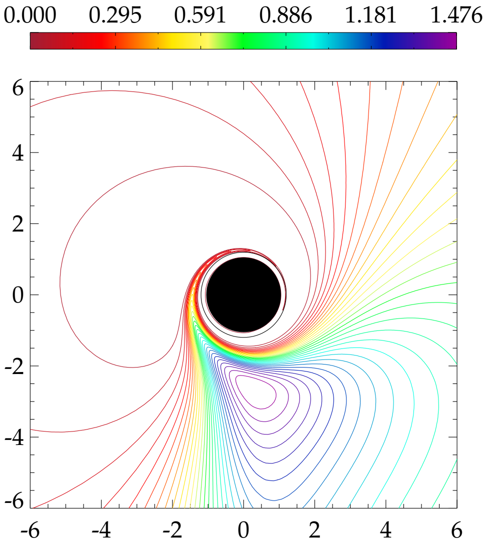
Integration of the Stokes parameters

$$\begin{aligned}
\Delta I_\mathrm{o}(E,\Delta E) &= \int \mathrm{d}S\, F \int \mathrm{d}E\, I(E) \\
\Delta Q_\mathrm{o}(E,\Delta E) &= \int \mathrm{d}S\, F \int \mathrm{d}E\, [Q(E)\cos 2\Psi - U(E)\sin 2\Psi] \\
\Delta U_\mathrm{o}(E,\Delta E) &= \int \mathrm{d}S\, F \int \mathrm{d}E\, [Q(E)\sin 2\Psi + U(E)\cos 2\Psi] \\
\Delta V_\mathrm{o}(E,\Delta E) &= \int \mathrm{d}S\, F \int \mathrm{d}E\, V(E)
\end{aligned}$$

$\mathrm{d}S \equiv r\,\mathrm{d}r\,\mathrm{d}\varphi$

$\boxed{F \equiv F(r,\varphi) \equiv g^3\, l\, \mu_\mathrm{e}}$ – transfer function

Transfer function



$a = 0.9987$

$r_h = 1.05$

$r_{ms} = 1.20$

$\theta_o = 70^\circ$

Adding primary radiation

Photon flux from the primary source:

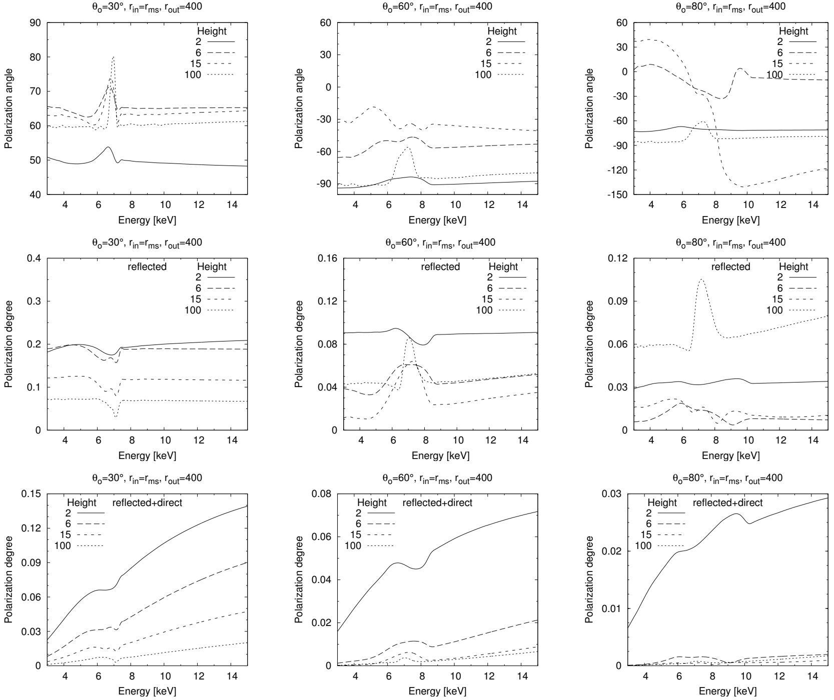
$$N_\mathrm{d}(E) \equiv \frac{\mathrm{d}n_\mathrm{d}(E)}{\mathrm{d}t\,\mathrm{d}\Omega} = g_\mathrm{h}^{2-\Gamma} I\, E^{-\Gamma}$$

$$g_\mathrm{h} = \sqrt{1 - \frac{2h}{a^2+h^2}}\,, \quad I \sim \text{only a few percent}$$

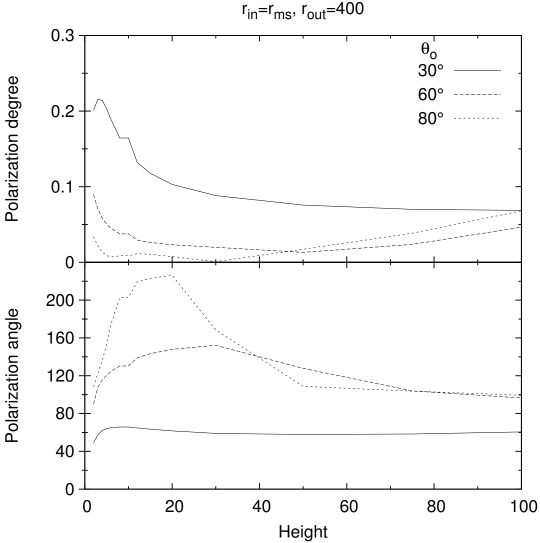
Total intensity measured:

$$I_\mathrm{t} = I + I_\mathrm{d}\,, \quad I_\mathrm{d} = E N_\mathrm{d}$$

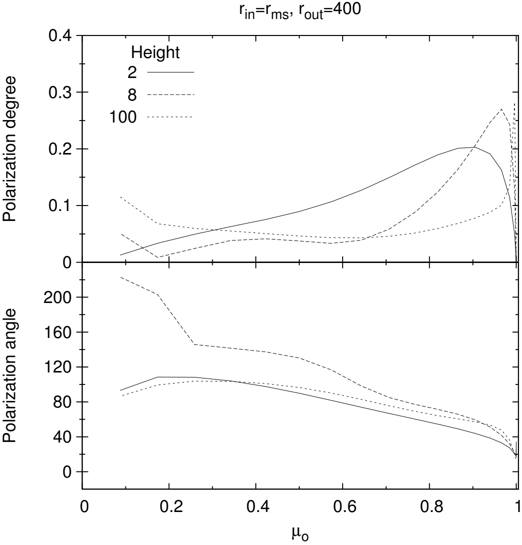
Primary radiation is unpolarized $\Rightarrow$ other Stokes parameters are unchanged $\Rightarrow$ angle of polarization is unchanged


θ_o=30°, r_{in}=r_{ms}, r_{out}=400
θ_o=60°, r_{in}=r_{ms}, r_{out}=400
θ_o=80°, r_{in}=r_{ms}, r_{out}=400
Polarization angle
Polarization degree
Energy [keV]
reflected
reflected+direct
Height
2
6
15
100

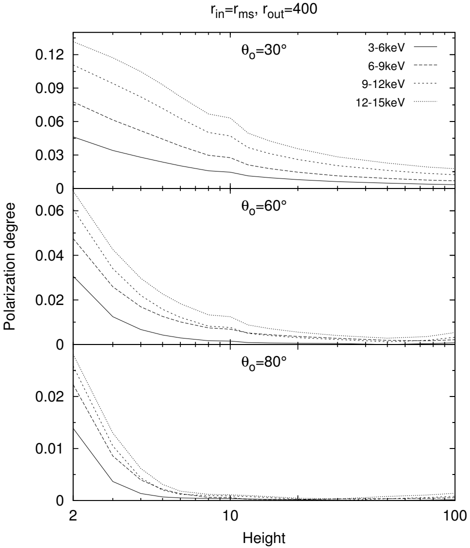
Polarization from the reflected radiation



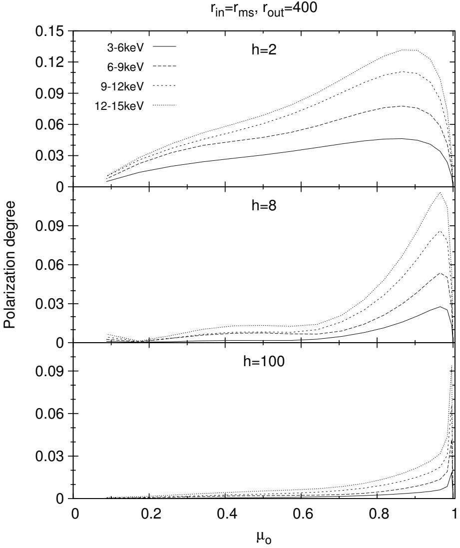
Polarization from the reflected radiation



Polarization from the direct + reflected radiation



Polarization from the direct + reflected radiation



Summary

- degree of polarization is increasing with energy (in the studied energy range)
- iron edge is visible in energy dependence of degree and angle of polarization
- high dependence of angle and degree of polarization on height of the primary source and on the inclination of the observer

- Outlook
  - investigate the dependence of the polarization on the spin of the black hole

Publications

- Dovčiak M., Karas V. & Matt G. (2004). Polarization signatures of strong gravity in active galactic nuclei accretion discs. *MNRAS*, 355, 1005.

- Dovčiak M. (2004). Radiation of Accretion Discs in Strong Gravity. *PhD thesis*, Faculty of Mathematics and Physics, Charles University, Prague, astro-ph/0411605

Publications

- Chandrasekhar S. (1960). Radiative transfer. Dover publications, New York.
- Connors P. A., Piran T. & Stark R. F. (1980). Polarization features of X-ray radiation emitted near black holes. *ApJ*, 235, 224.
- Connors P. A. & Stark R. F. (1977). Observable gravitational effects on polarised radiation coming from near a black hole. *Nature*, 269, 128.
- Matt G., Perola G. C. & Piro L. (1991). The iron line and high energy bump as X-ray signatures of cold matter in Seyfert 1 galaxies. *A&A*, 247, 25.
- Walker M. & Penrose R. (1970). On quadratic first integrals of the geodesic equations for type 22 space-times. *Commun. Math. Phys.*, 18, 265.