On polarization from radiativelly accelerated flows

Jiří Horák & Vladimír Karas

9.11.2006

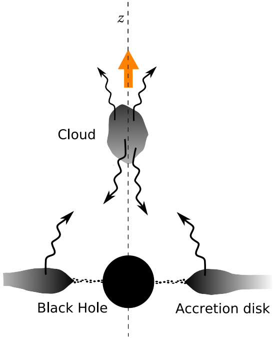
Outline

- Introduction
- Polarization and Thomson scattering
  - $\longrightarrow$ Stokes parameters
  - $\longrightarrow$ Derivation of the formulae
- Simple applications
  - $\longrightarrow$ Isotropic radiation field
  - $\longrightarrow$ Change of the polarization direction
  - $\longrightarrow$ Scattering on hot clouds
- Scattering on hot clouds above the accretion disk
  - $\longrightarrow$ Cloud dynamics
  - $\longrightarrow$ Scattered radiation
  - $\longrightarrow$ Effects of general relativity

External Compton scattering in jets

Dynamical influence:

- Noerdlinger (1974), O'Dell (1981):
  $\longrightarrow$ Radiation pressure accelerates jets
- Phinney (1982), Sikora et al. (1996):
  $\longrightarrow$ The net effect is rather deceleration
  $\longrightarrow$ Equilibrium (saturation) velocity
  $\longrightarrow$ Terminal Lorentz factors $\Gamma \sim 10$
- Renaud & Henri (1998):
  $\longrightarrow$ Compton scattering.



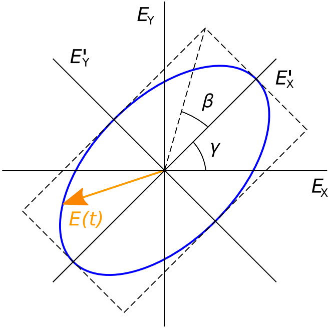
Scattered radiation:

- Highly blue-shifted and polarized (Begelman & Shikora, 1987)
- Important component of Blazars and GRBs (Lazzati 2004)

Stokes parameters

Definition (Rybicki & Lightman, 1979):

$$
\begin{aligned}
I &\equiv \langle \mathcal{E}_X^2 + \mathcal{E}_Y^2 \rangle \\
Q &\equiv \langle \mathcal{E}_X^2 - \mathcal{E}_Y^2 \rangle = I \cos 2\beta \, \cos 2\chi, \\
U &\equiv 2\langle \mathcal{E}_X \mathcal{E}_Y \cos(\phi_Y - \phi_X) \rangle = I \cos 2\beta \, \sin 2\beta, \\
V &\equiv 2\langle \mathcal{E}_X \mathcal{E}_Y \sin(\phi_Y - \phi_X) \rangle = I \sin 2\beta
\end{aligned}
$$

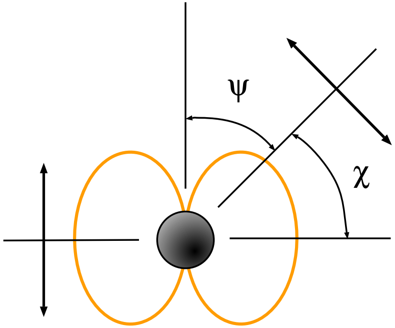


- Q and U depends on $\{X, Y\}$
- Linear polarization: $\beta = V = 0$
- Degree of polarization:

$$\Pi \equiv \frac{\sqrt{Q^2 + U^2 + V^2}}{I}.$$

Electron scattering (Thomson)

Dipole radiation (Rybicki & Lightman, 1979):



- Polarized incident wave:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) \propto \sin^2\psi$$

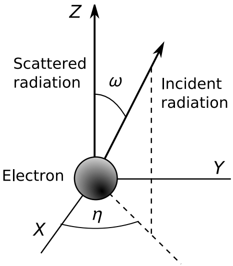
- Unpolarized incident wave:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right) \propto 1+\cos^2\chi$$

Scattered radiation and degree of the *linear* polariation:

$$I \propto 1+\cos^2\chi, \quad Q \propto 1-\cos^2\chi, \quad U = 0, \quad \boxed{\Pi = \frac{1-\cos^2\chi}{1+\cos^2\chi}}$$

General radiation field



Scattering photons from arbitrary direction

$$\vec{n} = (\sin\omega\cos\eta,\ \sin\omega\sin\eta,\ \cos\omega)$$

$$I = AI_{\rm i}(1+\cos^2\omega) = A\left(1 + n_{\rm i}^Z n_{\rm i}^Z\right) I_{\rm i}$$

$$Q = -AI_{\rm i}\cos 2\eta\,\sin^2\omega = A\left(n_{\rm i}^Y n_{\rm i}^Y - n_{\rm i}^X n_{\rm i}^X\right) I_{\rm i}$$

$$U = -AI_{\rm i}\sin 2\eta\,\sin^2\omega = -2A\,n_{\rm i}^X n_{\rm i}^Y I_{\rm i}$$

Integration over incident direction (Horák & Karas, 2006a):

$$\bar{I} = A\left(\bar{T}^{tt} + \bar{T}^{ZZ}\right), \quad \bar{Q} = A\left(\bar{T}^{YY} - \bar{T}^{XX}\right), \quad \bar{U} = -2A\bar{T}^{XY}$$

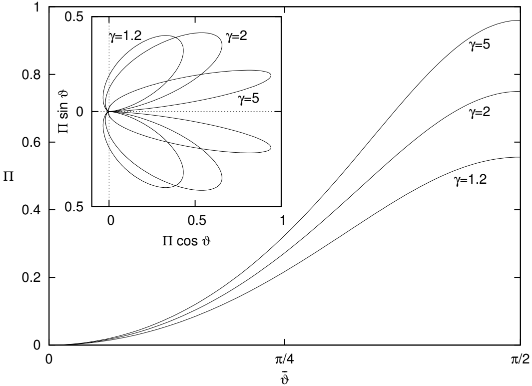
$T^{\alpha\beta}$ ... relativistic radiative stress-energy tensor

Scattering on moving electrons

Axisymmetric radiative field, motion along the axis

$$\begin{aligned}\bar{I} &= \tfrac{1}{2}A\left[\left(3\bar{T}^{tt}-\bar{T}^{zz}\right)-\left(\bar{T}^{tt}-3\bar{T}^{zz}\right)\cos^2\bar{\vartheta}\right]\\ \bar{Q} &= \tfrac{1}{2}A\left(\bar{T}^{tt}-3\bar{T}^{zz}\right)\sin^2\bar{\vartheta}.\\ \bar{V} &= 0\end{aligned}$$

Isotropic external radiation field (Lazzati 2004):

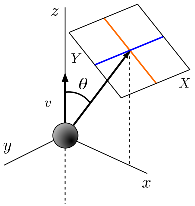


$$\Pi(\bar{\theta}) = \frac{|\Pi_{\rm m}|\sin^2\bar{\vartheta}}{1-\Pi_{\rm m}\cos^2\bar{\vartheta}}$$

$$\Pi_{\rm m} \equiv \frac{\bar{T}^{tt}-3\bar{T}^{zz}}{3\bar{T}^{tt}-\bar{T}^{zz}}$$

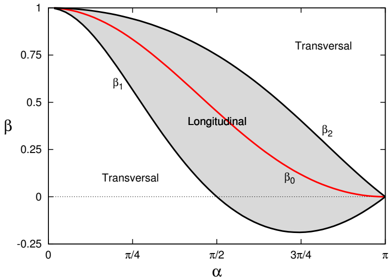
Change of the polarization direction

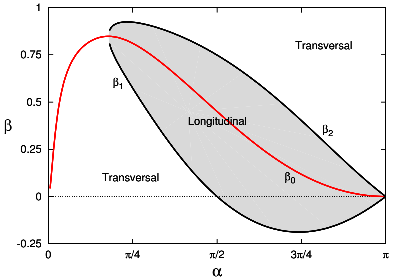
Polarization direction depends on sign of $Q \propto (\bar{T}^{tt} - 3\bar{T}^{zz})$



$$\left(1 - 3\beta^2\right) T^{tt} + 4\beta T^{tz} + \left(\beta^2 - 3\right) T^{zz} = 0$$

$$\beta_{1,2} = a \pm \sqrt{a^2 + b}, \quad a \equiv \frac{2T^{tz}}{3T^{tt} - T^{zz}}, \quad b \equiv \frac{T^{tt} - 3T^{zz}}{3T^{tt} - T^{zz}}$$





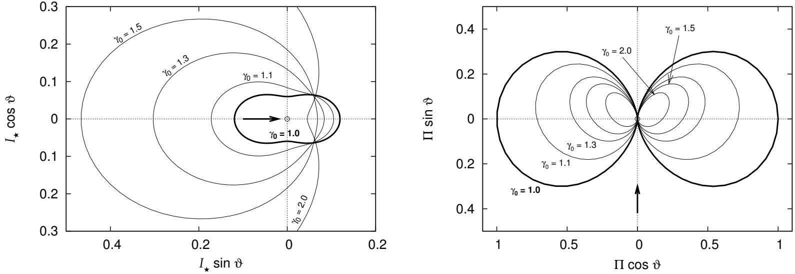
Scattering on hot electrons

Isotropic electron distribution: $n(\vec{\beta}_\mathrm{e}) = n_\mathrm{e} f(\gamma_\mathrm{e})$ (Horák, 2006):

$$I = A\left[(1+\mathcal{A})\left(T^{tt} + T^{ZZ}\right) + \mathcal{B}\left(T^{tt} - 3T^{ZZ}\right) - 2\mathcal{A}T^{tZ}\right]$$

where

$$\mathcal{A} \equiv \left\langle \tfrac{4}{3}\gamma_\mathrm{e}^2\beta_\mathrm{e}^2 \right\rangle, \quad \mathcal{B} \equiv 1 - \left\langle \frac{\ln[\gamma_\mathrm{e}(1+\beta_\mathrm{e})]}{\beta_\mathrm{e}\gamma_\mathrm{e}^2} \right\rangle$$



Gravitational and radiation fields

Gravitational field = Schwarzschild solution

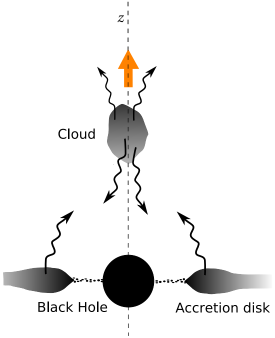
$$\mathrm{d}s^2 = -\xi \mathrm{d}t^2 + \xi^{-1}\mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\phi^2), \quad \xi \equiv 1 - \frac{R}{R_\mathrm{S}}$$

Radiation field (Shakura & Sunyaev 1972)

$$I_\mathrm{d}(r) = \frac{mc^3}{\sigma_\mathrm{T} R_\mathrm{S}} \Lambda I_{\mathrm{d}\star},$$

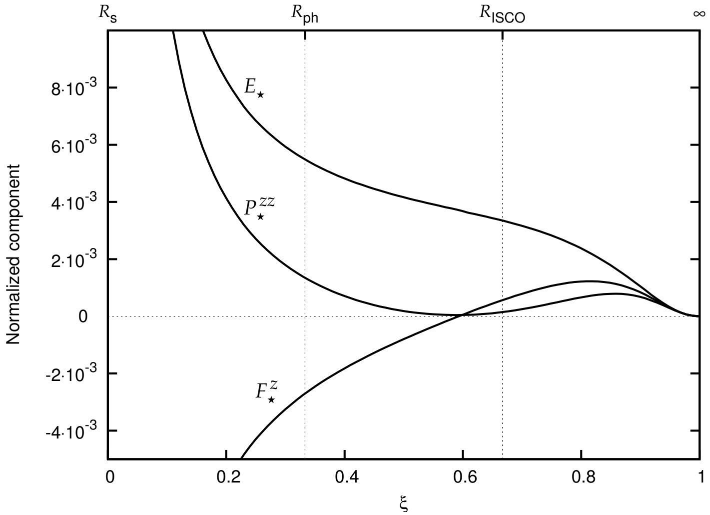
→ Normalized disk luminosity and intensity

$$\Lambda \equiv \frac{L}{L_\mathrm{Edd}}, \quad I_{\mathrm{d}\star} = \frac{6R_\mathrm{in}}{r^3}\left(1 - \sqrt{\frac{R_\mathrm{in}}{r}}\right),$$



Radiation stress-energy tensor

Values on the z-axis (Horák & Karas 2006b):



Dynamics of clouds

Equation of motion:

$$F^\alpha = \frac{\mathrm{D}p^\alpha}{\mathrm{D}s} = m_\mathrm{e} n_\mathrm{e} V \left(u^\alpha \frac{\mathrm{d}\bar{\gamma}_\mathrm{e}}{\mathrm{d}s} + \bar{\gamma}_\mathrm{e} a^\alpha \right)$$

The radiation four-force:

$$F^\alpha = n_\mathrm{e} V \langle f^\alpha \rangle = -\sigma_\mathrm{T} n_\mathrm{e} V \left[\mathcal{C} T^{\alpha\beta} u_\beta - (\mathcal{A} + \mathcal{C}) T^{\rho\sigma} u_\rho u_\sigma u^\alpha \right],$$

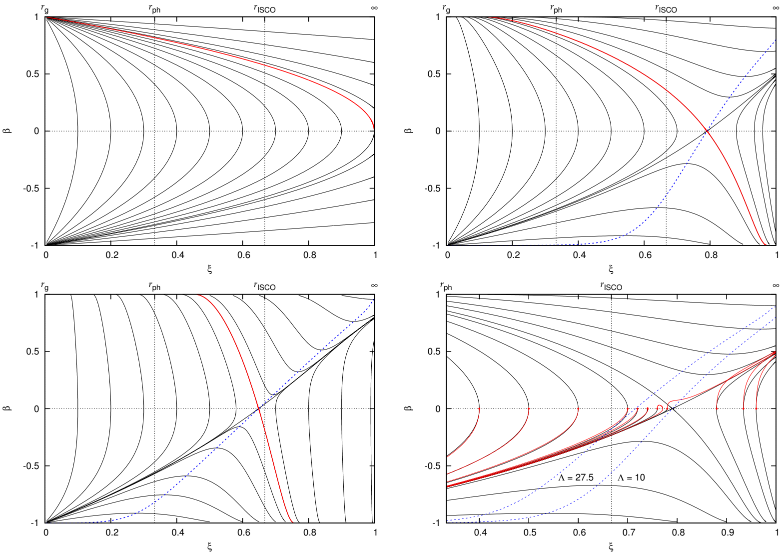
$$\mathcal{C} \equiv 1 + 2/3 \langle \gamma_\mathrm{e}^2 \beta_\mathrm{e}^2 \rangle$$

Governing equations:

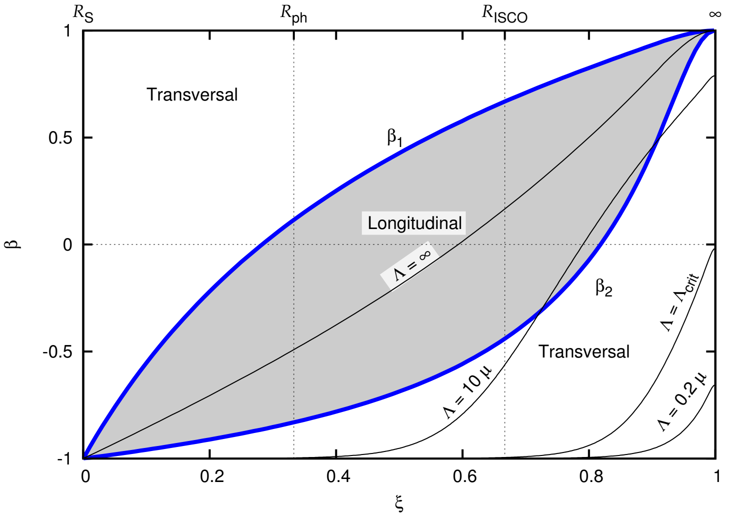
$$\frac{\mathrm{d}\bar{\gamma}_\mathrm{e}}{\mathrm{d}s} = -\gamma \mathcal{A} \Lambda \left[T_\star^{(t)(t)} - 2\beta T_\star^{(t)(z)} + \beta^2 T_\star^{(z)(z)} \right],$$

$$\frac{\mathrm{d}\beta}{\mathrm{d}s} = \frac{1}{\bar{\gamma}_\mathrm{e}} \mathcal{C} \Lambda \left[(1 + \beta^2) T_\star^{(t)(z)} - \left(T_\star^{(t)(t)} + T_\star^{(z)(z)} \right) \beta \right] - \frac{R_\mathrm{S}}{2\gamma z^2 \xi^{1/2}}$$

Cold and hot clouds

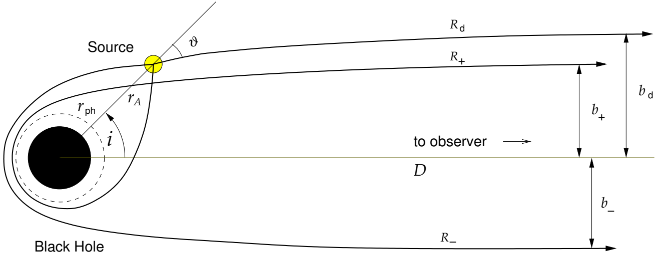


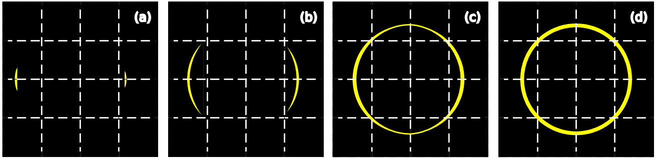
Polarization direction



Contribution of higher-order images

Under suitable conditions, grav. lensing becomes important...





Example light-curves