X-ray polarization and the physics of compact objects

René W. Goosmann

A review talk at the Second Ferrara workshop

X-ray Astrophysics up to 511 keV

16th September 2011

Ferrara, Italy
OUTLINE

Why should we care about polarization?
A quick warm-up about polarization of EM radiation
Measuring X-ray polarization
Polarization induced in accretion flows
Polarization induced in ejection flows
Conclusions and perspectives
Why should we care about (X-ray) polarization?

We practice observational astronomy *mainly* based on electromagnetic (EM) radiation. The EM radiation tells us about its emission processes and its interactions with matter.

The information is usually exploited as a function of wavelength, time, and space → *(time-resolved)* spectroscopy and imaging.
Why should we care about (X-ray) polarization?

**BUT:** almost any interaction of EM radiation with matter also **modifies its polarization state!**

**ERGO:** Considering the polarization state of light gives us a set of **two additional, independent observables** as a function of photon wavelength, time, and space.

Inglis et al. 1995
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The polarization ellipse

The linear polarization degree $P$ is defined by

$$ P = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}. $$

Note: $0 \leq P \leq 1$.

Herein, $I_{\text{max}}$ and $I_{\text{min}}$ are measured along the directions at which the length of the $E$-vector has a maximum or minimum, respectively.
This talk is focused on linear polarization.

Circular polarization will not yet be observable in the X-ray range.
Processes producing (de-)polarization

- Synchrotron emission
- Electron scattering
- Dust (Mie) scattering
- Resonant line scattering
- Dichroic absorption
- Faraday rotation
- Dilution (by unpolarized radiation)
- General Relativity

Scattering

**Strong** polarization: \( \Theta = 90^\circ \) (Reflection)

**Weak** polarization: \( \Theta = 0^\circ \) (Transmission)

\[
\frac{\partial \sigma}{\partial \omega} (\alpha)_{\text{tot}} = \frac{1}{2} r_0 \left( 1 + \cos^2 \theta \right).
\]

\[
P = \frac{1 - \cos^2 \theta}{1 + \cos^2 \theta}.
\]
Phase function for scattering-induced polarization

Electron scattering (Thomson, Compton, Rayleigh scattering)

Polarization phase function:

Differential cross section
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So-far X-ray polarization measurements

Sco-X1 and Cyg-X1 (OSO-8)
Long et al (1979, 1980)

Bragg-reflection polarimeter
So-far X-ray polarization measurements

Interpretation of the difference in polarization between 2.6 keV and 5.2 keV by energy-dependent Faraday rotation and multiple scattering.

\[
\chi = \frac{1}{2} \delta \tau_T \cos \theta,
\]

\[
\delta = \frac{3\omega_B c}{2r_e \omega^2} \approx 1.2 \left( \frac{B}{10^6 G} \right) \left( \frac{1\text{keV}}{\hbar \omega} \right)^2
\]

\[\rightarrow B > 10^7 \text{ G}\]

Sco-X1 and Cyg-X1 (OSO-8)
Long et al (1979, 1980)

Gnedin, Silant'ev & Titarchuk (2002)
So-far X-ray polarization measurements

Cygnus-X1
Laurent et al. (2011)

Hard X-ray measurement based on the polarization-dependent Compton effect

Crab Nebula (OSU-8)
Weisskopf et al (1978)

See talk by P. Laurent
Observational prospects – ready-to-fly technology

Photoelectric ionization of and subsequent Auger effect

Photo electron and Auger electron both know about the initial polarization of the incident photon

Active-matrix pixel prop. counter

Costa et al. (2001), Bellazzini et al. (2009), Muleri et al. (2009)
Soon observational prospects!

Gravity and Extreme Magnetism SMEX (2014)

NASA small explorer mission explicitly dedicated to X-ray polarimetry (Swank et al. 2010)

Stereo focusing telescope and X-ray polarimeter

Black et al. 2007, 2010
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Polarization from the accretion flow in X-ray binaries

Determining the local polarization (disk reference frame)
Intrinsically unpolarized radiation
multiple Thomson scattering in a disk/corona

Early modeling work done by Angel (1969)
Polarization from the accretion flow in X-ray binaries

Determining the local polarization (disk reference frame)
Intrinsically unpolarized radiation
multiple Thomson scattering in a disk/corona
Color correction for Comptonization (Novikov-Thorne)

X-ray radiative transfer modeling that includes polarization

See e.g.
Angel (1969)
Sunyaev & Titarchuk (1985)
Podzniakov, Sobol & Sunyaev (1986)
Matt et al. (1992)
Nagirner & Poutanen (1993)

Dovčiak et al. (2008)
Including relativistic effects

Applying relativistic ray-tracing methods in Kerr metric

Important to know the local polarization

see e.g.
Connors, Piran, Stark (1980)
Dovčiak et al. 2004
Schnittman 2009

$I, Q, U, V$

$$\Delta N_{\nu o}^{\Omega o}(E, \Delta E, t) = \int_{r_i}^{r_o} dr \int_{\phi}^{\phi+\Delta \phi} d\phi \int_{E/g}^{(E+\Delta E)/g} dE/N_l(E_l, r, \phi, \mu_e, t - \Delta t) g^2 l \mu_e r.$$
The observed polarization at infinity is obtained by integrating the transferred local polarization.

This gives a vast range in polarization angle...

Dovčiak et al. (2008)
Polarization from the accretion flow in X-ray binaries

Polarization observed at infinity

Integrating the transferred, local polarization across the accretion disk

Characteristic dependencies of the polarization as a function of energy

Pioneering modeling of this kind was done already by Connors, Stark, & Piran (1980)

Dovčiak et al. (2008)
Searching for the holy grail

X-ray polarization as a function of energy is going to put constraints on the black hole spin in X-ray binaries.

Polarization angle and percentage have a different signature for a Schwarzschild and a Kerr black hole.

GRS 1915+105 — Pathfinder Mission Scenario, T = 500 ksec, $i = 70^\circ$

Dovčiak, Muleri, Goosmann et al. (2008)
Light-bending and returning radiation

Schnittman & Krolik (2010)

Compton effects in the disk corona are consistently included with extreme light bending that may lead to secondary reprocessing.

Different coronal optical depth and electron temperatures are tested

A wedge-like corona is compared to spherical and patchy geometries
Light-bending and returning radiation

Schnittman & Krolik (2010)

\[ \frac{a}{M} = 0.9 \]
\[ \frac{H}{R} = 0.1 \]
\[ i = 75^\circ \]

Disk and coronal emission without returning radiation

...and including returning radiation
Light-bending and returning radiation

Schnittman & Krolik (2010)

\[
\tau_{es} = 1.4, \quad T_c = 50 \text{ keV} \\
\tau_{es} = 1.0, \quad T_c = 100 \text{ keV} \\
\tau_{es} = 0.5, \quad T_c = 200 \text{ keV}
\]
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What causes the hard X-ray emission of jets?

Two competing interpretations of leptonic models:

- Synchrotron-Self-Compton (SSC)
- External Comptonization (EC)

Differences in X-ray polarization are expected due to geometry and (un-)polarized seed photons.

McNamara, Kuncic & Wo (2009)
What causes the hard X-ray emission of jets?

**Modeling:**

**Polarized**

Synchrotron photons injected at different positions of the jet (SSC, $\zeta$)

**Unpolarized**

Photons (EC) from a disk (square) or the CMB radiation (triangles)

See also:

Bjornsson & Blumenthal (1982)
Celotti & Matt (1994)

McNamara, Kuncic & Wo (2009)

At a given viewing angle, there are characteristic differences in the polarization percentage between the two interpretations.
NGC 1068 – the first hidden type-1 AGN

A major break-through for the unified model of NGC 1068 (Antonucci & Miller 1985)

→ periscope view of AGN in polarised flux
Modeling polarization with STOKES

Monte-Carlo radiative transfer in 3D

Various geometries for the emission / scattering regions

Polarisation due to (multi-)electron scattering and dust (Mie-)scattering

Resonant line scattering routines implemented

Photo- and K-shell ionization

Variability and evolution of the system

Public access to Version 1.0
http://www.stokes-program.info/

STOKES was written by Rene W. Goosmann who is now at the Observatoire Astronomique de Strasbourg, France. If you have questions or comments about the code, please contact him.
X-ray polarimetry of NGC 1068

Modeling of an irradiated accretion disk, a dusty torus with $\Theta=60^\circ$, and inclined outflows as suggested by Raban et al. (2009).

Goosmann & Matt 2011

Possibility to constrain the relative angle between torus and outflows by broad-band polarimetry!
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Raban et al. 2009

GEMS pass band
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WHAT I NEGLECTED...

This talk did not cover all important aspects of X-ray polarimetry. I focused on the effects that do not involve strong magnetic fields.

Here are some references to theoretical work on X-ray polarization in magnetized plasma and/or jets (+references therein):

Davis et al. (2009) – effects of magnetic fields on the X-ray polarization from an accretion disk

Fernandez and Davis (2011) – polarization induced in the strong magnetic fields of magnetars

Comprehensive overviews for broad-band X-ray polarimetry and its science drivers can be found in Krawczynski et al. (2011) and Tagliaferri et al. (2011).

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SOME CONCLUSIONS

X-ray polarimetry is going to reveal details of the accretion and ejection geometry and the metric around compact objects.

Polarimetry will serve in particular to break degeneracies of existing spectroscopic and variability models.

To interpret the upcoming polarization data it is important to construct better models for the local (polarized) emission.

I think that the results obtained by GEMS are crucial for the future of all X-ray polarimetry.

Extension to harder X-ray polarimetry (10-35 keV) would be a very useful, following step. The technology is already available.

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