ixpeobssim: a Simulation and Analysis Framework for the Imaging X-ray Polarimetry Explorer

Melissa Pesce-Rollins[1], Luca Baldini[1,2], Niccolò Buccinatini[3], Niccolò Di Lalla[4], Steven R. Ehlert[5], Alberto Manfreda[1], Nicola Omodei[4], and Carmelo Sgrò [1]

[1]INFN - Pisa
[2]University of Pisa
[3]Osservatorio Astrofisico di Arcetri
[4]Stanford University
[5]NASA Marshall Space Flight Center

ixpeobssim is a simulation and analysis framework, based on the Python programming language and the associated scientific ecosystem, specifically developed for the Imaging X-ray Polarimetry Explorer (IXPE). Given a source model and the response functions of the telescopes, it is designed to produce realistic simulated observations, in the form of event lists in FITS format, containing a strict super-set of the information provided by standard IXPE level-2 files. The core ixpeobssim simulation capabilities are complemented by a full suite of post-processing applications, allowing for the implementation of complex, polarization-specific analysis pipelines, and facilitating the inter-operation with the standard visualization and analysis tools traditionally in use by the X-ray community. We emphasize that, although a significant part of the framework is specific to IXPE, the modular nature of the underlying implementation makes it potentially straightforward to adapt it to different missions with similar polarization capabilities.

Introduction

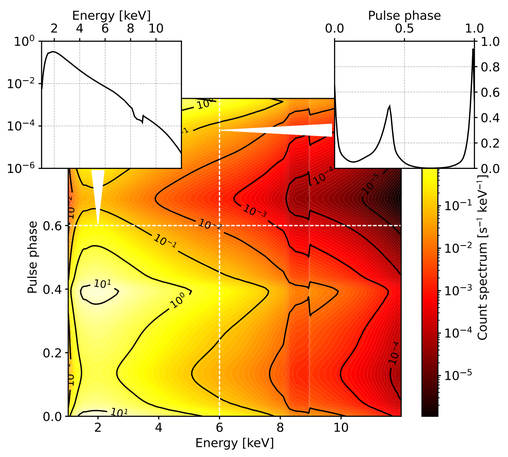
ixpeobssim is a simulation framework specifically developed for the Imaging X-ray Polarimetry Explorer (IXPE) mission launched on December 9, 2021. It is based on the Python programming language and the SciPy stack ixpeobssim is meant to produce fast and yet realistic observation-simulations, given as basic inputs:

- an arbitrary source model including morphological, temporal, spectral and polarimetric information;
- the response functions of the detector, i.e., the effective area, the energy dispersion, the point-spread function and the modulation factor.

The framework produces output files that can be directly fed into the standard visualization and analysis tools used by the X-ray community–making it a useful tool for simulating physical systems, to develop and test end-to-end analysis chains.

Source model definition

- Need four functions of the dynamical variables:
  1. Morphology: point sources, disks, extended source (from FITS image).
  2. Energy spectrum.
  3. Polarization model:
     - ▷ Polarization degree.
     - ▷ Polarization angle.
- Support for phase-dependent periodic sources provided.
- Can overlay an arbitrary number of components in the same input model.

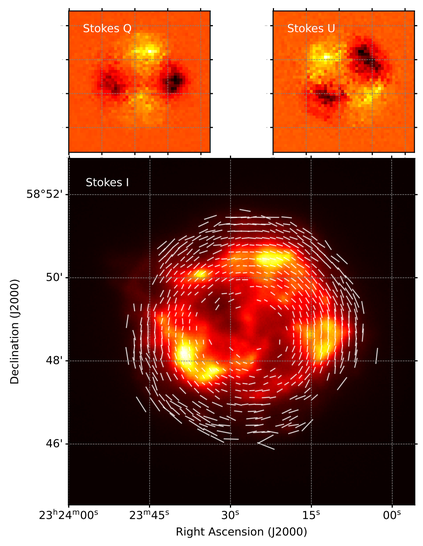


Crab pulsar count spectrum.

Observation simulation

Simulate an observation starting from an arbitrary source model:

1. Calculate the expected number of events based on the source spectrum and the effective area and extract the event times.
2. Extract the true energies and positions in the sky and smear them with the energy dispersion and the PSF.
3. Generate angular distribution of the photoelectrons according to polarization model.
4. Generate maps for the polarization degree and angle.

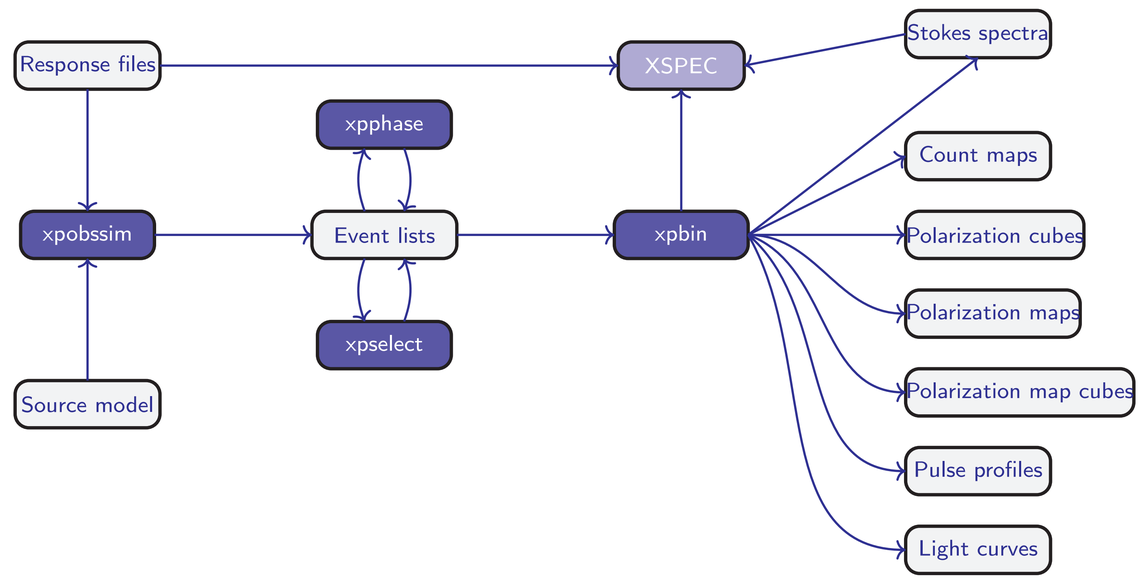


Polarization maps in the 2–8 keV energy band for a simulated, 2 Ms Cassiopea A

Analysis tools

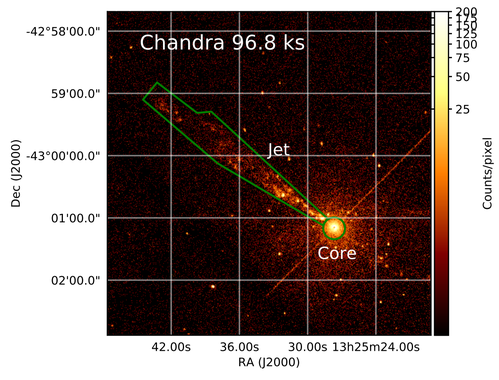
- Some basic analysis tools have been developed in order to:
  - ▷ Select subsamples of photons based on event energy, direction, time or phase.
  - ▷ Bin and fit the simulated data, producing count maps, spectr, phasograms, light and modulation curves.
- The produced output files can be fed into the standard analysis tools (e.g. XSPEC).
- Tools to fit the count spectra in phase to obtain the normalization and spectral index of input model

Architectural overview

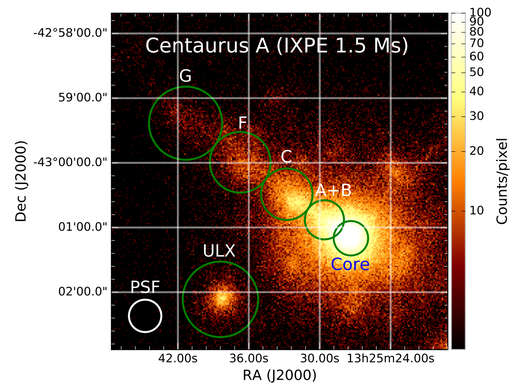


Chandra-to-IXPE converter

- Process an actual Chandra photon list and produce a IXPE simulation:
  1. Chandra measured energies, times and positions taken as the MC truth.
  2. Events are down-sampled and smeared with the provided response functions.
  3. Photoelectrons angular distribution generated according to the provided polarization model.
- Preserve the full correlation between the morphology and the energy spectrum.



Chandra image of Centaurus A.



IXPE simulation of Centaurus A.

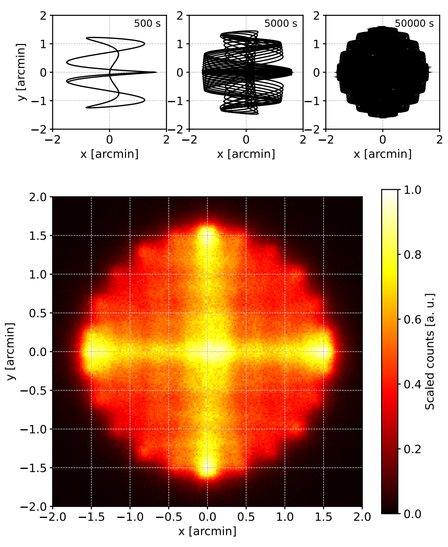
Dithering and pointing history

ixpeobssim has full capabilities to simulate the dithering and pointing history of the observatory

- Dithering pattern with amplitude, a = 1.6′:

$$\begin{cases} \delta x = a\cos(\omega_a t)\,\cos(\omega_x t) \\ \delta y = a\sin(\omega_a t)\,\sin(\omega_y t) \end{cases} \quad (1)$$

- Angular pulsations ω_a, ω_x and ω_y being 907 s, 101 s and 449 s, respectively
- Averages out spurious modulation over the detector surface
- Specifics of the observing strategy captured by the simulation
- Reproduce the morphology of the energy flux in detector coordinates
- Allows for correct calculation of exposure
- Pointing history and idthering stored in output fits files



Default dithering pattern over varying time scales. Normalized counts after convolution with the PSF of the telescope.