

XIMPOL: A new X-ray polarimetry observation-simulation and analysis framework

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Summary. — We present a new simulation framework, based on the `python` programming language and specifically developed for X-ray polarimetric applications, called XIMPOL. Starting from an arbitrary source model (including morphological, temporal, spectral and polarimetric informations), XIMPOL uses the response functions of the detector under study to produce fast and realistic observation-simulations. A *Chandra*-to-XIMPOL converter is also available within the framework, designed to convert a real *Chandra* observation into a XIMPOL simulation. The generated output files can be directly fed into the standard visualization and analysis tools, including XSPEC, which make XIMPOL a useful tool not only for simulating observations of astronomical sources, but also to develop and test end-to-end analysis chains.

1. – Introduction

XIMPOL is a new simulation framework specifically designed for X-ray polarimetry. It is based on the `python` programming language and the associated scientific ecosystem and it is publicly available under the GNU General Public License [1]. XIMPOL is able to produce realistic observation-simulations given as inputs a source model and the detector response functions. The generated output FITS files can be analyzed with standard analysis tools, such as XSPEC [2], and HEASARC `ftools` [3]. In addition, dedicated tools for the analysis of polarimetric informations are directly available within XIMPOL.

In this contribution we will give an overview of the basic architecture of the software and, although the framework is not tied to any specific mission or instrument design, we will present a few physically interesting case studies in the context of the the X-ray Imaging Polarimetry Explorer (*XIPE*) mission [4], currently in phase study for the M4 ESA call.

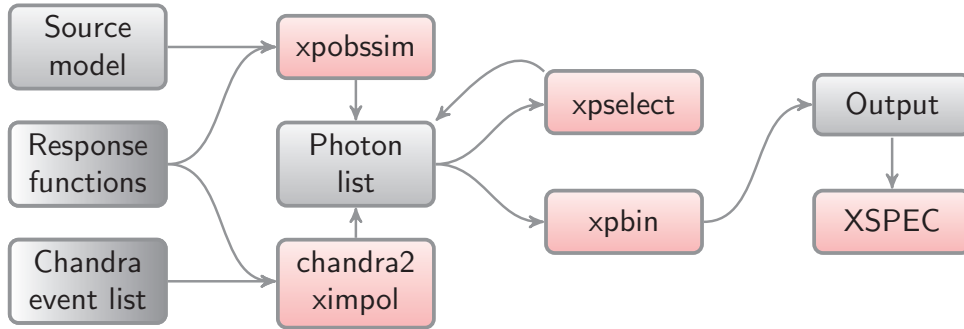


Fig. 1. – Architectural overview of XIMPOL. The executables are shown in red, while the input and the output files in gray.

2. – Architectural overview

The vast majority of the simulation and data preparation algorithms implemented in XIMPOL are available in four main executables, as illustrated in the block diagram of fig. 1. These consist in:

- *xpobssim*: given a source model, a set of instrument response functions, and a given observation time, it produces a photon list corresponding to a given observation time in the form of a binary FITS table.
- *chandra2ximpol*: given a *Chandra* event list and a set of instrument response functions, it converts the *Chandra* observation into a XIMPOL observation-simulation.
- *xpselect*: it allows to select subsamples of photons in a given event file, based on the event energy, direction, time or phase, producing a new (smaller) event file.
- *xpbins*: it allows to bin the data using several different algorithms, producing counts maps and spectra, light curves, phasograms and modulation cubes (*i.e.*, histograms of the measured azimuthal distributions in multiple energy layers).

Where applicable, the data formats are consistent with the common display and analysis tools used by the community, *e.g.*, the binned count spectra can be fed into XSPEC, along with the corresponding response functions, for standard spectral analyses. All the simulation and analysis tools are fully configurable via command-line interface. Also, XIMPOL provides a “pipeline” facility to easily concatenate all the aforementioned functionalities in `python` scripts.

3. – Source model definition

The basic setup for a generic simulation is specified via a `python` configuration file. In order to define a source model, three functions are needed:

- 1) Energy spectrum: $S(E, t)$ [$\text{ph cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$].
- 2) Polarization degree: $P(E, t, ra, dec)$.
- 3) Polarization angle: $\phi(E, t, ra, dec)$.

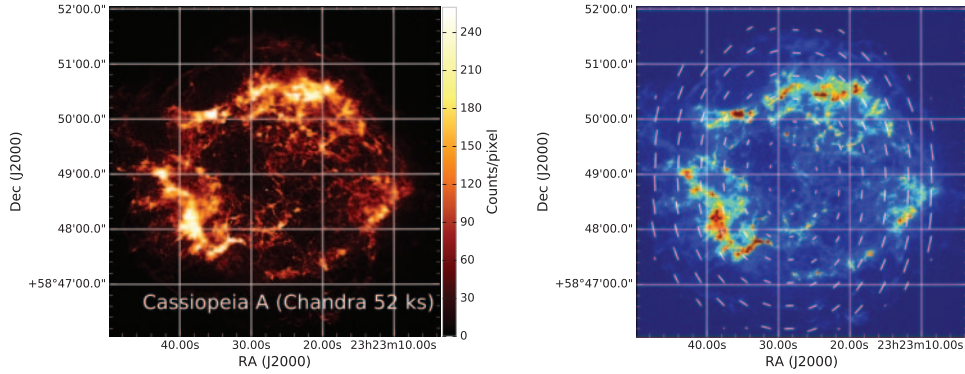


Fig. 2. – On the left, *Chandra* image for Cas A (taken from [5], observation id 114) in the 1–8 keV energy range. On the right, toy polarization model used in the simulation. The arrow length indicates the polarization degree and the direction is the polarization angle. The maximum value of polarization degree is $\sim 50\%$ at the outer edges.

There is a great flexibility in defining these functions: they can be defined analytically (*e.g.*, constants, power-laws,...), can be the result of interpolations built from a series of data points or, for the energy spectrum, can be a XSPEC spectral model. The source morphology can be defined as a variety of predefined structures: point sources, Gaussian or uniform disks, or an arbitrary extended sources (from FITS images). In addition, XIMPOL fully supports phase-dependent periodic sources and an arbitrary number of components can be easily overlaid in the same input model. For example, fig. 2 shows the *Chandra* image used to define the morphology of the source (Cas A, in this case) and the simple polarization pattern used in the simulation. Figure 3 shows the spectral model used. In this particular simulation, we have defined a thermal non-polarized spectral component overlaid with a polarized non-thermal component.

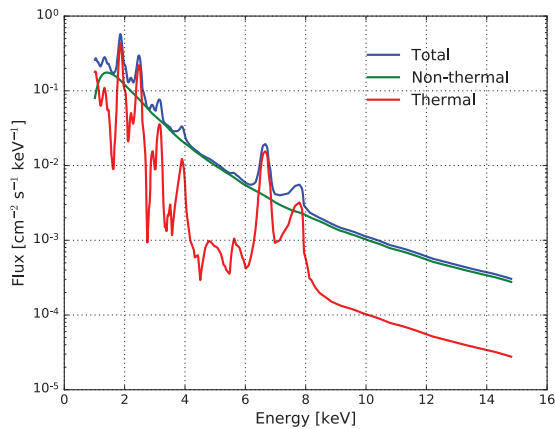


Fig. 3. – Cas A energy spectrum [6] as a superposition of thermal and non-thermal emission. For our purposes, we denote as thermal anything that is making up for the lines and non-thermal all the rest.

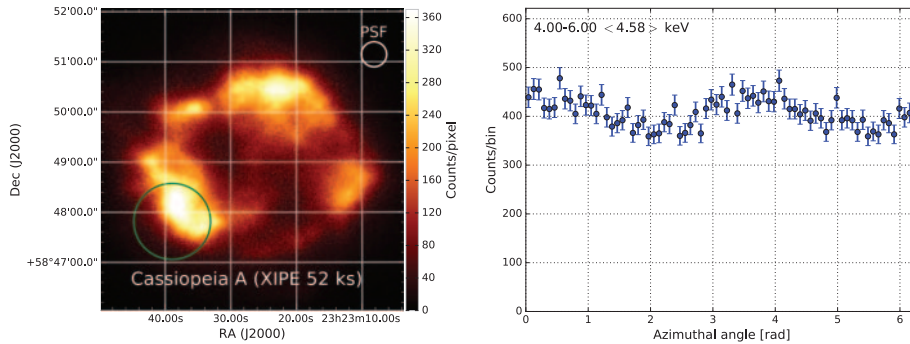


Fig. 4. – *XIPE* simulation result for Cas A (left). The white circle on the upper right shows the angular resolution of *XIPE*. The green circle on the bottom left corresponds to the selection region used to compute the modulation curve (right).

4. – Observation-simulation

The main purpose of the observation-simulation tool, called *xpobssim*, is to simulate a realistic observation of a source taking as inputs the source model and a set of suitable detector response functions. In the simulation work-flow, the first step consists in calculating the expected number of events. This is done convolving the provided source spectrum with the effective area of the instrument and integrating the curve in energy and in time. Then, using the count spectrum and the light curve as one-dimensional probability density functions, the event times (or phase) and the true energies are randomly sampled. The energies are also smeared with the energy dispersion. According to the source morphology and the instrument point spread function (PSF), the incoming photons direction in the sky is determined (fig. 4, left panel). In the last step, the tool generates the angular distribution of the photoelectron emission angles based on the given polarization model (fig. 4, right panel). The output of the simulation is a photon list that is saved in a FITS file containing all the information about the photons.

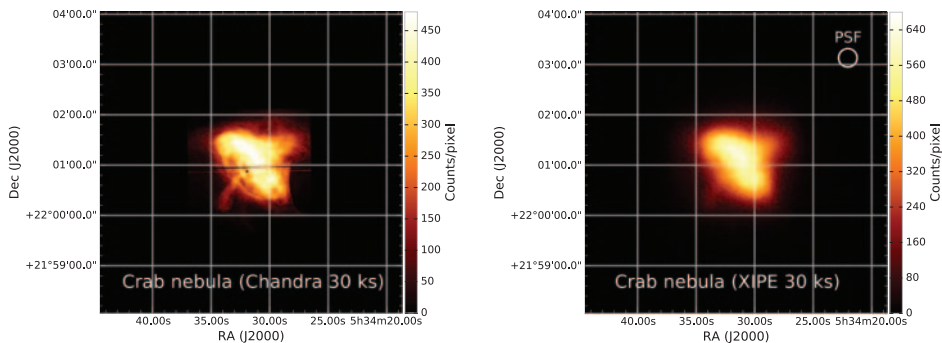


Fig. 5. – *Chandra* image for Crab nebula (taken from [5], observation id 1996) in the 1–8 keV energy range (left) and the corresponding *XIPE* simulation (right). The white circle on upper right shows the angular resolution of *XIPE*.

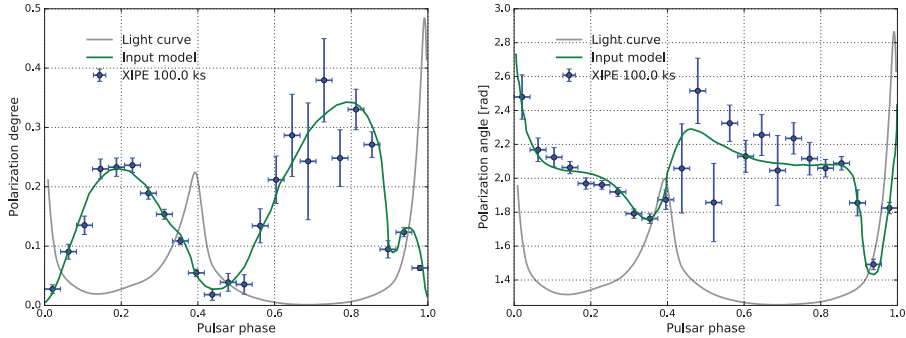


Fig. 6. – Simulated polarization degree (left) and polarization angle (right) for the Crab complex (nebula plus pulsar).

5. – Chandra2ximpol converter

The *chandra2ximpol* converter is a tool alternative to *xpobssim*, specifically designed to simulate a source starting from *Chandra* observations (for example, fig. 5, left panel). This technique has the advantage to preserve the full correlation between the source morphology and the spectrum, especially important for extended sources. The starting point of the conversion is the *Chandra* photon list, publicly available from the on-line database [5], which includes energies and spatial information of every event. The *Chandra* angular and energy resolutions are much better than those expected for the *XIPE* mission (angular resolution: ~ 1 arcsec *vs.* ~ 30 arcsec, energy resolution: $\lesssim 5\%$ *vs.* $\sim 20\%$ at 5.9 keV [7]), so that we can take the *Chandra* measured energies and positions as Monte Carlo truth. Based on the ratio of the effective areas and the given observation time, the events are down- or over-sampled and then smeared with the response functions (in this case *XIPE*: fig. 5, right panel). Finally, the emission angle is generated accordingly with the specified polarization model and the output event list is saved in a FITS file.

6. – Analysis tools

XIMPOL also comes with a basic set of command-line analysis tools. These allow the user to select subsamples of photons based on event energy, direction, time or phase (*xpselect*), or bin and fit the simulated data, producing count maps, spectra, phasograms, light and modulation curves (*xpbin*). The resulting spectra and the response functions are compatible with XSPEC, which can be therefore used to perform spectral analysis. All the tools, including XSPEC, can be seamlessly combined into analysis pipelines. As an illustrative example, fig. 6 shows the results of a 100 ks *XIPE* simulation of an observation of the Crab nebula (plus pulsar), based on [8], with superimposed the polarization model given as input. These figures show the result of the complete simulation-analysis pipeline. In each pulsar-phase bin, the data have been analyzed and the polarization degree and angle have been obtained. The comparison with the input model is also shown.

7. – Conclusions

In summary, XIMPOL is a newly developed observation-simulation and analysis framework that allows the user to easily produce fast and realistic simulation of astronomical

sources as well as analyze and display the simulation results. The entire software package is not tied to any specific mission and the user simply provides the instrument response functions to use. Thanks to its capabilities and flexibility it can play a relevant role in a context of growing interest for the X-ray polarimetry.

REFERENCES

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