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An unfolding method for X-ray spectro-polarimetry

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ABSTRACT

X-ray polarimetry has great scientific potential and new experiments, such as X-Calibur, PoGOLite, XIPE, and GEMS, will not only be orders of magnitude more sensitive than previous missions, but also provide the capability to measure polarization over a wide energy range. However, the measured spectra depend on the collection area, detector responses, and, in case of balloon-borne experiments, the absorption of X-rays in the atmosphere, all of which are energy dependent. Combined with the typically steep source spectra, this leads to significant biases that need to be taken into account to correctly reconstruct energy-resolved polarization properties. In this paper, we present a method based on an iterative unfolding algorithm that makes it possible to simultaneously reconstruct the energy spectrum and the polarization properties as a function of true photon energy. We apply the method to a simulated X-Calibur data set and show that it is able to recover both the energy spectrum and the energy-dependent polarization fraction.

1. Introduction

X-ray polarimetry holds the promise to resolve the inner regions of compact systems like mass accreting black holes in X-ray binaries and X-ray bright neutron stars [1]. For example, spectropolarimetric observations of pulsars and pulsar wind nebulae can constrain the geometry and locale of particle acceleration in these sources. Measurements of the polarization of X-rays from the Crab Nebula indicate an increase in the polarization fraction and a change in polarization angle in the energy range between a few keV and 100 keV indicating that the γ-ray emission must come from a small, highly ordered region, whereas X-rays are emitted from all morphological features of the pulsar wind nebula. Spectropolarimetric observations can constrain the magnetic structure of jets in Gamma Ray Bursts and Active Galactic Nuclei. Furthermore, X-ray polarimetry can be used to measure the masses and spins of black holes and the orientation of their inner accretion disk, as well as accretion disks and accretion disk coronae of Active Galactic Nuclei. See Ref. [1] and references therein for more details.

While this potential has long been appreciated, the OSO-8 satellite launched in 1978 has been the only mission with a dedicated X-ray polarimeter so far that measured X-ray polarization of an astrophysical source [2]. New technological developments enabled the design of compact wide-bandpass polarimeters with a large collection area such as the proposed satellites GEMS [3] and XIPE [4] or the balloon-borne hard X-ray polarimeters X-Calibur [5] and PoGOLite [6]. The collection areas and detection efficiencies of these experiments will allow spectropolarimetric observations with unprecedented sensitivity. In this paper we study statistical methods that can be used to analyze the data of such experiments.

The measurement of the polarization fraction and direction of the above mentioned experiments make use of the photo-electric effect (GEMS, XIPE) or the Compton effect (PoGOLite, X-Calibur).

Photoelectrons are emitted preferentially parallel to the electric field of the electromagnetic wave associated with the photon. The differential cross section of the photoelectric effect in the non-relativistic case can be approximated as [7]:

$$\frac{d\sigma}{d\Omega} = r_0^2 Z^5 \alpha^4 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta\cos^2\phi}{(1-\beta\cos\theta)^4}, \tag{1}$$

where r_0 is the classical electron radius, Z the atomic number of the absorbing material, α the fine-structure constant, m_e the electron rest mass, E the photon energy, θ the angle between the incoming photon and the emitted photoelectron, β its speed in units of c, and ϕ the azimuth angle of the emitted electron with respect to the polarization direction of the incident X-ray.

Photons scatter preferentially perpendicular to the electric field, as governed by the Klein–Nishina cross section (see e.g. Ref. [8]):

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1} + \frac{k_1}{k_0} - 2\sin^2\theta\cos^2\eta\right], \tag{2}$$

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where η is the angle between the electric vector of the incident photon and the scattering plane, $\mathbf{k}_0$ and $\mathbf{k}_1$ are the wave-vectors before and after scattering, and θ is the scattering angle.

The azimuthal scattering angle or emission direction of the photoelectron is, therefore, a proxy for the polarization angle. In general, scattering polarimeters measure the azimuthal scattering angle of an X-ray photon and the energy of the scattered photon. In some realizations an X-ray mirror is used to focus the beam onto the detector assembly.

Since typical source spectra exhibit steep power-laws, the energy resolution and energy-dependent detection efficiency have to be taken into account. The most important effects that must be considered are:

- the energy resolution of the detector;
- the energy lost in the scattering process, which is not measured by all experiments;
- the energy-dependent effective area of grazing incidence mirrors;
- absorption of photons in the atmosphere in case of balloon-borne instruments;
- the energy-dependent detection efficiency.

In this paper we describe an unfolding algorithm, and show that it can be used to determine flux and polarization fraction and direction as a function of photon energy with small biases.

In Section 2 we will define the problem. In Section 3 we will introduce an unfolding method that can be used to reconstruct the photon spectrum of the source while preserving the energy-dependent azimuth distribution of events. In Section 4, we apply the method to a set of simulated X-Calibur data. Finally, in Section 5, we summarize our findings and present our conclusions.

2. Formulation of the problem

Typical X-ray polarimeters measure the energy of the scattered photon or the energy of the recoil electron. This energy will differ from the energy of the incident photon by an unknown amount governed by underlying physical process (e.g. photoelectron emission or Compton scattering) and the finite energy resolution of the detectors.

Grazing-incidence X-ray mirrors focus the X-rays from a source onto a detector and make it possible to combine large detection areas with rather small detectors, and thus to achieve excellent signal to background ratios. In addition, they change the polarization properties of the incident photons by $< 1\%$ [9,10]. However, their effective areas depend strongly on the energies of incident photons. In case of a balloon-borne experiment, the atmosphere above the detector absorbs low-energy photons. For illustration, Fig. 1 shows the effective collection area of the InFOCμS mirror [11], folded with the energy-dependent transmissivity of the atmosphere (from [12]) for a flight altitude of 45 km (2.6 g cm^{-2} at 90° elevation).

Together, the strong energy dependence of the effective collection area, the finite energy resolution, and the steeply falling source spectra, lead to a significant distortion of the measured energy spectra, which needs to be taken into account in a spectro-polarimetric analysis.

Mathematically, these effects can be described by a convolution of a true spectrum with a detector response function which includes effects of the mirror and the atmosphere. If the spectrum is measured in n_e discrete energy bins, the measurement can be expressed as a vector of event counts $N_i^e (i = 1, \ldots, n_e)$ and the detector response is represented by the response matrix $\mathbf{R}$, which relates the true number of photons $N_j^c (j = 1, \ldots, n_c)$ in the jth energy bin to the observed counts in the ith bin:

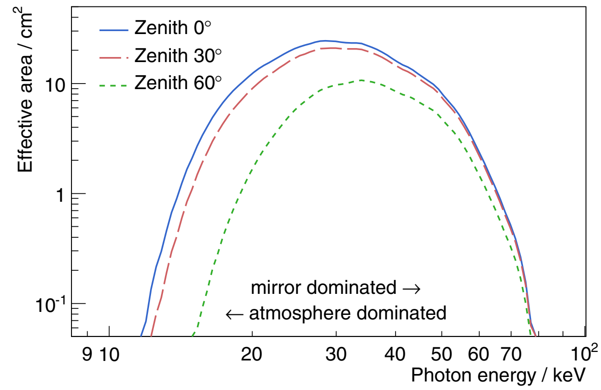

Fig. 1. Effective collection area of a balloon-borne polarimeter flown at an altitude of ~ 45 km (atmospheric depth of 2.6 g cm^{-2} at 90° elevation), taking into account the absorption of X-rays in the residual atmosphere. At low energies the limiting factor is absorption in the atmosphere, while at high energies the mirror effective area limits the collection area.

$$N_i^e = \sum_{j=1}^{n_c} R_{ij} N_j^c. \tag{3}$$

Each entry in the response matrix corresponds to the probability to measure an energy in bin i given a true energy in bin j:

$$R_{ij} = P(E_i^e | E_j^c). \tag{4}$$

More generally, what was referred to as "true spectrum" so far is a set of "*causes*", Φ_j^c, with a set of properties – one of them being the energy of the incident photon –, which lead to a set of "*effects*", Φ_i^e, with a set of properties that can be measured in the experimental setup (the "measured spectrum") – one of them for example the energy of the scattered photon. Therefore, instead of the "measured spectrum" we will from now on refer to the measured *effects*. The response matrix R_{ij} then describes the probability that cause j will lead to effect i.

In general, neither the binning of nor the number of properties associated with $\mathbf{\Phi}^e$ and $\mathbf{\Phi}^c$ need to be the same. Thus, it is straight-forward to generalize Eq. (3) to include information about the azimuthal scattering angle ϕ in cause bins $k = 1, \ldots, n_\phi^c$ and effect bins $\ell = 1, \ldots, n_\phi^e$ respectively. Then, each *cause* represents a combination of true energy and scattering angle, $\Phi_j^c = (E_p^c, \phi_k^c),\ j = 1, \ldots, n_E^c n_\phi^c$, and correspondingly each *effect* represents a combination of measured energy and scattering angle. The vectors $\boldsymbol{N^c}$ and $\boldsymbol{N^e}$ now represent event numbers in bins of these more general, higher-dimensional causes Φ_j^c and effects Φ_i^e.

Additional observables (i.e. parameters of the *effects*) or parameters of the *causes* (i.e. output parameters of the unfolding) can be added in the same way. For instance, when analysing the X-Calibur data in Section 4, we add the coordinate of the observed photon along the optical axis as an additional input parameter in order to improve the energy resolution.

The response matrix is normalized such that for a given *cause* bin j the sum over all *effect* bins is the detection efficiency ε_j for photons in the jth *cause* bin:

$$\sum_i R_{ij} = \varepsilon_j, \tag{5}$$

with $0 \leqslant \varepsilon_j \leqslant 1$.

In general, measurements will contain a significant fraction of background events caused by cosmic rays and albedo photons [5], despite active and passive shielding of the detector. If the background distributions of the input variables are known – ideally, they should be measured during flight in special off-source data