SIMPUT – A File Format for Simulation Input

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SUMMARY

We present a standard format for source input files used in simulations of astronomical observations. Each source file contains a catalog with one or multiple sources, which are described by particular properties like their position, brightness, energy spectrum, and optional characteristics like time variability, polarization, and spatial extension. This file format defines a common basis to exchange data between different software packages and scientific groups. It was developed in particular for the simulation of X-ray telescopes, but it can also be used in different wavelength domains.

LOG OF SIGNIFICANT CHANGES

Release **D**ate	**S**ections Changed	**B**rief Notes
2011 Feb 18		First draft

1 Introduction

In X-ray astronomy simulations of existing and future telescopes play an important role both to estimate the scientific capabilities provided by an instrument and to understand particular phenomena in measured data. Therefore there are a growing number of different simulation tools for particular issues, each implementing its own particular format for input data.

Astronomical X-ray sources are, e.g., modelled as point sources with coordinates given either on the command line or in a separate file. For extended sources there are also various approaches parameterizing the observable shape or specifying an input image. The range of possible input formats extends even further, when additional parameters like the spectral shape or brightness variability have to be considered.

Due to the large number of existing input formats it is difficult to use data generated for one particular simulation within another software package. We address this issue by introducing a common input data format for simulations of astronomical X-ray telescopes based on the Flexible Image Transport System (FITS) file format defined by Hanisch et al. (2001) and Pence et al. (2010). The proposed format enables modelling of all relevant source properties starting with source positions, spatial shapes for extended sources, energy spectra, polarization of the emitted radiation, as well as time-variable features such as brightness, spectral and spatial variations. It can be regarded as an interface between different simulations and different scientific groups like the users of a simulation and a Magnetohydrodynamic (MHD) modellier providing the input data. The use of this format simplifies the conversion processes necessary up to now and provides a clear and flexible way to describe all relevant features to model X-ray sources.

Although the file format has been developed in particular for simulations of X-ray telescopes, it can also be used in different wavelength domains of astronomy by adjusting the required units. The usage of physical units within this format is based on the specification defined by George & Angelini (1995).

In order to create SIMPUT files according to the presented format, one can use the C-library 'libsimput' developed in particular for this purpose. It contains basic routines to create a source catalog with one or several X-ray sources and to store the additional data like spectra, light curves, and images in separate FITS Header and Data Unit (HDU)'s.

2 File Format

A SIMPUT FITS file contains several different types of extensions with the formats described in this section. The main file must contain at least one source catalog extension defining the individual sources. Of course, the catalog can also consist of a single source. Additional data like spectra, light curves, or images can be stored in separate extensions in the same file or might be located in other FITS files. The basic layout of a SIMPUT file is shown in Fig. 1.

The file format can describe point-like and spatially extended sources. The sources might exhibit either a constant or time-variable brightness. The emitted radiation can have a particular polarization. The spectral shape, spatial extension, or polarization of the emitted photons might also be time-dependent. By combining different features of this format, one can describe almost any astronomical source. For instance a spatially extended source, which has different emission regions with particular spectra, can be described as a superposition of several separate source images with corresponding spectra. In addition each of these spectra can have different polarization.

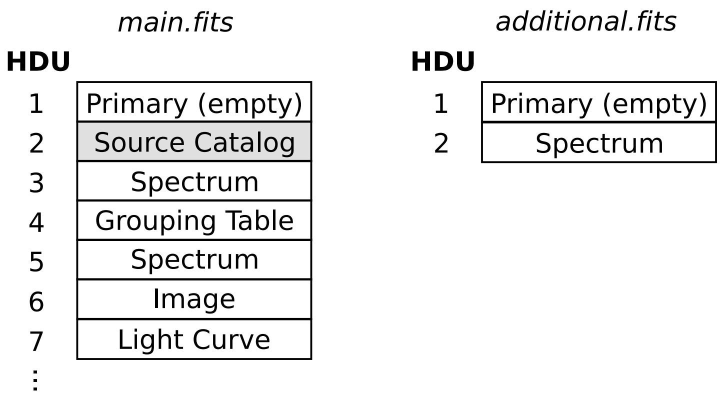

Figure 1: A SIMPUT file contains at least one source catalog extension with the basic source description. Additional data like spectra, light curves, and images can be stored in separate HDU's or even in separate FITS files.

The combination of multiple HDU's of the same type, like several spectra for a single source, is realized by using grouping tables (HEASARC, 2007; Jennings et al., 2007). These are basically binary FITS tables containing references to one or several other HDU's located either in the same or in different FITS files. The 'cfitsio' library contains particular functions to access grouping tables.

2.1 Source Catalog Extension

Description The main extension in a SIMPUT FITS file is a source catalog providing the basic properties of individual sources. It defines the most important source characteristics like the position and brightness. Additional information about the source spectrum, light curve, or spatial extension is stored in separate FITS file HDU's. The entries in the catalog contain links to the corresponding extensions using the extended filename syntax (Pence, 1999).

In order to be used as simulation input, a SIMPUT FITS file must contain at least one source catalog extension, even if it describes only one single source. The name of this extension should be **SRC_CAT**.

Extension Header The following keywords are mandatory:

- HDUCLASS - should contain the string 'OGIP'
- HDUCLAS1 - should contain the string 'SIMPUT'
- HDUCLAS2 - should contain the string 'SRC_CAT'
- HDUVERS = '1.0.0' - giving the version of the format
- RADECSYS - reference coordinate system, e.g. 'FK5'
- EQUINOX - reference coordinate system, e.g. '2000.0'

The usage of the RADECSYS and EQUINOX keywords is described by Calabretta & Greisen (2002).

Data Format The data within the extension are organised as a BINTABLE with the following columns:

1. *ID*, an 4-byte INTEGER value containing a unique identifier for each entry.
   The FITS column name is **SRC_ID**.
   (unitless).
2. *Name*, a STRING (fixed or variable length) containing the name of the source (optional).
   The FITS column name is **SRC_NAME**.
   (unitless).
3. α, a 4-byte REAL value containing the right ascension of the source.
   The FITS column name is **RA**.
   The recommended units are deg.
4. δ, a 4-byte REAL value containing the declination of the source.
   The FITS column name is **DEC**.
   The recommended units are deg.
5. *Flux density*, a 4-byte REAL value containing the source flux density in the specified reference energy band.
   The FITS column name is **FLUX**.
   The recommended units are $\mathrm{erg\,s^{-1}\,cm^{-2}}$.
6. E_{min}, a 4-byte REAL value specifying the lower value of the reference energy band.
   The FITS column name is **E_MIN**.
   The recommended units are keV.
7. E_{max}, a 4-byte REAL value specifying the upper value of the reference energy band.
   The FITS column name is **E_MAX**.
   The recommended units are keV.
8. *Spectrum*, a STRING (fixed or variable length) containing a reference to the FITS file HDU with the energy spectrum of the source or a grouping table. The reference is given via the extended filename syntax specifying the filename, EXTNAME, and EXTVER (might refer to another file, value is required).
   The FITS column name is **SPECTRUM**.
   (unitless).
9. *Image*, a STRING (fixed or variable length) containing a reference to the FITS file HDU with an image of the source or a grouping table. The reference is given via the extended filename syntax specifying the filename, EXTNAME, and EXTVER (might refer to another file, optional).
   The FITS column name is **IMAGE**.
   (unitless).
10. *Light Curve*, a STRING (fixed or variable length) containing a reference to the FITS file HDU with the light curve of the source. The reference is given via the extended filename syntax specifying the filename, EXTNAME, and EXTVER (might refer to another file, optional).
    The FITS column name is **LIGHTCUR**.
    (unitless).

The basic scheme of the source catalog extension is displayed in Fig. 2.

Points to note & Conventions

- The reference energy band defined in the E_MIN and E_MAX column must be covered by the assigned source spectrum.

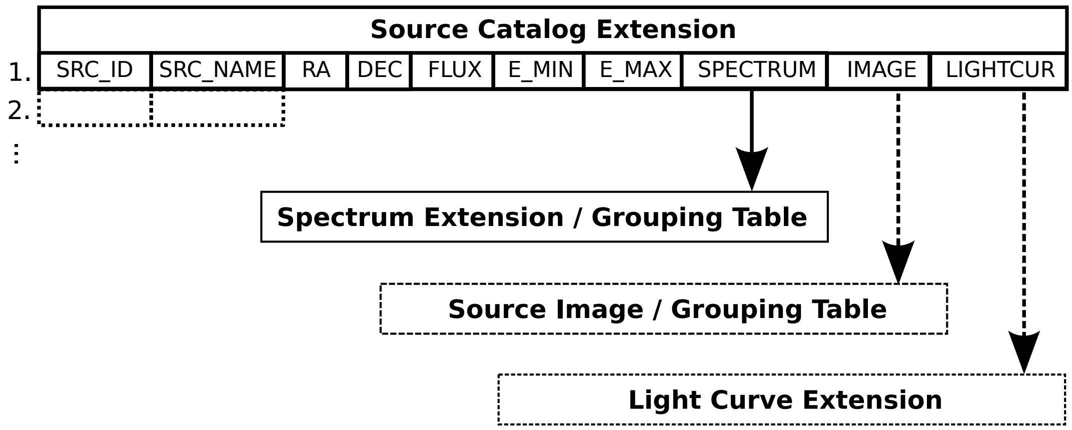

Figure 2: Layout of the source catalog extension. Each source must refer to at least one spectrum extension or several spectra combined in a grouping table, whereas the specification of a light curve and one or multiple source images is optional (indicated by the dashed lines).

- The links to additional FITS file HDU's containing spectra, light curves, or images are given by the name of the corresponding file, the extension name (EXTNAME) and version (EXTVER) according to the extended filename syntax (Pence, 1999).
- As a model for a time-variable source, each entry in the source catalog might have multiple energy spectra or image files, which are valid for particular times or phases. In that case a light curve has to be specified and the SPECTRUM or IMAGE column should contain a link to a grouping table (HEASARC, 2007; Jennings et al., 2007) referencing the set of corresponding FITS file HDU's.
- A single extended source with different energy spectra for different emission regions can be described by multiple entries in the source catalog with different images and spectra. The superposition of the individual entries in the simulation results in the complete image of the extended source.
- Different source entries in the catalog can refer to the same spectrum, light curve, or source image, which is scaled according to the flux density of each individual entry in the catalog. The flux density value given for a particular entry in the catalog determines the absolute flux for this source. The flux densities given in the additional extensions have to be scaled. This provide the possibility to use, e.g., the same spectral shape for multiple sources with different brightness.

2.2 Spectrum Extension

In SIMPUT files there are 4 different basic ways to describe the energy spectrum of a source. Each entry in the catalog must refer to at least one spectrum extension. Several sources with different brightness can refer to the same spectrum, which is scaled according to the particular energy flux density of the respective entries in the catalog.

A single source entry can also refer to multiple spectra combined in a grouping table, as shown in Fig. 3. This is useful, if the spectral shape is not persistent, but changes with time or phase in case of a periodic oscillation. In that case spectra for different points of time or phases during the simulated time interval can be stored in separate HDU's. The simulation software might, e.g., apply a linear interpolation for the intervals in between two separate spectra.

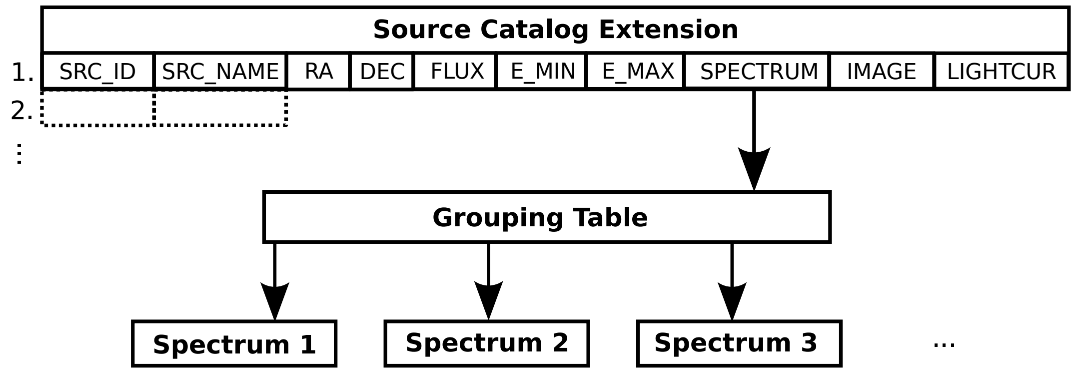

Figure 3: A single source in the catalog can have a set of multiple spectra by referencing a grouping table that combines all these spectra. Each spectrum is only valid for a particular time or phase. For phase-dependent spectra in a periodic system the source must also have a link to a light curve defining the periodicity.

In case of time-dependent spectra each spectrum extension must contain the following keywords:

- MJDREF - MJD for reference time
- TSTART - start time of valid interval
- TSTOP - stop time of valid interval
- TIMEZERO - zero time
- TIMESYS - the system used to define the time
- TIMEUNIT - unit for TSTART, TSTOP, TIMEZERO
- CLOCKCOR - if time is corrected to UT

The usage of the time definition keywords is described by Angelini et al. (1994).

For phase-dependent spectra each spectrum extension must contain the following keyword:

- PHASE - phase of the periodic oscillation the spectrum is valid for (recommended interval from 0 to 1)

The relation between the time and the different phases of the source state is given in a separate light curve extension (see Sec. 2.4).

A spectrum extension can also contain information about the polarization of the emitted radiation by specifying the following keywords:

- STOKES1 - Stokes parameter
- STOKES2 - Stokes parameter
- STOKES3 - Stokes parameter
- RADECSYS - reference coordinate system, e.g. 'FK5'
- EQUINOX - reference coordinate system, e.g. '2000.0'

The keywords STOKES1, STOKES2, and STOKES3 define the 2nd, 3rnd, and 4th compoment of the normalized Stokes vector (Stokes, 1852) specifying the polarization of the emitted radiation. The information about the absolute intensity of the measured radiation is neglected, such that the first component of the normalized Stokes vector (STOKES0) has always a value of 1, and therefore does not have to be specified explicitly. The intensity is given by the particular source brightness. The keywords RADECSYS and EQUINOX define the coordinate system the polarization direction is based on.

2.2.1 Mission-Independent Spectrum

This is the preferred format for the description of a source spectrum, because it is mission-independent and physically accurate at the same time. It can therefore be used for simulations of different telescopes covered by the specified energy range.

Description The spectrum extension describes the energy spectrum of a source in a mission- (and therefore effective area-) independent way giving the photon flux density in a particular energy range. In order to determine the spectrum for a specific telescope, it has to be multiplied with the corresponding effective area (George & Zellar, 1995) or Ancillary Response File (ARF) (George et al., 1998, 2007) respectively.

Extension Header The following keywords are mandatory:

- HDUCLASS - should contain the string 'OGIP'
- HDUCLAS1 - should contain the string 'SIMPUT'
- HDUCLAS2 - should contain the string 'SPECTRUM'
- HDUVERS = '1.0.0' - giving the version of the format

Data Format The data within the extension are organised as a BINTABLE with the following columns:

1. E_{min}, a 4-byte REAL value containing the lower value of the energy bin.
   The FITS column name is **E_MIN**.
   The recommended units are keV.
2. E_{max}, a 4-byte REAL value containing the upper value of the energy bin.
   The FITS column name is **E_MAX**.
   The recommended units are keV.
3. *Flux density distribution*, a 4-byte REAL value containing the photon flux density distribution for the respective energy bin.
   The FITS column name is **FLUX**.
   The recommended units are photons $\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{keV}^{-1}$.

Points to note & Conventions

- The energy bins defined by the E_MIN and E_MAX columns should not overlap or have any gaps in between. They should be ordered in ascending order.
- The energy flux density can be easily obtained by multiplying the photon flux density with the photon energy corresponding to each spectral bin.

2.2.2 PHA File

The source spectrum can also be modelled by a standard Pulse Height Amplitude (PHA) file (Arnaud et al., 2009; George & Arnaud, 2004).

Points to note & Conventions

- PHA files contain the convolution of the source spectrum with a mission-dependent detector response matrix. Since the convolution with the response matrix is an non-invertible process, the original spectrum cannot be reconstructed from these data. This has to be taken into account, when using PHA files to describe source spectra for input to a simulation.

  The specification of a PHA spectrum might be useful, if an existing observation of a source with a particular telescope should be simulated for a different telescope. The energy resolution of the telescope the PHA file was made for should be comparable or better than the resolution of the telescope in the simulation.

  In general the mission-independent spectral format (Sec. 2.2.1) should be preferred in terms of simulation input data.

2.2.3 Photon List

Description The energy spectrum of an X-ray source can also be described by specifying a sample of photons distributed according to the respective spectrum. This can in particular be useful, if the photon sample is obtained, e.g., from a complicated MHD simulation.

Extension Header The following keywords are mandatory:

- HDUCLASS - should contain the string 'OGIP'
- HDUCLAS1 - should contain the string 'SIMPUT'
- HDUCLAS2 - should contain the string 'PHOTONS'
- HDUVERS = '1.0.0' - giving the version of the format
- E_MIN - lower value of the reference energy band
- E_MAX - upper value of the reference energy band
- FLUX - flux density in the reference energy band given in $\mathrm{erg\,s^{-1}\,cm^{-2}}$
- RADECSYS - reference coordinate system, e.g. 'FK5'
- EQUINOX - reference coordinate system, e.g. '2000.0'

The usage of the RADECSYS and EQUINOX keywords is described by Calabretta & Greisen (2002).

In addition a photon list with information about the arrival time of the photons should contain the following time definition keywords, even if the energy spectrum is not time-dependent:

- MJDREF - MJD for reference time
- TSTART - start time
- TSTOP - stop time
- TIMEZERO - zero time
- TIMESYS - the system used to define the time

- TIMEUNIT - unit for TSTART, TSTOP, TIMEZERO
- CLOCKCOR - if time is corrected to UT

The usage of the time definition keywords is described by Angelini et al. (1994).

Data Format The data within the extension are organised as a BINTABLE with the following columns:

1. *Time*, a 8-byte REAL value containing the arrival time of the photon (relative to the offset given by the header keyword TIMEZERO).
   The FITS column name is **TIME**.
   The units are defined by the header keyword TIMEUNIT.
2. α, a 4-byte REAL value containing the right ascension of the origin of the photon.
   The FITS column name is **RA**.
   The recommended units are deg.
3. δ, a 4-byte REAL value containing the declination of the origin of the photon.
   The FITS column name is **DEC**.
   The recommended units are deg.
4. *Energy*, a 4-byte REAL value containing the energy of the photon.
   The FITS column name is **ENERGY**.
   The recommended units are keV.

The column TIME is optional.

Points to note & Conventions

- In contrast to most of the general format definitions presented in this document the photon lists are mainly related to X-ray astronomy in particular and are usually not applicable for other wavelengths.
- The main advantage of photon lists is that event lists obtained from real observations can be easily converted to this format and therefore be used as input for simulations of different telescopes.
- The reference energy band defined by the E_MIN and E_MAX header keywords must be covered by the specified source spectrum.
- The number of photons in the list should be sufficiently large for the statistical purpose of the simulation. Depending on the particular algorithm not all photons in the list are used in a simulation, but only some of them will be selected by a randomization process. The number of actually required photons depends on the length of the simulated time interval and the effective area of the selected telescope.

  For a particular telescope the photon rate R in the reference energy band can be obtained from the FLUX keyword and the effective area. If N is the number of photons in the list with an energy in the appropriate range and T is the simulated time interval, R should be at least a factor of 5 smaller than N/T in order to guarantee a sufficiently large number of photons. The simulation software has to make sure that this criterion is fulfilled.

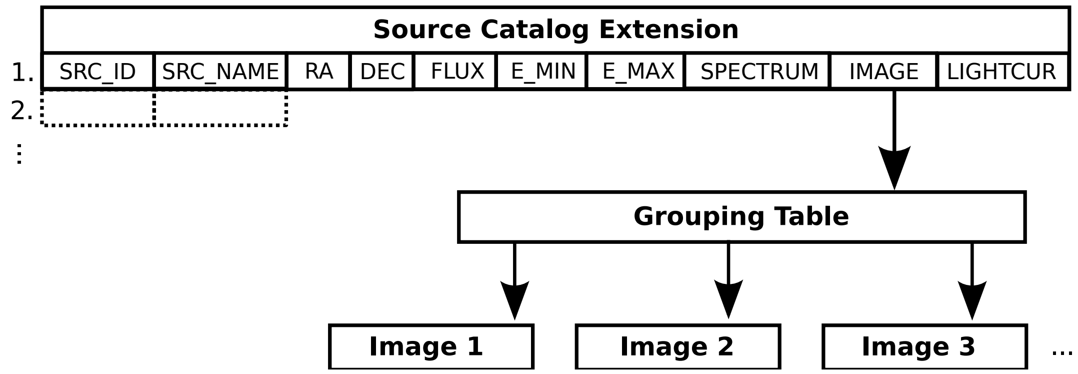

Figure 4: A single source in the catalog can have a set of images by referencing a grouping table that combines all these images. Each image is only valid for a particular time or phase in a periodic system. For phase-dependent images the source must also have a link to a light curve defining the periodicity.

2.2.4 Spectral Model

The spectrum of an X-ray source can also be defined by an appropriate spectral model stored in an ASCII file including all required parameters. The file can be either an XSPEC[1] '*.xcm' model file with a format compatible to XSPEC version 12.6.0 or an ISIS[2] '*.par' file compatible to ISIS version 1.6.1-26.

The definition of a spectral model is specific for X-ray spectra.

2.3 Image Extension

Description Extended sources can be described by an image obtained from an observation or from a simulation. The image represents the spatial distribution of the flux density. The position of the image is given via the World Coordinate System (WCS).

If the spatial shape of a source is time-dependent, this can be described by several images, which are valid for particular times or phases in case of a periodic system. The multiple images are combined in a grouping table, as indicated in Fig. 4. The IMAGE field in the corresponding source catalog refers to this grouping table.

Extension Header The following keywords are mandatory:

- HDUCLASS - should contain the string 'OGIP'
- HDUCLAS1 - should contain the string 'SIMPUT'
- HDUCLAS2 - should contain the string 'IMAGE'
- HDUVERS = '1.0.0' - giving the version of the format
- CTYPE1 - WCS axis type
- CTYPE2 - WCS axis type
- CUNIT1 - units of CRVAL1 and CDELT1
- CUNIT2 - units of CRVAL2 and CDELT2

[1] `https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html`
[2] `http://space.mit.edu/cxc/isis/`

- CRPIX1 - reference point in pixels
- CRPIX2 - reference point in pixels
- CRVAL1 - coordinate value at reference point
- CRVAL2 - coordinate value at reference point
- CDELT1 - coordinate increment at reference point
- CDELT2 - coordinate increment at reference point
- RADECSYS - reference coordinate system, e.g. 'FK5'
- EQUINOX - reference coordinate system, e.g. '2000.0'
- E_MIN - lower value of the reference energy band
- E_MAX - upper value of the reference energy band
- FLUX - flux density in the reference energy band given in $\mathrm{erg\,s^{-1}\,cm^{-2}}$

The usage of the WCS header keywords is described by Greisen & Calabretta (2002) and Calabretta & Greisen (2002).

An individual source in the catalog might refer to several images via a grouping table. This is especially useful, if the spatial shape is time-dependent. In that case the header of each individual image must contain the following keywords specifying the time the image is valid for:

- MJDREF - MJD for reference time
- TSTART - start time of valid interval
- TSTOP - stop time of valid interval
- TIMEZERO - zero time
- TIMESYS - the system used to define the time
- TIMEUNIT - unit for TSTART, TSTOP, TIMEZERO
- CLOCKCOR - if time is corrected to UT

The usage of the time definition keywords is described by Angelini et al. (1994).

For phase-dependent spatial variations each image must contain the following keyword:

- PHASE - phase of the periodic oscillation the image is valid for (recommended interval from 0 to 1)

The relation between the time and the different phases of the source state is given in a separate light curve extension (see Sec. 2.4).

Data Format The source image is basically a 4-byte REAL FITS image. The value of each pixel represents the relative flux density with respect to the reference value defined in the FITS header of the image extension. For instance a value of 0.012 means 1.2 % of the reference flux density.

Points to note & Conventions

- The sum of all pixel values should be 1.
- The WCS keywords of a source image overwrite the RA and DEC values of the respective entry in the source catalog table.
- A spatially extended source with different emission regions characterized by particular spectra can be modelled by a superposition of different images in combination with the spectra describing the particular emission features of the corresponding regions. An example of that is shown in Sec. 3.2.

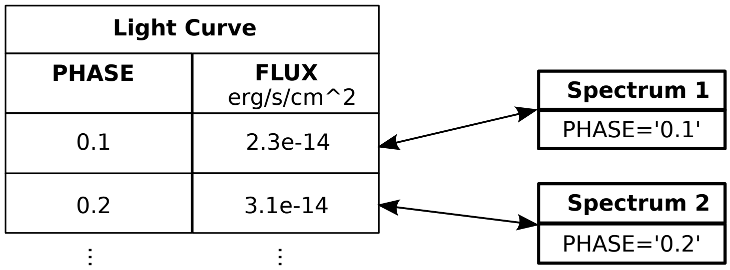

Figure 5: The light curve presented in this figure represents a periodic system with spectral variations over the different phases of the oscillation. The connection between the phases in the light curve and the corresponding spectra is established via the PHASE column in the light curve and the header keywords in the spectra respectively. In an analog way different source images can be assigned to particular phases of points of time.

2.4 Light Curve Extension

Description Brightness variability of a source can be modelled by a light curve describing the time-dependence of the flux density. If the variability is periodic, one can also specify the phase of the oscillation instead of the time in the light curve. A light curve can, e.g., be used to model the pulse profile of the Crab.

In combination with spectra and source images, which are only valid for a particular time (see corresponding sections), light curves can also describe time-dependent spectral and spatial variations. If a source, e.g., is oscillating between a hard and a soft spectrum, it can be modelled by a light curve describing the brightness variation during the different phases of this oscillation and several spectra in separate extensions, which are assigned to the respective phases via their header keywords (see Fig. 5 and Sec. 2.2).

Extension Header The following keywords are mandatory:

- HDUCLASS - should contain the string ‘OGIP’
- HDUCLAS1 - should contain the string ‘SIMPUT’
- HDUCLAS2 - should contain the string ‘LIGHTCUR’
- HDUVERS = ‘1.0.0’ - giving the version of the format
- MJDREF - MJD for reference time
- TSTART - start time
- TSTOP - stop time
- TIMEZERO - zero time
- TIMESYS - the system used to define the time
- TIMEUNIT - unit for TSTART, TSTOP, TIMEZERO
- CLOCKCOR - if time is corrected to UT
- E_MIN - lower value of the reference energy band
- E_MAX - upper value of the reference energy band
- FLUX - flux density in the reference energy band given in $\mathrm{erg\,s^{-1}\,cm^{-2}}$
- PERIODIC - flag whether the light curve is periodic (‘1’) or not (‘0’)

The usage of the time definition keywords is described by Angelini et al. (1994).

If the light curve describes a period system, the following additional keywords are required:

- PHASE0 - phase of periodic oscillation at TIMEZERO (recommended value between 0 and 1)
- PERIOD - duration of one oscillation period (units given by TIMEUNIT)

Data Format The data within the extension are organised as a BINTABLE with the following columns:

1. *Time*, a 8-byte REAL value containing the time (relative to the offset given by the header keyword TIMEZERO).
   The FITS column name is **TIME**.
   The units are defined by the header keyword TIMEUNIT.
2. *Phase*, a 4-byte REAL value containing the phase in a periodic system.
   The FITS column name is **PHASE**.
   (unitless, value in the interval from 0 to 1).
3. *Flux density*, a 4-byte REAL value containing the relative source flux density in the reference energy band at the corresponding time or phase. All values are relative to the reference flux density defined by the header keyword FLUX.
   The FITS column name is **FLUX**.
   (unitless).

Points to note & Conventions

- For periodic systems the PHASE column should be used instead of the TIME column.
- The TIME and PHASE columns should have ascending chronological order.
- The reference energy band defined by the E_MIN and E_MAX header keywords must be covered by the specified source spectrum.

3 Examples

In order to illustrate the intuitive structure of the SIMPUT file format, this section lists 2 examples. One of them describes a simple system of two single X-ray point sources with constant brightness each having its own spectrum. The other one describes an extended X-ray source with different polarized emission regions and a point source oscillating between 2 states.

3.1 Simple Example

The following example describes a simple system of two single point-like X-ray sources. Both sources have a constant brightness and each of them has its own spectrum. All data are combined in one FITS file 'simple.fits' with 4 HDU's (1 empty primary, 1 source catalog, and 2 spectra).

3.1.1 simple.fits

The primary HDU is empty and therefore neglected here.

HDU 2 This HDU contains the source catalog.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   57 / width of table in bytes
NAXIS2  =                    2 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                   10 / number of fields in each row
TTYPE1  = 'SRC_ID  '           / label for field   1
TFORM1  = 'J       '           / data format of field: 4-byte INTEGER
TTYPE2  = 'SRC_NAME'           / label for field   2
TFORM2  = '8A      '           / data format of field: ASCII Character
TTYPE3  = 'RA      '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
TTYPE4  = 'DEC     '           / label for field   4
TFORM4  = 'E       '           / data format of field: 4-byte REAL
TTYPE5  = 'FLUX    '           / label for field   5
TFORM5  = 'E       '           / data format of field: 4-byte REAL
TTYPE6  = 'E_MIN   '           / label for field   6
TFORM6  = 'E       '           / data format of field: 4-byte REAL
TTYPE7  = 'E_MAX   '           / label for field   7
TFORM7  = 'E       '           / data format of field: 4-byte REAL
TTYPE8  = 'SPECTRUM'           / label for field   8
TFORM8  = '23A     '           / data format of field: ASCII Character
TTYPE9  = 'IMAGE   '           / label for field   9
TFORM9  = '1A      '           / data format of field: ASCII Character
TTYPE10 = 'LIGHTCUR'           / label for field  10
TFORM10 = '1A      '           / data format of field: ASCII Character
EXTNAME = 'SRC_CAT '           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SRC_CAT '
HDUVERS = '1.0.0   '
RADECSYS= 'FK5     '
EQUINOX =                2000.
TUNIT3  = 'deg     '
TUNIT4  = 'deg     '
TUNIT5  = 'erg /s /cm**2'
TUNIT6  = 'keV     '
TUNIT7  = 'keV     '
END

        SRC_ID      SRC_NAME RA              DEC             FLUX
                             deg             deg             erg /s /cm**2
```

```
      1           1 SIMPLE-1   2.3469999E+01  -8.1199999E+00   5.3299999E-12
      2           2 SIMPLE-2   2.3920000E+01  -7.8800001E+00   2.1799999E-11

        E_MIN           E_MAX           SPECTRUM                IMAGE LIGHTCUR
        keV             keV
      1   1.0000000E+00   1.0000000E+01 simple.fits[SPECTRUM,1]
      2   5.0000000E-01   1.2000000E+01 simple.fits[SPECTRUM,2]
```

HDU 3 This HDU contains the spectrum of the first source in the catalog.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   12 / width of table in bytes
NAXIS2  =                  199 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / number of fields in each row
TTYPE1  = 'E_MIN   '           / label for field   1
TFORM1  = 'E       '           / data format of field: 4-byte REAL
TTYPE2  = 'E_MAX   '           / label for field   2
TFORM2  = 'E       '           / data format of field: 4-byte REAL
TTYPE3  = 'FLUX    '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
EXTNAME = 'SPECTRUM'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SPECTRUM'
HDUVERS = '1.0.0   '
EXTVER  =                    1
TUNIT1  = 'keV     '
TUNIT2  = 'keV     '
TUNIT3  = 'photon /s /cm**2 /keV'
END

        E_MIN           E_MAX           FLUX
        keV             keV             photon /s /cm**2 /keV
      1   1.0000000E-01   2.0000000E-01   2.4728054E-31
      2   2.0000000E-01   3.0000001E-01   6.2420354E-06
      3   3.0000001E-01   4.0000001E-01   9.5439591E-02
      4   4.0000001E-01   5.0000000E-01   1.7395179E+00
      5   5.0000000E-01   6.0000002E-01   3.5762501E+00
      ...
```

HDU 4 This HDU contains the spectrum of the second source in the catalog.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
```

```
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   12 / width of table in bytes
NAXIS2  =                  199 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / number of fields in each row
TTYPE1  = 'E_MIN   '           / label for field   1
TFORM1  = 'E       '           / data format of field: 4-byte REAL
TTYPE2  = 'E_MAX   '           / label for field   2
TFORM2  = 'E       '           / data format of field: 4-byte REAL
TTYPE3  = 'FLUX    '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
EXTNAME = 'SPECTRUM'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SPECTRUM'
HDUVERS = '1.0.0   '
EXTVER  =                    2
TUNIT1  = 'keV     '
TUNIT2  = 'keV     '
TUNIT3  = 'photon /s /cm**2 /keV'
END

        E_MIN           E_MAX           FLUX
        keV             keV             photon /s /cm**2 /keV
      1   1.0000000E-01   2.0000000E-01   1.3464495E+00
      2   2.0000000E-01   3.0000001E-01   6.6499883E-01
      3   3.0000001E-01   4.0000001E-01   4.2314768E-01
      4   4.0000001E-01   5.0000000E-01   2.8910592E-01
      5   5.0000000E-01   6.0000002E-01   2.2885039E-01
      ...
```

3.2 Elaborate Example

The following example file contains an extended X-ray source with 2 different polarized emission regions described by 2 separate images, and a point source oscillating between 2 states, one with a hard spectrum and low intensity and one with a soft spectrum and high intensity.

In the source catalog the extended source is split up in 2 separate entries, each with a specific spectrum and image of the particular emission regions. The periodic point source consists of a single entry in the catalog with a periodic light curve and 2 spectra for the different states. The source catalog and the light curve of the second source are stored in the file 'elaborate.fits', the spectra and images in the separate file 'data.fits'.

3.2.1 elaborate.fits

The primary HDU is empty and therefore neglected here.

HDU 2 This HDU contains the source catalog.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   99 / width of table in bytes
NAXIS2  =                    3 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                   10 / number of fields in each row
TTYPE1  = 'SRC_ID  '           / label for field   1
TFORM1  = 'J       '           / data format of field: 4-byte INTEGER
TTYPE2  = 'SRC_NAME'           / label for field   2
TFORM2  = '10A     '           / data format of field: ASCII Character
TTYPE3  = 'RA      '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
TTYPE4  = 'DEC     '           / label for field   4
TFORM4  = 'E       '           / data format of field: 4-byte REAL
TTYPE5  = 'FLUX    '           / label for field   5
TFORM5  = 'E       '           / data format of field: 4-byte REAL
TTYPE6  = 'E_MIN   '           / label for field   6
TFORM6  = 'E       '           / data format of field: 4-byte REAL
TTYPE7  = 'E_MAX   '           / label for field   7
TFORM7  = 'E       '           / data format of field: 4-byte REAL
TTYPE8  = 'SPECTRUM'           / label for field   8
TFORM8  = '21A     '           / data format of field: ASCII Character
TTYPE9  = 'IMAGE   '           / label for field   9
TFORM9  = '18A     '           / data format of field: ASCII Character
TTYPE10 = 'LIGHTCUR'           / label for field  10
TFORM10 = '26A     '           / data format of field: ASCII Character
EXTNAME = 'SRC_CAT '           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SRC_CAT '
HDUVERS = '1.0.0   '
RADECSYS= 'FK5     '
EQUINOX =                2000.
TUNIT3  = 'deg     '
TUNIT4  = 'deg     '
TUNIT5  = 'erg /s /cm**2'
TUNIT6  = 'keV     '
TUNIT7  = 'keV     '
END

        SRC_ID      SRC_NAME   RA              DEC             FLUX
                               deg             deg             erg /s /cm**2
      1           1 EXTENDED-1  -1.0500000E+01  -3.0999999E+00   7.6999998E-14
      2           2 EXTENDED-2  -1.0500000E+01  -3.0999999E+00   9.9999998E-14
      3           3 PERIODIC    -9.6999998E+00  -4.1999998E+00   5.6999998E-11

        E_MIN           E_MAX           SPECTRUM
```

```
     keV             keV
  1   5.0000000E-01   1.0000000E+01 data.fits[SPECTRUM,1]
  2   5.0000000E-01   1.0000000E+01 data.fits[SPECTRUM,2]
  3   1.0000000E-01   1.5000000E+01 data.fits[GROUPING,1]

     IMAGE              LIGHTCUR

  1 data.fits[IMAGE,1]
  2 data.fits[IMAGE,2]
  3                     elaborate.fits[LIGHTCUR,1]
```

HDU 3 This HDU contains the light curve of the periodic source.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   16 / width of table in bytes
NAXIS2  =                   10 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    2 / number of fields in each row
TTYPE1  = 'PHASE   '           / label for field   1
TFORM1  = 'D       '           / data format of field: 8-byte DOUBLE
TTYPE2  = 'FLUX    '           / label for field   2
TFORM2  = 'D       '           / data format of field: 8-byte DOUBLE
EXTNAME = 'LIGHTCUR'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'LIGHTCUR'
HDUVERS = '1.0.0   '
MJDREF  =               48043.
TSTART  =                   0.
TSTOP   =                   0.
TIMEZERO=             49123.98
TIMESYS = 'MJD     '
TIMEUNIT= 'd       '
CLOCKCOR= 'YES     '
E_MIN   =                   1.
E_MAX   =                   8.
FLUX    =             1.24E-10
PERIODIC=                    1
PHASE0  =                 0.31
PERIOD  =                 78.8
END

     PHASE                    FLUX

  1   0.000000000000000E+00   1.000000000000000E+00
  2   1.000000000000000E-01   1.276259068577462E+00
  3   2.000000000000000E-01   1.446996562658722E+00
```

```
     4   3.000000000000000E-01   1.446996562658722E+00
     5   4.000000000000000E-01   1.276259068577462E+00
     6   5.000000000000000E-01   1.000000000000000E+00
     7   6.000000000000001E-01   7.237409314225376E-01
     8   7.000000000000001E-01   5.530034373412779E-01
     9   8.000000000000000E-01   5.530034373412778E-01
    10   9.000000000000000E-01   7.237409314225376E-01
```

3.2.2 data.fits

HDU 1 This HDU contains one of the 2 emission region images of the first source.

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                  -32 / number of bits per data pixel
NAXIS   =                    2 / number of data axes
NAXIS1  =                    3 / length of data axis 1
NAXIS2  =                    3 / length of data axis 2
EXTEND  =                    T / FITS dataset may contain extensions
COMMENT   FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT   and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
EXTNAME = 'IMAGE   '
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'IMAGE   '
HDUVERS = '1.0.0   '
EXTVER  =                    1
CTYPE1  = 'RA---CAR'
CTYPE2  = 'DEC--CAR'
CUNIT1  = 'deg     '
CUNIT2  = 'deg     '
CRPIX1  =                   2.
CRPIX2  =                   2.
CRVAL1  =                -10.5
CRVAL2  =                 -3.1
CDELT1  =                 0.25
CDELT2  =                 0.25
E_MIN   =                   2.
E_MAX   =                   5.
FLUX    =              8.7E-14
RADECSYS= 'FK5     '
EQUINOX =                2000.
END
```

HDU 2 This HDU contains the other emission region image of the first source.

```
XTENSION= 'IMAGE   '           / IMAGE extension
BITPIX  =                  -64 / number of bits per data pixel
NAXIS   =                    2 / number of data axes
```

```
NAXIS1  =                    3 / length of data axis 1
NAXIS2  =                    3 / length of data axis 2
PCOUNT  =                    0 / required keyword; must = 0
GCOUNT  =                    1 / required keyword; must = 1
EXTNAME = 'IMAGE   '
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'IMAGE   '
HDUVERS = '1.0.0   '
EXTVER  =                    2
CTYPE1  = 'RA---CAR'
CTYPE2  = 'DEC--CAR'
CUNIT1  = 'deg     '
CUNIT2  = 'deg     '
CRPIX1  =                   2.
CRPIX2  =                   2.
CRVAL1  =                -10.5
CRVAL2  =                 -3.1
CDELT1  =                 0.25
CDELT2  =                 0.25
E_MIN   =                   2.
E_MAX   =                   5.
FLUX    =              8.7E-14
RADECSYS= 'FK5     '
EQUINOX =                2000.
END
```

HDU 3 This HDU contains a grouping table with references to the 2 spectra of the periodic source.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   31 / width of table in bytes
NAXIS2  =                    2 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    6 / number of fields in each row
TTYPE1  = 'MEMBER_XTENSION'    / label for field   1
TFORM1  = '8A      '           / data format of field: ASCII Character
TTYPE2  = 'MEMBER_NAME'        / label for field   2
TFORM2  = '8A      '           / data format of field: ASCII Character
TTYPE3  = 'MEMBER_VERSION'     / label for field   3
TFORM3  = 'J       '           / data format of field: 4-byte INTEGER
TTYPE4  = 'MEMBER_POSITION'    / label for field   4
TFORM4  = 'J       '           / data format of field: 4-byte INTEGER
TTYPE5  = 'MEMBER_LOCATION'    / label for field   5
TFORM5  = '4A      '           / data format of field: ASCII Character
TTYPE6  = 'MEMBER_URI_TYPE'    / label for field   6
TFORM6  = '3A      '           / data format of field: ASCII Character
EXTNAME = 'GROUPING'           / name of this binary table extension
```

```
EXTVER  =                    1
END

        MEMBER_XTENSION MEMBER_NAME MEMBER_VERSION MEMBER_POSITION

      1 BINTABLE        SPECTRUM                 3              6
      2 BINTABLE        SPECTRUM                 4              7

        MEMBER_LOCATION MEMBER_URI_TYPE

      1 NULL            URL
      2 NULL            URL
```

HDU 4 This HDU contains the emission spectrum of the first source, which is assigned to the first image in HDU 1.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   12 / width of table in bytes
NAXIS2  =                  199 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / number of fields in each row
TTYPE1  = 'E_MIN   '           / label for field   1
TFORM1  = 'E       '           / data format of field: 4-byte REAL
TTYPE2  = 'E_MAX   '           / label for field   2
TFORM2  = 'E       '           / data format of field: 4-byte REAL
TTYPE3  = 'FLUX    '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
EXTNAME = 'SPECTRUM'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SPECTRUM'
HDUVERS = '1.0.0   '
EXTVER  =                    1
TUNIT1  = 'keV     '
TUNIT2  = 'keV     '
TUNIT3  = 'photon /s /cm**2 /keV'
STOKES1 =                   0.
STOKES2 =                   1.
STOKES3 =                   0.
RADECSYS= 'FK5     '
EQUINOX =                2000.
END

        E_MIN           E_MAX           FLUX
        keV             keV             photon /s /cm**2 /keV
      1   1.0000000E-01   2.0000000E-01   2.2559837E+01
      2   2.0000000E-01   3.0000001E-01   9.4416389E+00
```

```
      3   3.0000001E-01   4.0000001E-01   5.4318242E+00
      4   4.0000001E-01   5.0000000E-01   3.6110122E+00
      5   5.0000000E-01   6.0000002E-01   2.6105325E+00
      ...
```

HDU 5 This HDU contains the emission spectrum of the first source, which is assigned to the second image in HDU 2.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   12 / width of table in bytes
NAXIS2  =                  199 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / number of fields in each row
TTYPE1  = 'E_MIN   '           / label for field   1
TFORM1  = 'E       '           / data format of field: 4-byte REAL
TTYPE2  = 'E_MAX   '           / label for field   2
TFORM2  = 'E       '           / data format of field: 4-byte REAL
TTYPE3  = 'FLUX    '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
EXTNAME = 'SPECTRUM'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SPECTRUM'
HDUVERS = '1.0.0   '
EXTVER  =                    2
TUNIT1  = 'keV     '
TUNIT2  = 'keV     '
TUNIT3  = 'photon /s /cm**2 /keV'
STOKES1 =                  -1.
STOKES2 =                   0.
STOKES3 =                   0.
RADECSYS= 'FK5     '
EQUINOX =                2000.
END

        E_MIN           E_MAX           FLUX
        keV             keV             photon /s /cm**2 /keV
      1   1.0000000E-01   2.0000000E-01   2.4982677E+01
      2   2.0000000E-01   3.0000001E-01   8.3232021E+00
      3   3.0000001E-01   4.0000001E-01   4.1594806E+00
      4   4.0000001E-01   5.0000000E-01   2.4944277E+00
      5   5.0000000E-01   6.0000002E-01   1.6621149E+00
      ...
```

HDU 6 This HDU contains the spectrum assigned to the soft state of the periodic point source. This spectrum corresponds to phase 0 of the oscillation.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   12 / width of table in bytes
NAXIS2  =                  199 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / number of fields in each row
TTYPE1  = 'E_MIN   '           / label for field   1
TFORM1  = 'E       '           / data format of field: 4-byte REAL
TTYPE2  = 'E_MAX   '           / label for field   2
TFORM2  = 'E       '           / data format of field: 4-byte REAL
TTYPE3  = 'FLUX    '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
EXTNAME = 'SPECTRUM'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SPECTRUM'
HDUVERS = '1.0.0   '
EXTVER  =                    3
TUNIT1  = 'keV     '
TUNIT2  = 'keV     '
TUNIT3  = 'photon /s /cm**2 /keV'
PHASE   =                   0.
END

        E_MIN           E_MAX           FLUX
        keV             keV             photon /s /cm**2 /keV
      1   1.0000000E-01   2.0000000E-01   4.5130976E-31
      2   2.0000000E-01   3.0000001E-01   9.5680871E-06
      3   3.0000001E-01   4.0000001E-01   1.3151404E-01
      4   4.0000001E-01   5.0000000E-01   2.2179375E+00
      5   5.0000000E-01   6.0000002E-01   4.2885494E+00
      ...
```

HDU 7 This HDU contains the spectrum assigned to the hard state of the periodic point source. This spectrum corresponds to phase 0.5 of the oscillation.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   12 / width of table in bytes
NAXIS2  =                  199 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / number of fields in each row
TTYPE1  = 'E_MIN   '           / label for field   1
TFORM1  = 'E       '           / data format of field: 4-byte REAL
TTYPE2  = 'E_MAX   '           / label for field   2
TFORM2  = 'E       '           / data format of field: 4-byte REAL
```

```
TTYPE3  = 'FLUX    '           / label for field   3
TFORM3  = 'E       '           / data format of field: 4-byte REAL
EXTNAME = 'SPECTRUM'           / name of this binary table extension
HDUCLASS= 'OGIP    '
HDUCLAS1= 'SIMPUT  '
HDUCLAS2= 'SPECTRUM'
HDUVERS = '1.0.0   '
EXTVER  =                    4
TUNIT1  = 'keV     '
TUNIT2  = 'keV     '
TUNIT3  = 'photon /s /cm**2 /keV'
PHASE   =                  0.5
END

        E_MIN           E_MAX           FLUX
        keV             keV             photon /s /cm**2 /keV
      1   1.0000000E-01   2.0000000E-01   6.1018019E-32
      2   2.0000000E-01   3.0000001E-01   1.9368645E-06
      3   3.0000001E-01   4.0000001E-01   3.4101035E-02
      4   4.0000001E-01   5.0000000E-01   6.8907481E-01
      5   5.0000000E-01   6.0000002E-01   1.5370889E+00
      ...
```

4 Summary

The presented format provides a common standard to define elaborate models of astronomical sources as input for telescope simulation programs. It comprises approaches to specify simplistic point sources up to detailed descriptions of time-variable spatially extended systems with polarized emission. Although it has been developed in the context of X-ray astronomy it provides sufficient flexibility to be suitable for other wavelength fields.

For the generation of SIMPUT FITS files there is a C-library called 'libsimput', which contains basic write routines. It is currently still under development. The recent version can be obtained via Git[3] by using the clone command:

```
git clone http://www.sternwarte.uni-erlangen.de/git.public/simput.git/
```

The 'libsimput' package is based on the 'cfitsio' library. For the management of grouping tables it is recommended to use a 'cfitsio' version newer than 3.25. With older versions there might be some problems in particular operating system environments affecting the handling of grouping tables.

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A List of Acronyms

ARF Ancillary Response File

FITS Flexible Image Transport System

HDU Header and Data Unit

MHD Magnetohydrodynamic

PHA Pulse Height Amplitude

WCS World Coordinate System