IXPE Data Preparation & Analysis Tools

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IXPE Imaging X-Ray Polarimetry Explorer

Purpose

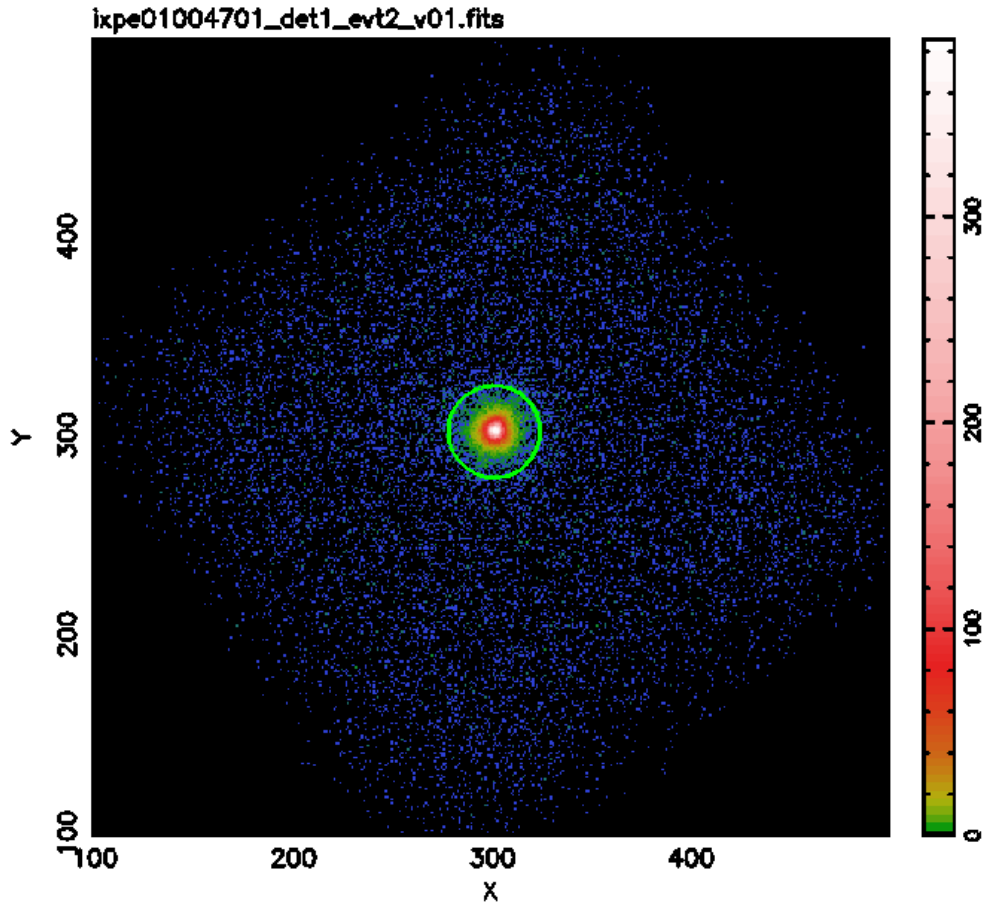
Outline:

- Data Retrieval & Reduction
- Model-independent Polarimetry
- Building Response Matrices
- Spectral Analysis with XSPEC
- Helpful Starter Scripts

Resources:

- IXPE Documentation https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/
- Quick Start Guide https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/ixpe_quickstart.pdf
- IXPE-specific FTOOLS https://heasarc.gsfc.nasa.gov/lheasoft/ftools/headas/ixpe.html
- IXPE Helpdesk https://heasarc.gsfc.nasa.gov/cgi-bin/Feedback?selected=ixpe

Uniqueness of IXPE Observations



IXPE is an IMAGING photon counting polarimeter

You can select regions for analysis using, e.g., ds9

Why are such long exposures needed?

The smallest polarization that can be measured at 99% C.L. (MDP99):

$$\mathrm{MDP}_{99} = \frac{4.29}{\langle\mu\rangle C_S}\left[\frac{C_S + C_B}{T}\right]^{1/2} \approx \frac{4.29}{\langle\mu\rangle\sqrt{N}}$$

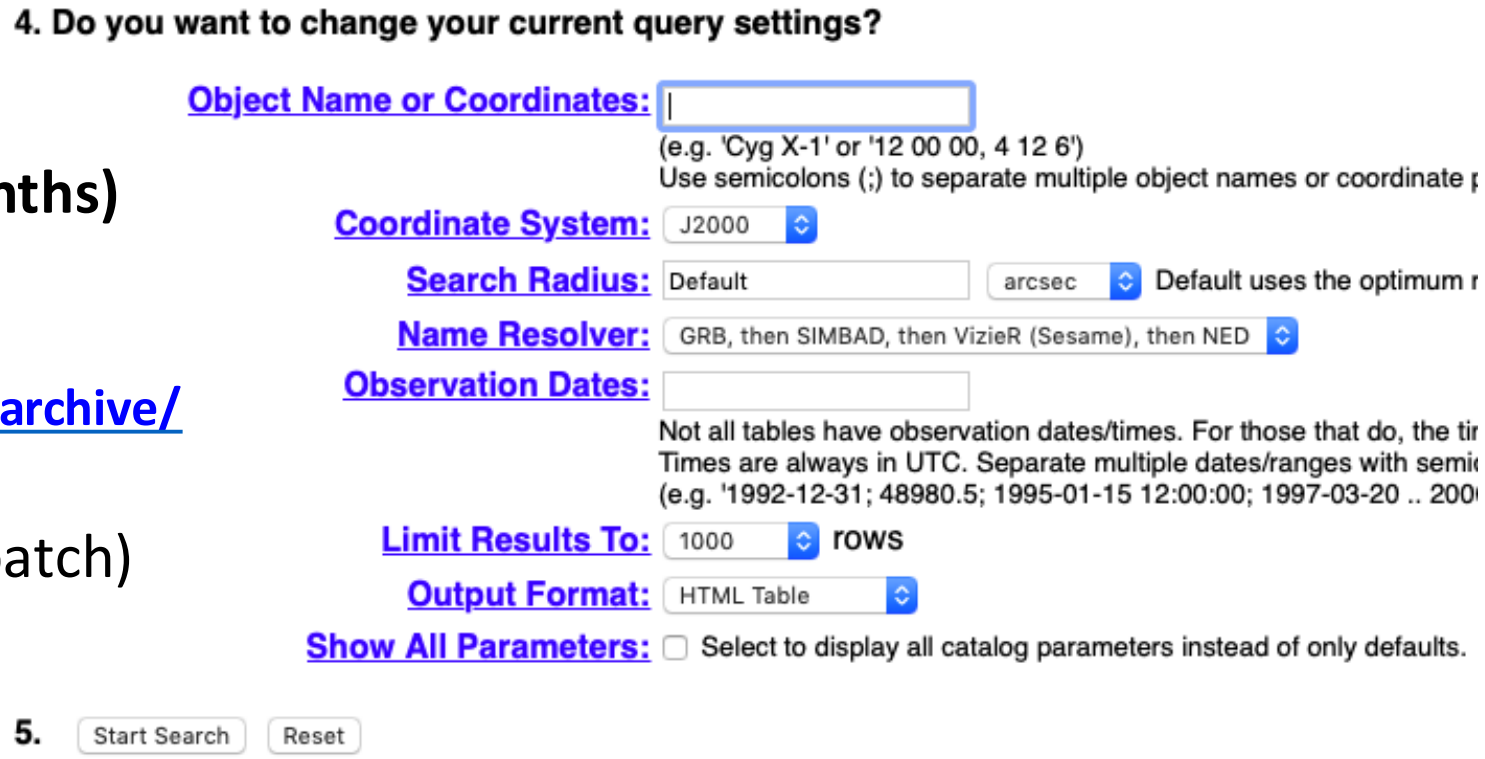
where C_S & C_B are Source and Background count rates, T is the exposure time, $\langle\mu\rangle$(E) ~ 0.3 is the modulation factor, and $N = C_S T$ is the total number of counts when $C_S >> C_B$

Roughly 2 million source counts needed to obtain an MDP99 of 1% (Crab is ~200c/s)

IXPE Data Archive

- **All IXPE data become public once processed & validated (or after an exclusive use period of up to 6 months)**

- **Public access is through HEASARC** https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/
  - Classic browse interface
  - Xamin interface (+ command-line batch)
  - FTP via HTTPS
  - Python



https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3query.pl

A note on file naming conventions

File naming convention for ObsID, e.g., 01004701

```
ixpe01004701_det1_evt2_v01.fits
ixpe01004701_det1_evt1_v02.fits
(hk) ixpe01004701_det1_att_v01.fits
(hk) ixpe01004701_det1_gti_v01.fits
```

similar for `det2` and `det3`

IXPE Level 2 Data

- IXPE Level 2 files are cleaned, gain- and aspect-corrected FITS event lists
- Columns: `TIME`, `PI` (Pulse Invariant energy), `X`, `Y` sky locations
- Additional Stokes parameter columns: `I=W_MOM`, `Q`, `U`

Let $q = \langle q_i \rangle$ and $u = \langle u_i \rangle$ then

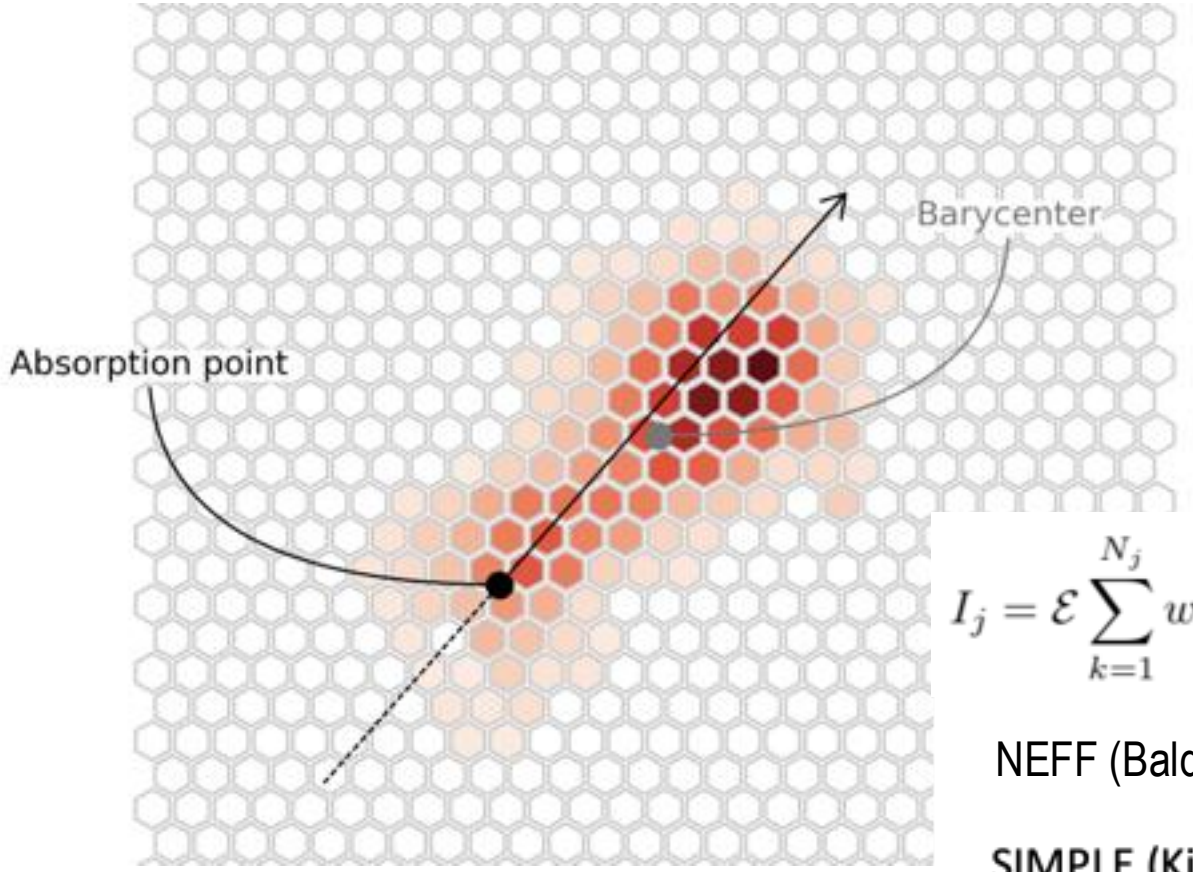
Polarization Degree: $\Pi = \sqrt{q^2 + u^2}$

Polarization Angle: $\psi = \frac{1}{2}\tan^{-1}\left(\frac{u}{q}\right)$

$$q = \Pi \cos(2\psi)$$
$$u = \Pi \sin(2\psi)$$

where the data can be binned by time and/or energy and/or sky location

Event Weighting



Pipeline processing computes moments of the electron track distribution to determine the photon absorption point and photoelectron initial direction.

The event weight is defined in terms of the 2nd moment track length (TL) and width (TW) as:

event weight = (TL - TW / TL + TW)$^{0.75}$ = w_k

$$I_j = \mathcal{E}\sum_{k=1}^{N_j} w_k = \mathcal{E}\sum_{k=1}^{N_j} \texttt{W\_MOM}_k \qquad Q_j = \mathcal{E}\sum_{k=1}^{N_j} w_k \texttt{Q}_k \qquad U_j = \mathcal{E}\sum_{k=1}^{N_j} w_k \texttt{U}_k$$

NEFF (Baldini+22) $\mathcal{E} = (1/T)(\sum_{k=1}^{N} w_k / \sum_{k=1}^{N}(w_k)^2) \equiv (1/TI)N_{\rm eff}$

SIMPLE (Kislat+15) $\mathcal{E} = 1/T$ **UNWEIGHTED** $\mathcal{E} = 1/T \quad w_k \equiv 1$

Note the Stokes *I* spectrum has units of (effective) counts/sec; not the familiar counts

Model-Independent Polarimetry

The FTOOL ***ixpepolarization*** will compute the overall Stokes Q and U values over a user-defined sky region, energy range, and time interval , e.g.:

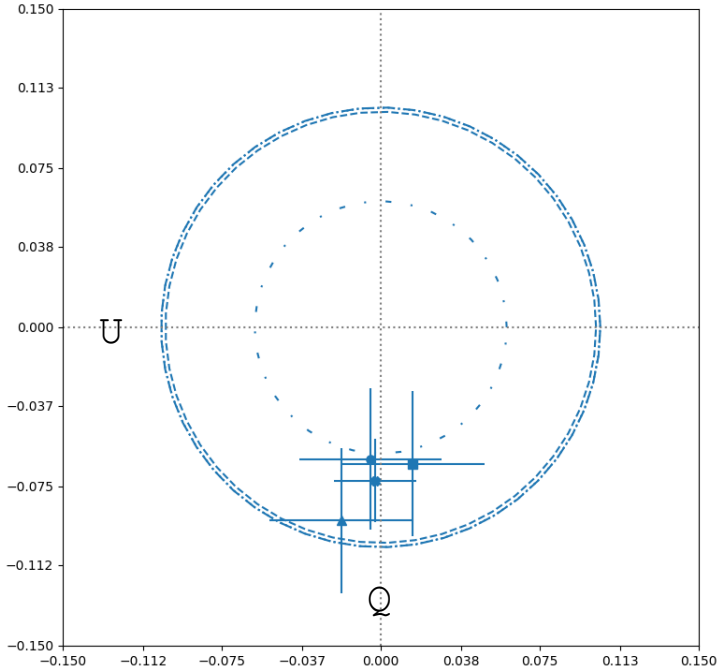
```
> ixpepolarization infile1=ixpe01004701_det1_evt2_v01.fits regfile=src.reg
pi_lo=2.0 pi_hi=8.0  weight_scheme=neff outfile=outfilename
```

Where:

- `weight_scheme` = UNWEIGHTED, NEFF, or SIMPLE
- `regfile` is an existing ds9-formatted region file
- up to 3 infiles can be specified (`infile3,infile2,infile3`)
- `src.reg` contents: `circle(253.4657,39.7623,60")`

ixpepolarization produces a FITS file containing Q, U, and their standard errors, the net polarization degree, angle, modulation factor, and minimum detectable polarization at 99% confidence (MDP99).

ixpeplot_polarization displays the output of ***ixpepolarization*** in the Q,U plane for each DU and for the 3 DUs combined (*right*)



combined: Π = 7.2%, ψ= -46.1 deg

Spectral Extraction with Xselect

https://heasarc.gsfc.nasa.gov/lheasoft/ftools/xselect/xsel.html

```
> xselect prefix=mrk501
xsel> read event "./ixpe01004701_det1_evt2_v01.fits.gz"
xsel> filter region "src.reg"
xsel> extract SPEC stokes=NEFF
xsel> save spec ixpe_det1_src_
```

Saves 3 spectral FITS files:

```
ixpe_det1_src_I.pha
ixpe_det1_src_Q.pha
ixpe_det1_src_U.pha
```

For the 3 Stokes spectra I, Q & U:

`stokes` takes one of 4 values:

```
xsel> extract SPEC stokes=NEFF
xsel> extract SPEC stokes=SIMPLE
xsel> extract SPEC stokes=UNWEIGHTED
xsel> extract SPEC stokes=NONE
```

Repeat for all 3 DUs; similar commands for other filters, e.g., a background region

Instrument Response Files

- There are 3 instrument response files needed: RMF, ARF, and MRF
- There are 3 choices of weights: SIMPLE, NEFF, and UNWEIGHTED

The FTOOL ***ixpecalcarf*** is used to build the ARF and MRF files, e.g.:

```
> ixpecalcarf  evtfile=ixpe01004701_det1_evt2_v01.fits.gz
attfile=ixpe01004701_det1_att_v01.fits.gz  arfout=ixpe_det1_Q.mrf
specfile=none  radius=1.0  weight=1  resptype=mrf
```

Where, for this example, (use the FTOOL fhelp to learn all the many options and alternatives):

- `weight`= 0, 1, or 2 for UNWEIGHTED, NEFF, SIMPLE
- `resptype=mrf` for modulated (Q,U); `=arf` for ancillary response function (I)
- `radius`= the source extraction region radius in arcminutes

The RMFs are in the CALDB, e.g.:

- for NEFF or SIMPLE weighting: `ixpe_d1_20211209_alpha075_01.rmf`
- for UNWEIGHTED: `ixpe_d1_20211209_01.rmf`

(use the FTOOL quzcif for help finding names and locations of correct CALDB files)

Spectro-polarimetry with *XSPEC*

- You now have 9 source spectral files (3 DUs x 3 Stokes parameters) and, potentially, 9 companion background files.
- And you have RMF & ARF or RMF & MRF for all 9 source spectra
- Form 3 data groups, one for each DU:

```
xspec> data 1:1 ixpe_det1_src_I.pha
xspec> data 1:2 ixpe_det1_src_Q.pha
xspec> data 1:3 ixpe_det1_src_U.pha

xspec> data 2:4 ixpe_det2_src_I.pha
xspec> data 2:5 ixpe_det2_src_Q.pha
xspec> data 2:6 ixpe_det2_src_U.pha

xspec> data 3:7 ixpe_det3_src_I.pha
xspec> data 3:8 ixpe_det3_src_Q.pha
xspec> data 3:9 ixpe_det3_src_U.pha
```

…and similarly for `xspec> background`

Spectro-polarimetry with *XSPEC*

Limit analysis to 2-8 keV:

```
xspec> ignore *:0.0-2.0 8.0-**
```

Pick a model including a multiplicative polarization component: `polconst, pollin, polpow`

```
xspec> model constant*tbabs(polconst*powerlaw)
```

Tie Group 2 & 3 parameters to Group 1 values except let `constant` set overall normalization

Simultaneously fit the model to all the data:

```
xspec> fit
```

The parameters of interest are `A` and `psi`, the polarization degree and angle; here, about 7.45% and -47^0 (measured East of North), respectively

```
========================================================================
Model constant<1>*TBabs<2>(polconst<3>*powerlaw<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
                            Data group: 1
   1    1   constant   factor             1.00000      frozen
   2    2   TBabs      nH         10^22    0.646199     +/-  0.103537
   3    3   polconst   A                   7.45137E-02  +/-  1.80681E-02
   4    3   polconst   psi        deg      -47.4491     +/-  6.99991
   5    4   powerlaw   PhoIndex            2.75111      +/-  5.02693E-02
   6    4   powerlaw   norm                0.106061     +/-  7.93573E-03
                            Data group: 2
   7    1   constant   factor             0.955110     +/-  9.46462E-03
   8    2   TBabs      nH         10^22    0.646199     = p2
   9    3   polconst   A                   7.45137E-02  = p3
  10    3   polconst   psi        deg      -47.4491     = p4
  11    4   powerlaw   PhoIndex            2.75111      = p5
  12    4   powerlaw   norm                0.106061     = p6
                            Data group: 3
  13    1   constant   factor             0.907673     +/-  9.00732E-03
  14    2   TBabs      nH         10^22    0.646199     = p2
  15    3   polconst   A                   7.45137E-02  = p3
  16    3   polconst   psi        deg      -47.4491     = p4
  17    4   powerlaw   PhoIndex            2.75111      = p5
  18    4   powerlaw   norm                0.106061     = p6
------------------------------------------------------------------------
```

Bringing it all together with *ixpeproduct*

The FTOOL ***ixpeproduct*** can be used to perform most of the preparatory tasks, e.g.:

```
> ixpeproduct indir=./01004701 outdir=ixpeproduct
srcregfile=src.reg bgregfile=bg.reg weight=1
```

- `indir` has the structure of the IXPE archive with /event_l2/ and /hk/ subdirs containing `evt2` and `att` files for all DUs, respectively
- `weight`= 0, 1, or 2 for UNWEIGHTED, NEFF, SIMPLE
- `srcregfile, bgregfile` are ds9-format region files

Bringing it all together with *ixpeproduct*

- ***ixpeproduct*** extracts Stokes spectra and binned light curves (same core functions as *Xselect*)
- generates response files (using the CALDB and ***ixpecalcarf***)
- updates spectral file header keywords that identify response and background files and scale factors
- calculates Stokes parameters and their derivatives using ***ixpepolarization.***
- The tool also generates an *XSPEC* initialization script (`.xcm` file).
- When `srcregfile` is specified, ***ixpeproduct*** will generate pointing maps (needed for response file generation) using the FTOOL ***ixpeexpmap***.