XIMPOL: AN X-RAY POLARIMETRY SIMULATION FRAMEWORK

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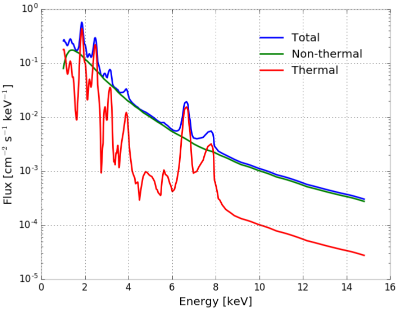
Introduction

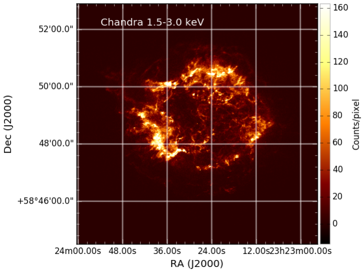
Why do we need a X-ray polarimetry simulation tool?

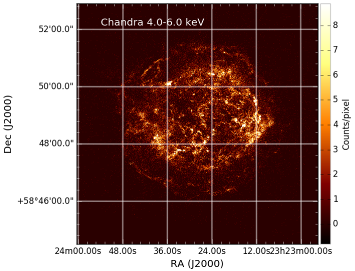
- X-ray polarimetry is the last unexplored field in X-ray astronomy
- It is a valuable diagnostic tool for studying a wide range of processes in the Universe
- Polarization can depend on the spatial and spectral morphology of a source, also on the phase of the source
- Some examples are:
  - Cassiopeia A – spatial and spectral dependent polarization
  - Crab nebula and pulsar – phase-dependent polarization + background
  - GRB 130427A – time-dependent polarization
- Important to have a simulation framework to study the capabilities of a detector of observing these various polarization signatures

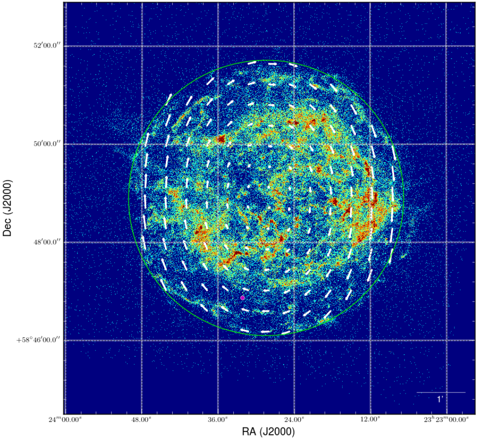
- A simulation framework specifically developed for X-ray polarimetric applications
  - Based on the Python programming language and SciPy
- It is not tied to any specific mission or instrument design – the user provides the IRFs to use
- The output of the simulation is a fits file with all the relevant information of the simulated photons
  - Reconstructed (and MC) direction and energy, time, reconstructed photoelectron angle and phase (when applicable)
- The output files can be directly fed into the standard visualization and analysis tools such as XSPEC
  - We have also developed some basic tools to select and bin the simulated data
- `XIMPOL` is useful not only for simulating physical systems, but also to develop and test end-to-end analysis chains.



- Spectral model taken from paper by E.A. Helder and J. Vink, ApJ 2008
- Spectrum is a superposition of thermal and non-thermal emission
- We take all the line emission to be of thermal origin and assume that the remaining emission is non thermal

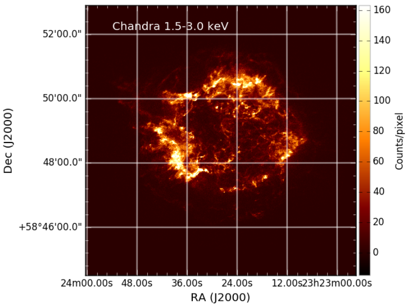


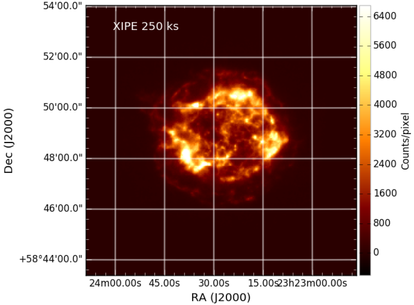




- For the polarization we assume that the thermal component is unpolarized
- The non-thermal component we use a simple geometrical, radially symmetric model
- Polarization angle is tangential and polarization degree is zero at the center of the source and increases to 50% at the edges

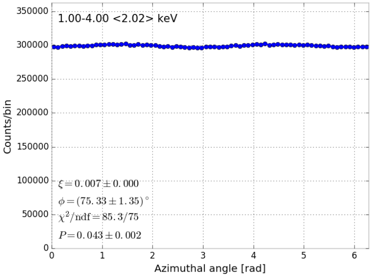
Our final model is the superposition of two independent components, with different spectral, morphological and polarimetric properties.

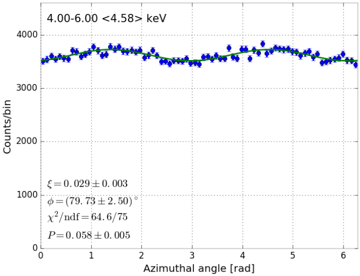




- We simulate 250 ks of XIPE observation of Cas A based on our model
  - Left is Chandra image
  - Right is the simulated XIPE observation
- The XIPE count map is convolved with baseline response functions
  - i.e. this is a simulation of the actual imaging of Cas A with XIPE

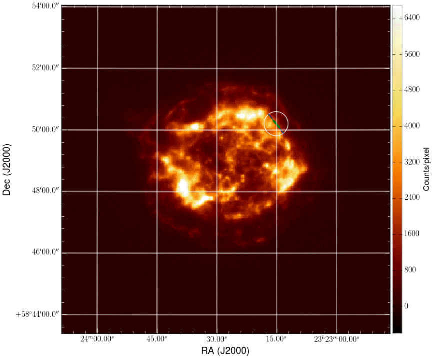
Modeling Cassiopeia A: Simulation output

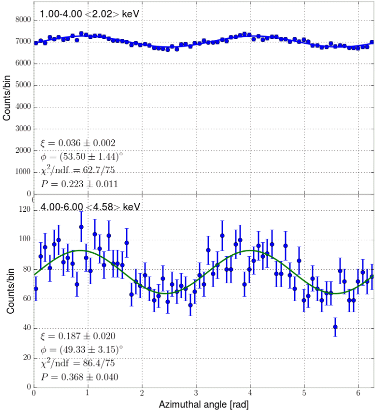




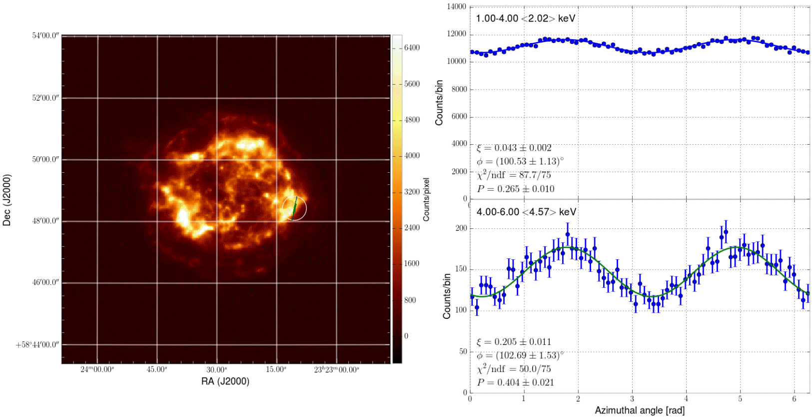
- Azimuthal distribution in two energy bands
  - Left panel shows 1-4 keV and right 4-6 keV
- When the entire source is analyzed, the polarization averages out, even in the high- energy band where the emission is predominantly non-thermal
- The residual polarization degree is of the order of 5%

Imaging Cassiopeia A with XIPE

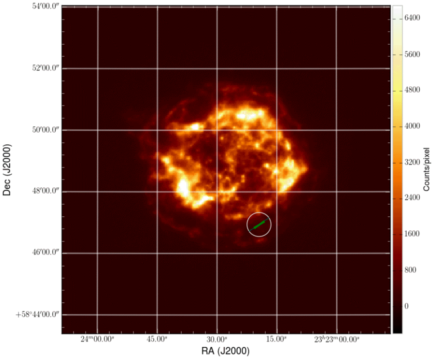


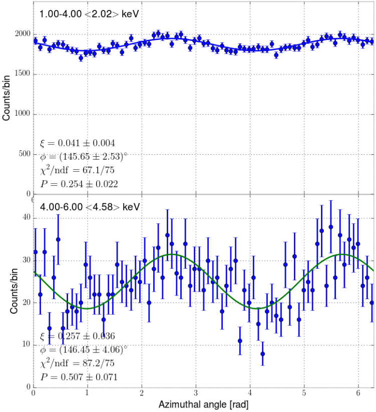


- When we analyze smaller regions within the source we can start to reveal the richness of the polarization pattern.
- The flux integrated in the region is about 3.5% of the entire source

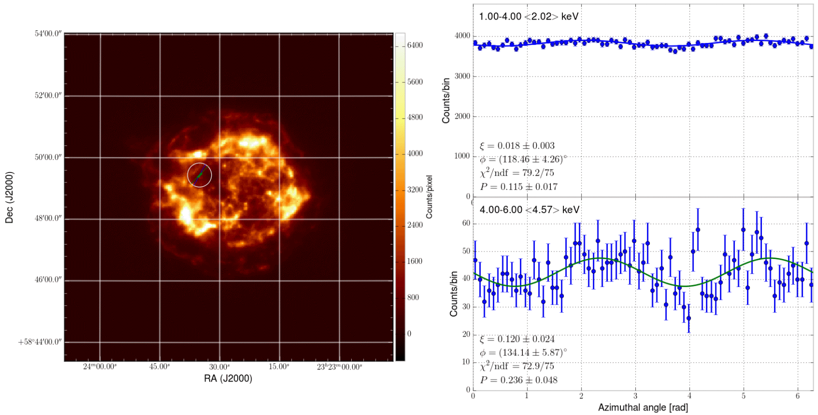


- Analyzing the outer edges of the nebula where there is a larger contribution from the non-thermal emission we find
  - A polarization degree of about 40% in the 4-6 keV energy range
  - A polarization degree of about 26% in the 1-4 keV energy range





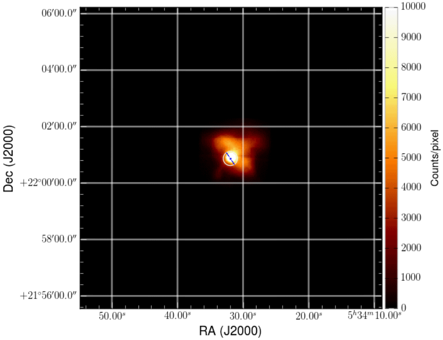
- Analyzing the outer edges of the nebula where there is a larger contribution from the non-thermal emission we find
  - A polarization degree of about 50% in the 4-6 keV energy range
  - A polarization degree of about 25% in the 1-4 keV energy range

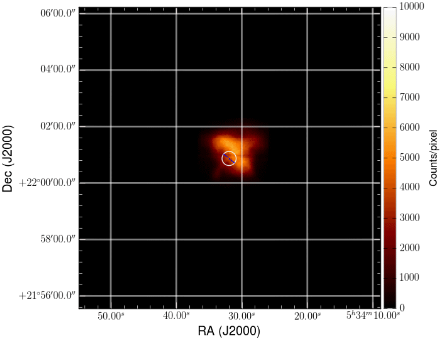


- We are able to analyze even the dimmer regions of the nebula
- You can find a movie with a wider range of sampling regions here: `http://ximpol.readthedocs.org/en/latest/showcase.html`

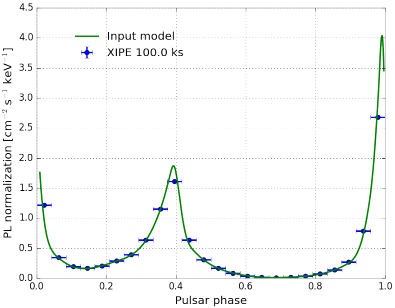
The Crab complex: Simulation input

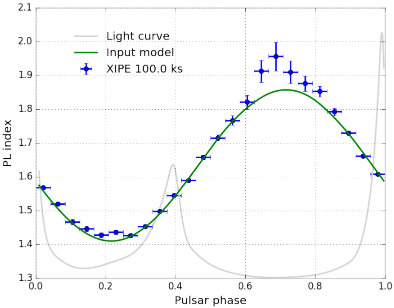
- The pulsar
  - Tabulated models for the phase-resolved optical polarization angle and degree and X-ray spectral parameters for the pulsar
    - Main reference is Weisskopf, M. C. et al., *Chandra Phase-Resolved X-Ray Spectroscopy of the Crab Pulsar*, ApJ 2011
  - Polarization degree and angle are energy independent
  - Spectral model is simple power-law with normalization and spectral index dependent on the phase
  - Input spatial model is not a simple point source but is based on the timing ephemeris taken from Weisskopf et al. ApJ 2004
- The nebula
  - Chandra image of the nebula in the 2–8 keV energy range
  - Spectrum taken to be a simple power-law
  - Fixed polarization degree and angle



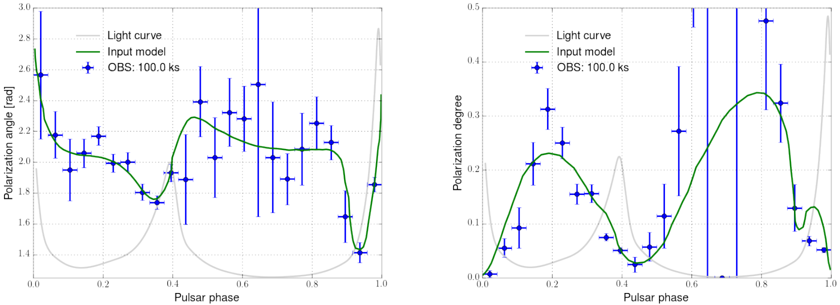


- Simulated 100 ks of the Crab pulsar and nebula based on model described in previous slide
  - Left panel is for on phase and right panel off phase
- White circle is ROI with radius of 0.25 arc-min centered on pulsar position
- You can find a movie with a wider range of sampling regions here: `http://ximpol.readthedocs.org/en/latest/showcase.html`



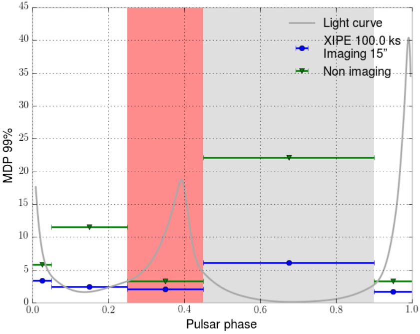


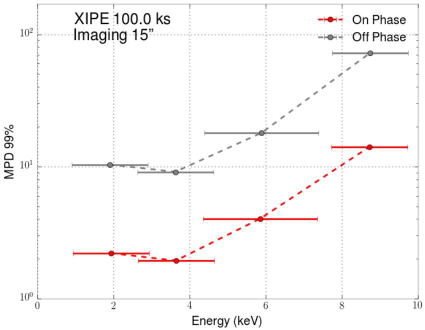
- Simulation 100 ks of only the Crab pulsar
- Split the sample in 20 phase bins and create count spectra in PHA1 format
- Fit the count spectra in each phase bin with XSPEC to obtain the normalization and spectral index
- The fitted parameters agree reasonably well with the input model



- Simulation with Crab pulsar + nebula
- To obtain the polarization (degree and angle) of the pulsar we take all photons within a ROI centered around the pulsar
- And subtract the polarization measurement in the off-phase (i.e. the from the nebula)
- A more *realistic* example of a complete simulation and analysis chain
- Again, the results agree well with the input model

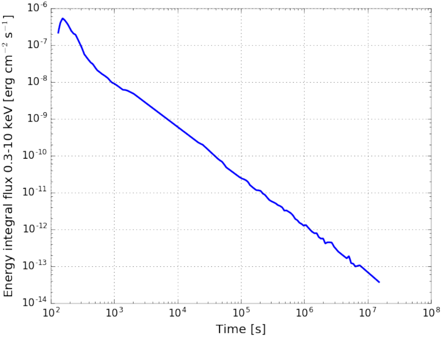
The importance of imaging





- Crab pulsar phasogram for simulation 100 ks
- Thanks to our imaging capabilities we can reduce the background contamination from the nebula
- Which decreases the MDP by a factor of 2 for the on-pulse and a factor of 4-5 off-pulse
- The MDP $<20\%$ up to 10 keV for on-pulse

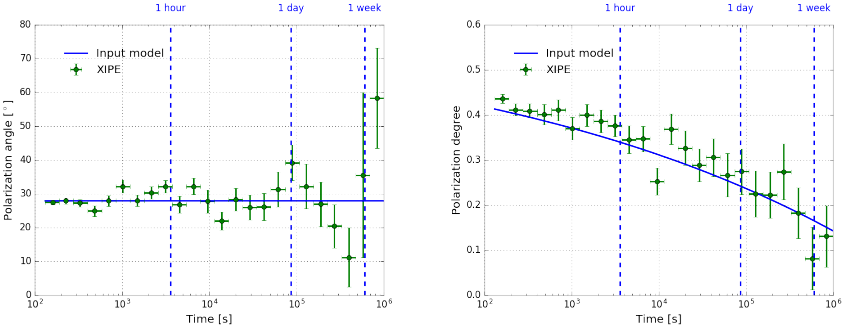
GRB 130427A: Simulation input



- GRB 130427A was one of the brightest GRBs ever observed in X-rays
- We use this GRB as an example of a time-dependent source model
- The GRB was located at $z = 0.34$

- Data points to build the light curve were taken from the Swift XRT light-curve catalog
- Polarization is taken to decrease with time, starting from 40% to 10% 1Ms after the burst
- Polarization angle is taken to be constant

GRB 130427A: Simulation output



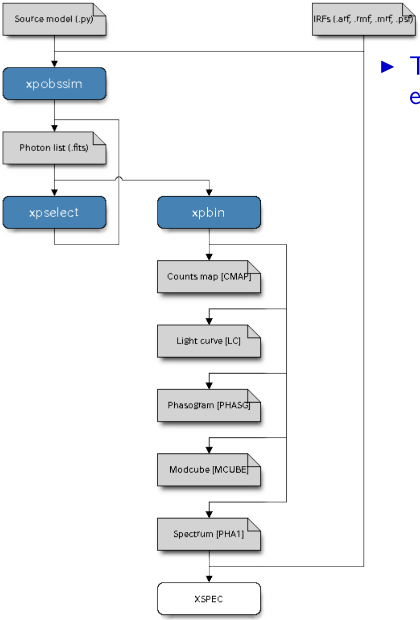
- We sub-selected the event file into non-overlapping time slices whose width is increasing logaritmically with time
- We reconstructed polarization degree and angle in each of the time bins, with the corresponding input model overlaid
- If we were able to re-point the telescope to the GRB direction within a day from the burst, we would still be sensitive to a 10-20% polarization degree in an integration time of the order of 100 ks.

Summary

- XIMPOL is a simulation framework specifically developed for X-ray polarimetric applications
- We have shown a few case studies to illustrate the capabilities of the package
- XIMPOL is available on github: http://ximpol.readthedocs.io/en/latest/index.html
- We welcome discussions and input!

Spare slides

Main Architecture



- The core of `ximpol` is made of three executables:
  1. `xpobssim`
     - Observation simulation
     - Source model:
       morphological, temporal, spectral and polarimetric information
     - IRFs:
       $A_{eff}(E,\theta)$, D(ch,E), PSF(θ), $\mu(E)$
  2. `xpselect`
     - select subsamples of photons based on: the event energy, direction, time or phase
  3. `xpbin`
     - bin the data in several different flavors: producing count maps, spectra, light curves, phasograms
     - and modulation cubes, i.e. histograms of the measured azimuthal distributions in multiple energy layers

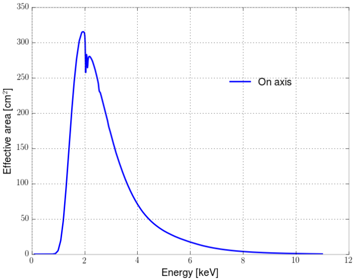
Minimum detectable polarization

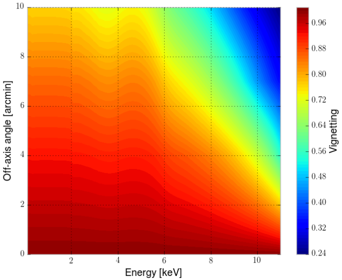
- The Minimum detectable polarization (MDP) is the degree of polarization corresponding to the amplitude of modulation that has only a 1% probability of being detected by chance

$$MDP_{99,S} = \frac{4.292}{\langle \mu \rangle_S} \sqrt{\frac{C_S + (\Omega_S/\Omega_B) C_B}{C_S}}$$

- C_S, C_B are the source and background counts
- μ is the instrument modulation factor
- Ω is the solid angle subtended by the source (background)
- All in the energy band of interest

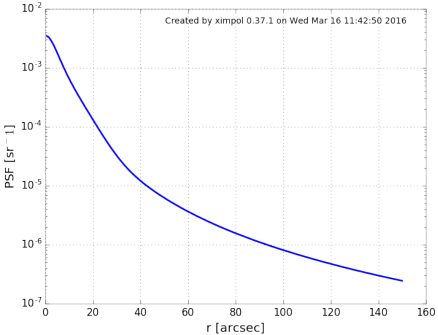
IRFs: effective area





- On-axis effective area as a function of the photon energy (left).
  - Includes the optics and the GPD efficiency.
  - Stored into a .arf FITS file that can be fed into XSPEC (use the exact same IRF file for the simulation and the analysis).
- The relative effective area loss off-axis (right) is also stored but not used, yet.
  - Mainly because we would have to implement the vignetting on the analysis side.

IRFs: point-spread function

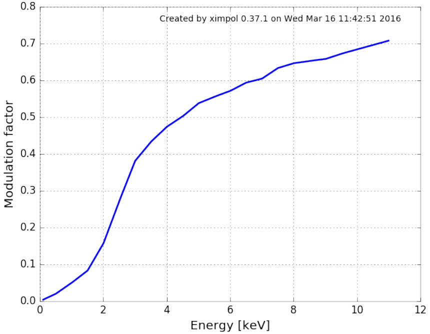


- Exact same parametrization and parameters values of Fabiani et al. (2014).

$$PSF(r) = We^{-\frac{r^2}{2\sigma^2}} + N\left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-\eta}$$

- Parameter values stored into a FITS file.
- Energy dependence of the parameters not implemented, but trivial to do so.

IRFs: modulation factor



- Matching the detector configuration used for the calculation of the effective area.
- Data points stored exactly in the same FITS format as the effective area.

Some XIMPOL capabilities

Science cases implemented so far

- Cassiopeia A
  - Example of spatial and spectral dependent polarization
- Crab nebula and pulsar
  - Example with multiple sources in the field of view
  - Example of phase-dependent polarization
- GRB 130427A
  - Example of point source with time-dependent polarization

Modeling inputs

- Source images in fits format
- Spectral models
  - Tabulated values in ascii files
  - or analytical description of shape with normalization and index
- Expected polarization degree and angle
  - Tabulated values in ascii files
  - or detailed description with shape and type
    - radial implemented so far