# X-RAY AND GAMMA-RAY POLARIMETRY

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## Introduction

At the subatomic level all radiation processes that produce X-rays or γ-rays are inherently polarized and anisotropic. However, by symmetry, the total emission from any homogeneous and isotropic source will be isotropic and unpolarized. Most astrophysical X-ray/γ-ray sources are expected to have some anisotropy or a preferred orientation and they will show a net polarization of the radiation. Such polarization can be measured relative to the plane defined by this preferred direction and the direction to the observer. For gamma-ray bursts, for example, the preferred direction may be the axis of the jet; in pulsars, it may be the magnetic axis; near black holes or neutron stars, it may be the strong gravitational field; for the nonthermal emission in solar flares, it is the direction of the magnetic field where the electrons emit the bremsstrahlung; for thermal emission it is the direction of the temperature gradient. Thus, in all cases, the magnitude and direction of the observed polarization from an astrophysical X-ray/γ-ray source can provide crucial information to discriminate between different models that cannot be distinguished using conventional measurements of spectra and time variations. In addition to these geometrical constraints, the energy-dependence of the polarization is also capable, in some cases, of providing constraints on the emission mechanism (e.g., distinguishing between synchrotron and inverse Compton emission). *Polarization measurements therefore have the potential to tell us something about both the mechanisms and source geometries responsible for the observed emissions.*

Despite the great inherent promise of astrophysical X-ray/γ-ray polarimetry, progress has been slow. The first successful X-ray polarization measurements (of the Crab nebula) were made some 30 years ago. Subsequent measurements have proven to be extraordinarily difficult due to inadequate instrumentation with systematic asymmetries that mask the polarization signal. The recent claims of polarized γ-rays from both γ-ray bursts (GRBs) and solar flares, although somewhat controversial, have helped to spawn a renewed interest in high-energy polarimetry. *New observational techniques and dedicated instrumentation now being developed offer the first clear possibilities for definitive breakthroughs in the next ten years.* In what follows, we outline some of the unique information that polarization can be expected to provide for several types of astrophysical X-ray/γ-ray sources (covering energies from ~1 keV up to several hundred MeV).

## Radio Pulsars

A key problem in pulsar astrophysics is the origin of the high-energy nonthermal radiation. Controversy remains over the site of this emission - directly above the polar cap, where the coherent radio pulses originate [e.g., 1], in the the outer magnetosphere near the light cylinder radius [e.g., 2], or in the so called "slot gap" along the open magnetic field lines between the polar cap and the outer magnetosphere [e.g., 3]. Each of these models can approximately reproduce the observed intensity pulse shapes, even in the γ-ray regime. Although recent γ-ray observations from *Fermi* suggest that the higher energy emissions (> 100 MeV) most likely originate in the outer region of the magnetosphere, *polarization measurements can also be used to reliably discriminate among the different models for the emissions*, particularly at lower energies (Fig. 1).

Optical polarimetry of the Crab pulsar [e.g., 4] has shown high linear polarization (up to 35%), varying rapidly through each pulse component. Such behavior might be explained by a version of the slot gap model [5], but it remains unclear from the observation in only one (optical) band how unique this interpretation is. We expect similar values of the degree of polarization in X-rays. However, the phase dependence of the polarization, particularly of the polarization position angle, may be different. This results from the fact that the directional distribution of radiation depends on the electron's energy and therefore on the frequency of the emitted radiation

[5] and because vacuum birefringence in the nonuniform magnetic field leads to an energy-dependent rotation of the polarization direction [6]. Thus, measuring the high-energy swing of the polarization across the pulse and comparing it with the optical not only will locate the sites of emission but it will also be a sensitive probe of the magnetospheric particle population, including the energy distribution of the relativistic particles in the emission zone.

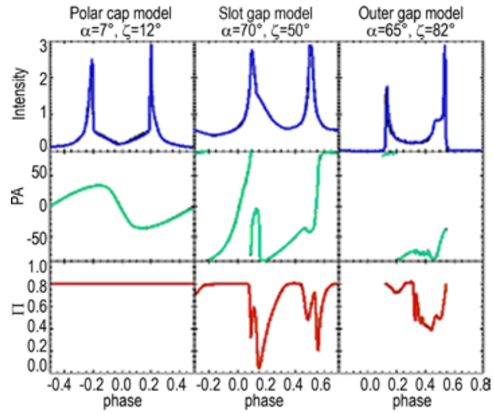

Figure 1: Intensity and predicted polarization position angle and degree of polarization for the polar cap (left; [51]); slot gap (middle; [5]), and outer gap (right; [52]) models.

The X-ray emission of pulsar wind nebulae (PWNe) is synchrotron radiation of the ultrarelativistic pulsar wind shocked in the ambient medium. The polarization position angle is perpendicular to the direction of the magnetic field at the site of emission and the degree of polarization depends on the energy spectrum of emitting electrons. Spatially resolved polarization measurements will therefore be needed to probe the magnetic field topology and its connection with the PWN morphological elements, as well as the spatial dependence of the particle spectrum. To understand the presently unknown particle acceleration mechanism(s), it is critical to compare the optical and radio polarization maps with the spatial dependence of the X-ray polarization because the X radiation may be generated by a different population of particles, hence producing a different degree of polarization. A systematic polarization study of PWNe should therefore afford new insights into the underlying physics.

Recent polarization measurements of the high energy (0.1 - 1 MeV) radiation from the Crab nebula [7, 8] suggest that the high-energy electrons responsible for the polarized radiation are produced in a highly organized structure in the vicinity of the pulsar. More detailed studies of the energy dependence and perhaps also the spatial dependence of the polarized emissions will provide additional clues regarding the nature of the acceleration processes within the nebula.

## Accreting X-Ray Pulsars

Most theoretical models of accreting X-ray pulsars predict that the linear polarization of this X radiation is high and varies with pulse phase (due to rotation) and with energy (due to energy dependent opacity), but the predicted dependences on energy and pulse phase are drastically different for different models. *Polarimetry will provide new information necessary to understand the geometry of the emitting regions, measure the magnetic field, temperature and density distributions, and to study vacuum birefringence, as predicted by quantum electrodynamics (QED).*

### Classical X-Ray Pulsars

The interpretation of absorption features between 10 and 100 keV, observed in about a dozen pulsating X-ray binaries, as cyclotron absorption lines implies very strong magnetic fields — $10^{12-13}$ G. In such magnetic fields, X-ray emission, absorption, and scattering depend strongly on energy, direction, and polarization. Detailed theoretical studies [e.g., 9] show that the observed spectra and pulse shapes can be matched by models with rather different geometries and physical properties of the emitting region. The polarization signatures of the models, however, are distinct [e.g., 10, 11]. For example, only phase-resolved polarimetry can distinguish between "pencil" and "fan" radiation patterns, corresponding to different emission-region geometries, which has been a long-standing problem in astrophysics of these objects, important for understanding of the fraction of “missed pulsars’’. Because the degree of linear polarization is maximal for emission perpendicular to the magnetic field, the flux and degree of polarization are in-phase for fan beams, but out-of-phase for pencil beams.

Because the linear-polarization direction is either parallel or perpendicular (depending upon photon energy and absorption depth) to the magnetic field, rotation of polarization position angle with pulse phase provides a probe of the magnetic-field geometry. The existence of a non-dipolar field [12] would support other evidence for such fields in some accreting pulsars [13], due perhaps to thermomagnetic effects [14] or crustal breaking and migration of field-carrying platelets [15], which would have broad implications for neutron star astrophysics.

The energy dependence of the degree of polarization is mostly determined by the ratio $E/E_{ec}$, where $E_{ec}$ is the electron cyclotron energy. Observing a sample of pulsars with different values of $E_{ec}$, one will be able to investigate this dependence and compare it with models. Moreover, it may happen that some of the pulsars have magnetic fields of a few times $10^{11}$ G. Observing such pulsars one may obtain the first magnetic field measurements for such sources based on the long-predicted prominent energy dependence of polarization near the electron cyclotron resonance [11].

X-ray polarimetry of accreting pulsars may also detect effects of vacuum birefringence. Recent studies of neutron-star atmospheres [16, 17] and magnetospheres [6] treat this phenomenon. The most vivid polarization signatures are a strong energy dependence of the Stokes parameters and a 90°-position-angle jump at an energy-dependent phase, occurring where the normal-mode propagation through the so-called “vacuum resonance” [18] changes from adiabatic to nonadiabatic [19]. Detection of such features would not only be the direct observation of this QED effect but it would constrain the density and magnetic field in the emission region.

### Accreting Millisecond Pulsars (AMXPs) and X-ray Bursters

Over 20 accreting millisecond pulsars (AMSPs) have been discovered during the last decade. Many of these are X-ray bursters, which exhibit bursts due to unstable thermonuclear burning of the accreted matter. The pulsations were observed in both persistent emission and during the bursts. In both cases linear polarization (with values up to ~30%) is expected because photon scattering in an anisotropic environment determines the properties of the emission. Spectral studies suggest that the radiation is typically comprised of a blackbody component, from hot spots (polar caps) with a temperature, kT ~ 1 keV, at the star surface, and a hard power-law component, interpreted as comptonization in a radiative shock, with a temperature of 30 - 60 keV and optical depth $\tau \sim 1 - 2$. As the observed pulsations indicate that the shock covers only a small part of the neutron-star surface, the scattered radiation should be linearly polarized up to 20%-30%, depending on the photon energy and geometry of the system [20] (Fig. 2). These model de-

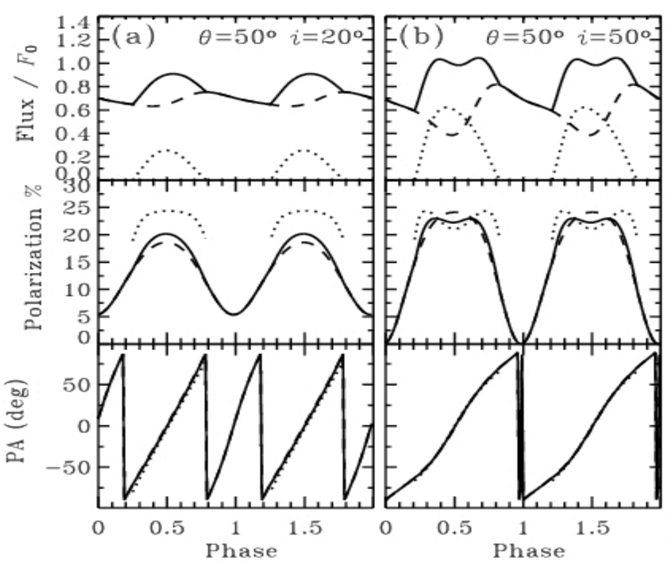


Figure 2: Phase dependence of the flux, position angle and degree of polarization for an accreting millisecond pulsar model with two antipodal hot spots [20], for a period of 3.3 ms and neutron star radius R = 2.5 Rg, and different sets of angles i, between the rotation axis and line of sight, and θ, between the rotation and magnetic axes.

pendent variations of the polarization amplitude and position angle make polarimetry a powerful probe of the physical conditions. Polarization studies will either confirm the basic model, establishing the geometry of the system and the parameters of the hot spot(s) and the shock, or perhaps result in a qualitatively new model.

Even if an X-ray burster has not been detected as an AMSP, we still can expect a linear polarization in both its persistent emission and during the bursts, if there is azimuthally asymmetric photon scattering. Particularly interesting would be polarimetry of a burster in its active state, when it can burst many times during the observation [21]. The polarization of the persistent radiation, due to scattering in a localized shock near the neutron-star surface, is expected to drop during bursts as their emission comes from most of the surface, except for a short time at the burst onset. Detection of such polarization behavior would constrain the emitting-region geometry and the physics of accretion and thermonuclear explosions in LMXBs.

The X-ray flux from many LMXBs, including some AMSPs, show Quasi-Periodic Oscillations (QPOs), whose behavior is correlated with different spectral states. While these spectral states may correspond to different accretion-flow modes, the QPOs' true nature remains elusive. Since most QPO models involve inhomogeneities of the inner disk [22], we expect X-ray polarization to be correlated with QPO behavior. Polarization observations of QPOs in different spectral states will help to distinguish between QPO models.

## Galactic Black Hole Binaries

The polarization properties are significantly altered when photons travel on null geodesics in a strong gravity field, as it happens in the vicinity of a black hole or a neutron star [23-26]. In practice, this results in a rotation of the polarization angle - as seen by a distant observer - with respect to a fixed direction. The amount of rotation depends on the geodesics parameters, and is larger the smaller the impact parameter with respect to the compact object. Even if the overall result is a depolarization of the radiation, unique energy and time variations of the polarization angle are obtained, which provide a probe of gravity in a strong field regime and a tool to estimate the black hole parameters, and in particular its spin.

*Galactic Black Hole Binaries (GBHB) provide possibly the cleanest example of the use of polarimetry to test strong gravity.* In these systems, when in the so-called soft or high state, the X-ray emission, at least in the classic 2-10 keV band, is dominated by thermal emission from the accretion disk. The disc temperature decreases with the disk radius, and therefore the highest energy photons are emitted close to the black hole, where the rotation of the polarization plane is the largest. As a result, a variation of the polarization angle with energy is expected [27-29]. Because the innermost radius of a disk (customarily assumed to coincide with the innermost stable circular orbit, ISCO) depends on the black hole spin (being 6 gravitational radii for a static black hole, only 1 for a maximally rotating black hole), the variation of the polarization angle is larger for a rotating black hole, so providing a powerful tool to estimate the spin. In Fig.3 this effect is shown for three inclination angles and two values of the black hole angular momentum, i.e. a static (a=0) and a maximally rotating (a=1) black hole.

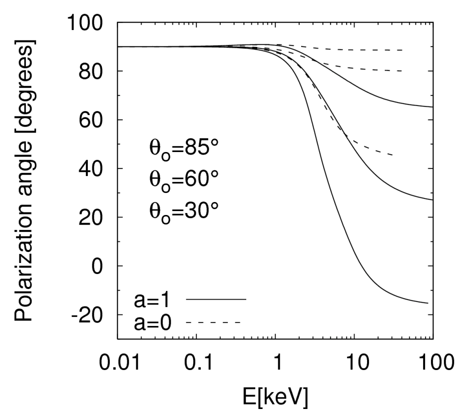

Figure 3: Rotation of the polarization angle of the thermal emission in GBHB[28].

## Gamma-Ray Bursts

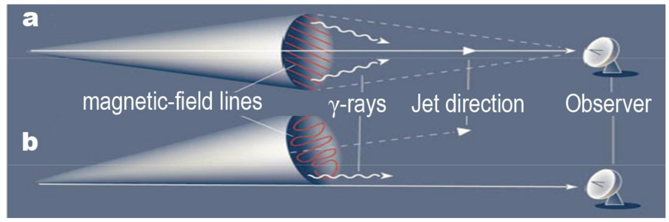


Figure 4: Two types of GRB models [5]: (a) the physical model: synchrotron emission from an ordered magnetic field; (b) the geometric model: preferred viewing direction is slightly outside the jet cone.

Gamma-ray bursts (GRBs) are brief, energetic bursts of gamma-rays that mark the most violent, cataclysmic explosions in the universe. Extensive multi-wavelength observations of GRBs and their long-wavelength afterglows have revealed the following physical picture [30-32]: long-duration (typically > 2 s) GRBs are associated with deaths of massive stars, and short-duration (typically < 2 s) GRBs are related to mergers of compact objects. Regardless of the progenitor and the central engine, a generic "fireball" model suggests that a relativistic jet with bulk Lorentz factor over 100 beams towards the Earth. Internal dissipation of energy within the jet (internal shocks or magnetic reconnection) leads to the prompt GRB emission. Interaction between the jet and the circumburst medium leads to a long-lasting multi-wavelength afterglow.

In spite of extensive observational efforts, several key questions related to the nature of GRBs remain unsolved, some of which are very difficult or even impossible to infer with the spectral and lightcurve information currently collected. Theoretically, two types of source models can give rise to strong polarization in GRBs (Fig. 4, [33]). Polarization measurements of the prompt gamma-ray emission can address the following open questions: 1) *Magnetic composition of GRB jets:* It is speculated that strong magnetic fields are generated at GRB central engine. Polarization measurements can address whether the GRB emission region is penetrated by a globally structured, dynamically important magnetic field, and shed light on the profound question whether the GRB ejecta carry a significant fraction of Poynting flux [34]. The same applies also to X-ray flares following GRBs, originated from reactivation of the central engine. 2) *Radiation mechanisms of GRBs:* It is unclear whether the observed GRB emission is synchrotron radiation in an ordered or random magnetic field, Compton scattering off other soft photons, or superposition of a thermal and a non-thermal emission component. These different models predict distinctly different polarization properties [33-37]. Polarization measurements can unambiguously constrain the GRB radiation mechanism. 3) *Geometric structure of GRB jets:* Statistical analyses of the polarization properties can also probe the geometric configuration of GRB jets, and diagnose the possible small-scale geometrical structure within the jets.

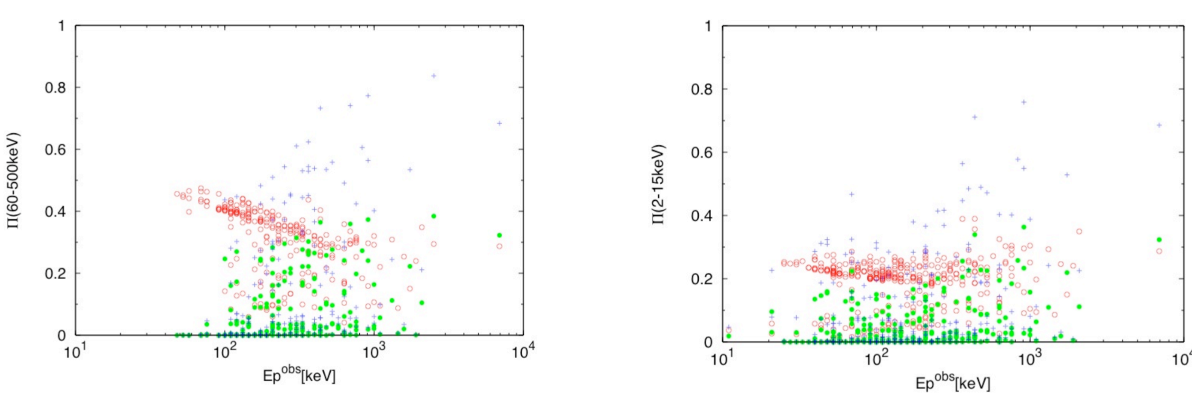


Figure 5: Simulated GRB polarization degree (π) distribution for three models: Synchrotron emission in ordered magnetic fields (red), synchrotron emission in random fields (green), and Compton drag (blue). Left: 60-500 keV; Right: 2-15 keV. From [13].

Currently the GRB polarization measurements are sparse and inconclusive [38-40]. *A number of more definitive polarization measurements of the prompt GRB emission, spanning an energy range above and below the peak spectral energy ($E_p$), will be needed to distinguish amongst the models.* Simulations [41] suggest that 2-500 keV polarization data from ~50 GRBs would lead to differentiation of several competing GRB models (Fig. 5).

## Solar Flares

Solar flares release as much as $10^{33}$ ergs of energy stored in stressed coronal magnetic fields, accelerating ions up to tens of GeV and electrons to hundreds of MeV in the process. The details of how such a high-efficiency acceleration occurs are presently unknown. Such a rapid acceleration of such a large flux of charged particles also imposes formidable constraints on the global electrodynamics of the system, even in moderately anisotropic acceleration geometries [42], although these challenges can be alleviated somewhat if the particle acceleration is nearly isotropic, such as in stochastic acceleration models [43]. A determination of the extent to which the accelerated electrons are beamed (anisotropic) therefore constitutes an essential step towards a greater understanding of particle acceleration in the cosmos.

There are several ways in which the anisotropy of the accelerated electrons can be ascertained from high energy photon emissions. However, statistical directivity studies [44] are inconclusive and multi-spacecraft stereoscopic observations [45] are sparse. Polarimetry is the most effective means of measuring the anisotropy of the accelerated electrons, yet reliable measurements of the polarization of solar flare hard X-ray and γ-ray radiation lag well behind theoretical predictions of this key diagnostic.

Electrons accelerated in the flare spiral around guiding magnetic field lines, emitting bremsstrahlung hard X-rays (E >10 keV or so) from collisions with ambient protons and heavier ions. In conventional models of a solar flare, the magnetic field forms a loop structure that penetrates the chromosphere in a vertical direction. Since most of the hard X-ray emission is emitted in the dense chromospheric regions of the loop [46], the direction of the magnetic field in these layers represents a preferred direction in the source. Hence, one expects the hard X-ray emission to be linearly polarized either in, or perpendicular to, the plane defined by this preferred (vertical) direction and the direction to the observer, i.e., along the radial direction from the center of the disk to the source. Extensive modeling [e.g., 47, 48] shows that, for the generally-accepted "thick-target" model, in which the accelerated electrons are preferentially accelerated downward, the polarization is from (10-20)%, aligned along the radial on the solar disk. However, it has been shown that non-radial polarization orientations are possible both for thermal models of the hard X-ray emission, or for deviations of the chromospheric magnetic field direction from the local vertical [49, 50]. *Measurements of the magnitude and direction of the polarization vector, especially when combined with other context observations, provide key diagnostic evidence to distinguish between particle acceleration scenarios.*

## The Future

There is great potential for new insights with high energy polarization measurements in the next decade. New measurements will require carefully-designed instrumentation that is capable of high sensitivity observations and, in some cases, high angular resolution imaging. Fortunately, there are already several efforts underway to develop such instrumentation, spanning the energy range from soft X-rays (1 keV) up to high energy γ-rays (several hundred MeV). *Continued support of such efforts will be required to fully benefit from the discovery potential afforded by high energy polarimetry.*

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