Data Analysis Challenges in the Chandra Orion Ultradeep Project

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ABSTRACT

The Chandra Orion Ultradeep Project (COUP) combines 6 consecutive ACIS-I observations of the Orion Nebula Cluster obtained in January 2003, with a total exposure time of 0.84 Ms. Over 1600 point sources are detected in this star-forming region; most show variability in their lightcurves. We describe some of the data analysis challenges specific to this observation, including: source detection with complex backgrounds due to bright sources, resolving crowded sources, spectral fitting of sources lying under readout streaks, and time-varying pile-up. We show example output from the custom software we have developed to automate the spatial, spectral, and timing analysis of these sources and to collate the results into user-friendly viewing formats.

INTRODUCTION OF CHANDRA COUP OBSERVATIONS

Obs. ID	Obs. Start	Exposure Time (ks)	Aim Point R.A. (J2000)	Aim Point DEC. (J2000)	Roll Angle (degrees)	Obs. Mode
4395	2003 Jan 8 20:58:18.8	99.9	83.8210052	-5.394400	310.90882	VF
3744	2003 Jan 10 16:17:38.7	164.2	83.8210086	-5.394406	310.90882	VF
4373	2003 Jan 13 07:34:43.5	171.5	83.8210098	-5.394403	310.90882	VF
4374	2003 Jan 16 00:00:37.4	168.9	83.8210079	-5.394404	310.90882	VF
4396	2003 Jan 18 14:34:48.3	164.5	83.8210094	-5.394403	310.90882	VF
3498	2003 Jan 21 06:10:27.7	69.1	83.8210025	-5.394402	310.90882	VF

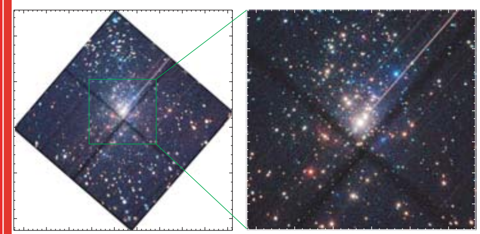


Fig. 1. - (Left) Chandra three color raw image of the merged event 2 file. It has been constructed from the 0.5-1.5 keV (red), 1.5-2.5 keV (green), and 2.5-8.0 keV (blue) raw images. **The merger of all six observations was greatly simplified by keeping the aim point and the roll angle constant!** A few dozens of X-ray sources suffer miled photon pileup (10% - 30%) in the CCD detector. θ^1 Ori C, the massive O6 star dominating the Trapezium at virtually all wavelengths, suffers very significant pileup. Dozen of readout streaks from bright pileup sources can be easily seen in this image. The sencitivity of sources rapidly deteriorates as one approaches within ~ 2' of θ^1 Ori C due to the elevation of background from the O star's PSF wings. (Right) Enlarged view of the central (7.5' x 7.2' ~ size of the deep near-IR VLT survey) area. Hundreds of X-ray sources are visible in this field. The X-ray source surface density drops from 0.02 sources/arcsec^2 at the central parts of the image (θ ~ 0.5') to 0.007 sources/arcsec^2 at off-axis angles of θ ~ 2' to 0.002 sources/arcsec^2 at θ ~ 5'.

DATA REDUCTION ROADMAP

Filter on 4 CCDs; mark bg. in VF mode; perform PSU CTI correction; filter on 02346 grades, status, except 16-19,23; apply GTI; remove hot pixels; apply coarse energy filter; see details in [16].

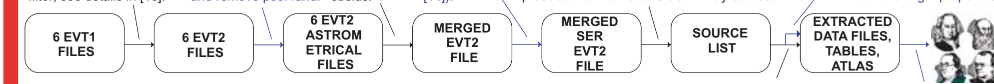
Cross-identify bright sources; shift ra,dec,ra_nom, dec_nom of aspect timeseries; reproject events to improve absolute astrometry and remove pos. rand.

Reproject events of 5 obsids to match the tangent plane of obsid 4395; merge all obsids.

Recalculate x,y positions using Subpixel Event Relocation tool (RIT group, see details in [14]).

Run PWDETECT (Palermo group, see details in [e.g. 6]) and WDETECT (Penn State group, see details in [e.g. 5]) with different thresholds, on events/images with different energy bands, filtered/nonfiltered on bg. in VF mode; perform visual inspection; remove spurious sources, many of which are detected on the trails of the bright sources; merge source lists; produce the final list of COUP X-ray sources.

Associate COUP X-ray sources with optical/IR sources including: Chandra ACIS [5], Chandra HRC [6], optical Hillenbrand [9], IR VLT [3], IR 2MASS [13], IR MLLA [15]. Tablulate their multiwavelength properties.



Run acis_extract (see details in [1,12]) in order to: 1. refine the accuracy of source positions; 2. extract event lists for each source, using the polygonal region generally chosen to match the contour of 90% encircled energy from the PSF (the smallest apertures were chosen for crowded sources) at the fiducial energy of 1.5 keV; 3. extract the background from the sweeze-cheese event list and to scale it, using the integrated exposure in the region; 4. compute instrumental responses (RMF and ARF) with ARFs, corrected for the PSF fraction enclosed by the extraction regions and for the hydrocarbon build-up on the detectors [10]; 5. create source spectra and scaled local background spectra; 6. group spectra; 7. compute photometry; and 8. perform automated spectral fitting spawning the XSPEC v11.2 tool. Run Bayesian block IDL package (see details in [4]) to perform timing analysis. Create source tables with integrated X-ray properties.

Deliver the reduced data and tables to science groups.

HIGH NUMBER OF GTI RECORDS

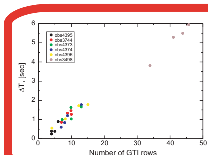


Fig. 2. - While creating the merged asphist histograms for COUP project we found the difference between the EXPOSURE of the merged evt file and the duration of the merged asphist histogram to be unusually high ΔT ~ 11 seconds, which lead to the flux errors on the order of ~ 10^{-5}. The reason of the high ΔT is the unusually high number of Good Time Intervals recorded for six COUP observations, especially for the last one, when it reachs 45 rows in the GTI table. Each time a real-valued GT interval is used to filter the quantized (1/4 sec) TIME column in the asol table the rows near the START & STOP times will fall inside or outside the interval depending on how the times line up. It appears that this error does not even have a zero mean, but has a small positive mean, for whatever reason. **What caused the huge number of GTI rows?** Official version is the Van Allen Belts.

ABSOLUTE ASTROMETRY

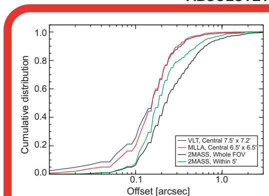


Fig. 3. - Cumulative distributions of offsets between X-ray and IR positions. **Our X-ray positions are superb!** Median offsets are 0.15" for VLT counterparts, 0.22" for 2MASS counterparts, and 0.15" for MLLA counterparts. There is virtually never any ambiguity between catalogued sources and COUP sources, except for couple dozens of close doubles, when Chandra detects a double star with a single IR counterpart, and vise-versa.

DOUBLE SOURCES

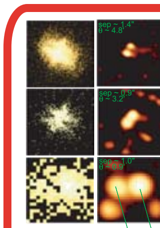


Fig. 4. - The source detection programs often consolidate closely spaced sources easily resolved by eye; this failure begins for source separation < 2.5" on-axis. We employed the perl tool "coup_viewer" [7] to perform a visual search for faint sources and close doubles. We found a few dozens cases in which ACIS resolved close (1"-5") doubles, but detect programs failed. As an example, three of them are shown in the figure. (Left) Raw ACIS images of close doubles at sub-sub-pixel resolutions. (Right) To confirm our findings we ran IDL tool "maxlik.pro" [11] to create PSF deconvolved images.

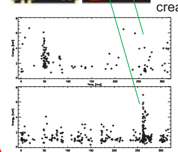


Fig. 5. - The other tricks can be used to confirm findings of double sources. For example, photon arrival diagrams indicate two different flares, which occured from each of the components, the flare at ~ 50hr for the first component and the flare at ~260hr for the second component.

PILEUP SOURCES

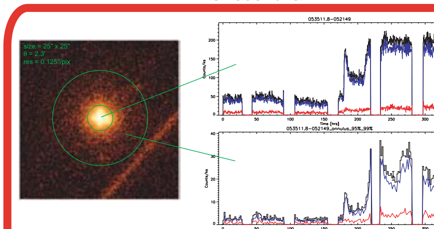


Fig. 6. - We recover from pileup problem in an approximate fashion by extracting events from the annular region around the source, creating a special arf file appropriate for this annulus using the IDL tool "xpsf.pro" [2], and calculating a corrected spectral fit. In most cases the flare time intervals from the lightcurve can be recovered as well.An example is shown for the radio flaring source [8]. For more details on the pileup treatment refer to [18].

SPECTRAL ANALYSIS

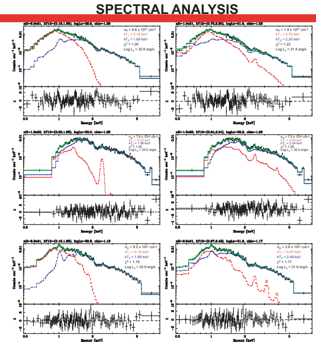


Fig. 8. - Our principal obligation as the COUP Data Reduction & Catalog group is to produce preliminary column densities and broad-band luminosities. Other groups will analyze selected sources in much more details, seeking precise n_Hs and/or abundances, and providing time-sliced spectral analysis for exceptional source and flare states. Once number of sources >~ 200, one needs 2Tmodels most of the time to simultaneously fit the low and high channels. The problem then arises that XSPEC needs to be coaxed into doing a physically (vs. statistically) reasonable 2T fit. For the hundreds of bright COUP sources XSPEC provides two different solutions with equally good χ^2. Examples of three typical sources are shown in the figure. Left panels represent the "wrong" solution with the lower energy kT_1 of 0.1-0.3 keV and higher energy kT_2 of 1-2 keV. Right panels represent the "right" solution with kT_1 ~ 0.6-0.9 keV and kT_2 ~ 2-3 keV. Whenever possible we tried to avoid accepting spectral fit results from the first solution (of extremely soft kT_1 component), that often gives an implausibly high n_H (compared with optical A_V), and L_X. Looking for physical meaning, see the discussion on the origin of the 2T plasma from PMS in [17].

SOURCES ON READOUT TRAILS & PSF WINGS

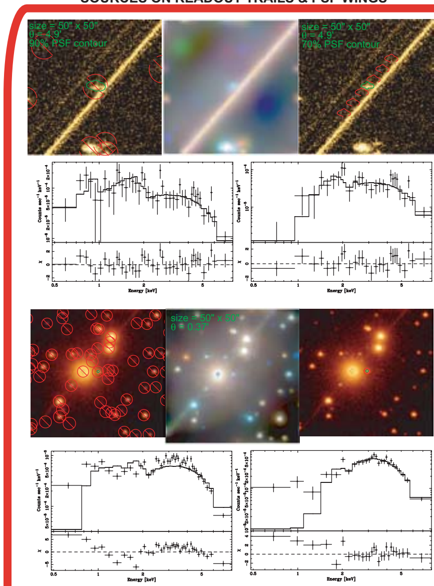
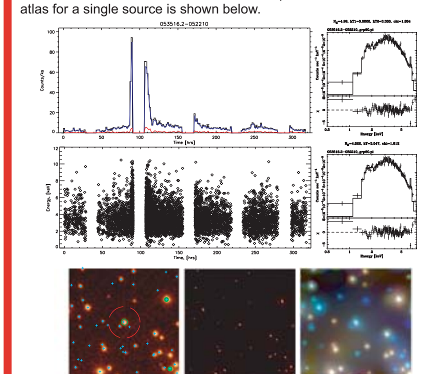


Fig. 7. - In addition to cosmic background , particle background and instrumental background the PSF wings of bright sources, especially from θ^1 Ori C, and readout tracks give the essential contribution to the local background. By default the "acis_extract" automatically defines mask regions, that completely cover the sources, and extracts the local background from the "sweeze-cheese". But it also provides the option to work with the user-defined backgound regions. In case of the weak sources that lie within the PSF wings of bright sources or near/on readout streaks we manually define the backgound regions to improve local background determination and obtain more realistic spectral fits.Two examples are shown: source near readout streak, and source within the PSF wings of θ^1 Ori C. The automatic definition of the background and the corresponding spectral fit are on the left, the user-defined backgound and the corresponding spectral fit are on the right. "True-color" images are in the middle.

ATLAS

Fig 9. - The atlas is a color PDF file summarizing each source on 1 page: it has light curve; photon arrival diagram; spectral fits, raw, PSF reconstructed and smoothed image postage-stamps of the source neighborhood; as well as various tabulated quantities. Eric Feigelson (PI of COUP Project) predicts that these atlas pages will prove very useful to the science efforts. As an example, the current version of atlas for a single source is shown below.



OBJECT	053516.2-052210	REF_NUM	686	RA	83.817837	DEC	-5.3695630
THETA	1.50543	PSF_FR	0.91861500	KS_BG	6.0762100e-10	MED_E	3488.21
CNTS_TOT	6312.00	CNTS_INBAND	6245	NET_CNTS	6198.51	BG_CNTS	47.4912
PGN_AREA	26.000000	CCD_FRAC	1.00000	SIGNIF	77.2626	F_PH	2.47249e-05
KS_LC	6.2657990e-143	L_SP1T_UNC	30.61	L_SP1T_C	31.10	PH/SP(1T)	0.81943282
L_SP2T_UNC	30.61	L_SP2T_C	34.04	PH/SP(2T)	0.82289755	NEI_SEP	704_2.75427
TILE_CCD	50_3	VLT_2MASS	0.39_22.25	PWDNO_SEP	705_0.03	POSERR_SIG_FG	0.09_193.81_0

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