Astronomical Data Analysis Software and Systems XIII
ASP Conference Series, Vol. 314, 2004
F. Ochsenbein, M. Allen, and D. Egret, eds.

The Chandra Multiwavelength Project (ChaMP): Optical Data Processing and Catalog Generation

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Abstract. One of the principal objectives of the Chandra Multiwavelength Project (ChaMP) is the optical identification and cataloging of serendipitously detected background X-ray sources in *Chandra* archival data. The ChaMP uses a program of multi-filter optical imaging of observed *Chandra* fields to detect optical counterparts to X-ray sources. We describe the methods used for reduction, analysis and cataloging of optical sources in the ChaMP fields. Automated pipeline processing of the optical data includes source extraction, photometric calibration and optical to X-ray source matching. Visual inspection tools have been developed for quality control of the resultant source lists and for identification of interesting objects for follow-up spectroscopic observations. Methods and tools for management, presentation and access of the ChaMP catalogs are also described.

1. Introduction

The *Chandra* Multiwavelength Project (ChaMP) is a serendipitous X-ray source survey based on archival *Chandra* AO1 and AO2 data. The ACIS data cover approximately 14 square degrees of sky, and are expected to provide ~ 8000 serendipitous X-ray sources, (Kim et al. 2004a, 2004b). The sensitive, wide-area ChaMP survey provides a X-ray source sample significantly more sensitive than previous ROSAT and ASCA sky surveys, and a survey with greater sky coverage than the *Chandra* Deep Field surveys is the only way to compile a significant sample of high-redshift QSOs.

Chandra's sub-arcsecond angular resolution and $1''$ celestial location capability (Aldcroft et al. 2000) is ideal for a corresponding optical survey, to allow unambiguous optical identification of the majority of the X-ray sources. A key component of the ChaMP is deep, wide-field optical imaging of the fields. We use the SDSS g', r', i' filters, to provide good object classification and photometric redshift determination. We use the NOAO 4m telescopes (KPNO and CTIO) with Mosaic CCD detectors to optically image the deeper ChaMP fields and SAO's FLWO 1.2m telescope with the 4Shooter camera to image northern shallow fields and to measure the brighter objects in the deeper fields. Each camera field of view is well matched to the ACIS-I and ACIS-S fields of view.

We scale our optical exposure times to the *Chandra* X-ray exposure times, to provide a uniform sensitivity to X-ray/optical flux ratios. The optical magnitude limit for each observation is scaled to the expected X-ray flux limit for each field, to include 90% of the ROSAT sky survey AGN at the X-ray flux limit. Individual CCD exposures are adjusted according to moon phase to limit background contribution to the exposure. Multiple exposures are stacked with median filtering to produce single night images in each filter for analysis. Total exposure times on each ChaMP field are tallied in database tables, using only photometric or near-photometric data, to track imaging completeness across multiple observing runs. We expect to match ~ 4000 sources to $r' \simeq 25$, matching 90% of X-ray sources with $\log f_x > -14.8$. Together with optical imaging, optical spectroscopy observations are being carried out to gather an AGN and QSO sample, using the FLWO 1.5m FAST, WIYN/HYDRA, CTIO4m/HYDRA, Magellan/LDSS-2 and MMT/BCS spectrographs. Green et al. (2004) present optical imaging and spectroscopy details and results for six fields from the ChaMP. For these six fields, using single-night stacked data, 55% to 78% of the X-ray sources in each field have optical matches.

2. Data Management

Two key issues drive the design of the data management system implemented for the ChaMP: (i) the large number of *Chandra* fields in the survey, and the associated large amount of optical data, and large numbers of detected optical sources and measured spectra, (ii) the primary project requirement to provide full, simple access to the X-ray and optical data and results.

To meet these requirements, standard data products and database tools are necessary, to provide pipelined data processing, automated database construction and retrieval and statistical analysis. The key features of data management in the ChaMP are:

- Pipeline processing for both X-ray and optical imaging data. The X-ray data are mainly with CIAO tools. The optical data are processed with standard IRAF tools, SExtractor, IDL and Perl/PDL scripts.
- Pipeline processing is driven by Perl and shell scripts and controlled by input parameter files.
- Intermediate data files generated by the pipeline processing are transported in RDB format between tasks.
- Final X-ray and optical pipeline products go through Verification and Validation (V&V) inspection by users before ingest into the final database archive tables.
- Product tables are archived in SYBASE. Separate database tables are defined for X-ray observation data, optical observation data, basic X-ray source data and optical source data, and optical to X-ray source cross-identifications.
- WWW access to the database tables is provided through scripts that generate HTML. Tools are being developed to provide database interaction for dynamic data selection through the WWW.

3. Data Reduction and Analysis

To efficiently process the large number of *Chandra* observations in ChaMP, and the corresponding large number of optical imaging datasets, we have implemented pipeline processing techniques. Pipeline processing automates the data reduction and analysis to the maximum possible extent and operates with standard data products for compatability with database management techniques.

Similar but not identical data reduction operations are applied to the Mosiac and 4Shooter imaging data. Standard IRAF tools from the mscred (v4.8) nproto and crutil packages are used for the data reduction. Basic reduction operations are applied to (i) correct crosstalk and remove bias, (ii) flat field with dome flats and super sky flats, (iii) remove pupil images (NOAO 4m), (iv) refine WCS J2000 astrometry, (v) filter cosmic rays, (vi) project multiple CCDs and stack multiple exposures into single images.

The standardized output products from data the reduction (a merged, stacked CCD image and bad pixel list) are identical for both program field and standard star field observations, and for Mosaic and 4Shooter observations. A common source extraction and photometric calibration pipeline is used for all subsequent data analysis. Source extraction is based on SExtractor (Bertin & Arnouts 1996). Because we want a good measure of stellarity for each source, we process the images through SExtractor twice, to first estimate and then use the correct field FWHM. The pipeline is controlled by a modular Perl script. Program fields and standard star fields are identified in an input parameter file to select the appropriate processing stream within the pipeline. The processing tasks are:

- Generate bad pixel mask image from bad/saturated pixel list
- Initial SExtractor source extraction with default FWHM
- Determine FWHM from objects with high stellarity
- Second SExtractor source extraction with correct FWHM
- Rejection of objects with invalid flux or FWHM measures
- Estimate of background rms for each object in the program fields
- Determine global background rms statistics for each program field
- Position match g', r', i' object detections ($1''$ tolerance)
- Identify detected standard stars from a master standard list ($1''$ tolerance)
- Perform interative photometric calibration
- Apply photometric calibration to program field objects
- Position match optical and X-ray source lists for the program fields
- Estimate program field magnitude limits

An iterative photometric calibration of the standard stars is used. Standard stars calibrated for the SDSS (Smith et al. 2002) plus standard stars from Landolt (1992) transformed to the SDSS system are used. Four coefficents (color coefficent, zero point, k_0 and k_1 extinction coefficents) are solved for, alternately freezing and solving for two pairs of coefficients. In addition, a σ-clip (typically 2 or 3 σ) is applied to remove outlier stars from the solution. Typical rms errors are $\sim$0.03 mag from > 30 stars.

Within the master optical pipeline, X-ray source products are imported from the X-ray data processing pipeline, and the master optical pipeline performs position matching of optical and X-ray source lists to provide the best (possibly multiple) candidate optical matches for each X-ray source.

All intermediate data products generated within the pipeline are transported and preserved in RDB files for simple user inspection and analysis. Diagnostic plots are also generated at intermediate processing stages to monitor pipeline performance. The master pipeline logfile tracks key statistics including source counts, FWHM, g', r', i' matching statistics, photometric calibration rms, and optical to X-ray source matching statistics. Finally, software scripts are used for automated ingest of the pipeline products into the master optical SYBASE tables.

3.1. Visual Inspection

Visual inspection of each ChaMP field is performed as the final step of discovering optical counterparts to each X-ray source. An IDL tool, `vi`, provides an interactive environment to inspect and assess the quality of the optical and X-ray data for each source, and to verify optical to X-ray source matches. For each X-ray source, `vi` displays optical (typically r' filter) and smoothed X-ray images of the source field, together with summary data for the X-ray source, and best-match optical source. Overlays on the optical and X-ray images indicate detected source positions, sizes and processing flags, and candidate matches.

4. WWW Access

All ChaMP data are being made available through the ChaMP web site[1], including X-ray and optical field lists and field images, X-ray and optical source lists with associated source images, and optical spectra. Also available are refereed papers describing the X-ray and optical datasets and analysis. Interactive database query tools are being developed to assist data selection.

Acknowledgments. This work was supported in part by NASA contract NAS8-39073 and by Chandra grants AR1-2003X and AR3-4018X. Optical data for the ChaMP are obtained in part through the National Optical Astronomy Observatory (NOAO), operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

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[1] `http://hea-www.harvard.edu/CHAMP`