A US COORDINATION FACILITY FOR THE SPECTRUM-X-GAMMA OBSERVATORY

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Final Report

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1 Introduction

We have completed our efforts in support of the Spectrum X Gamma mission. In the sections which follow we summarize these activities which include direct support to the mission, developing unifying tools applicable to SXG and other X-ray astronomy missions, and X-ray astronomy research to maintain our understanding of the importance and relevance of SXG to the field.

2 Support to the Spectrum X Gamma Mission

The Spectrum X Gamma (SXG) International Science Committee (ISC) met 28 February – 1 March in Moscow with attendance from the US SXGCF (SXG Coordination Facility) at SAO. We presented an updated plan detailing activities needed to continue SXG's progress towards launch. The activities included providing detailed information to national funding agencies, emphasizing the progress being made, and specifying the unique science that SXG can perform, even in the competitive environment with Chandra and XMM-Newton already flying. SXG provides

- Simultaneous Multiwavelength Capability
  - UV to Hard X-ray
  - Long continuous views to study variability
  - SIXA provides high count rate capability with 200 eV spectral resolution
- Large Field of View High Resolution Imaging Spectroscopy
  - OXS - large 1 degree FOV for 6 keV iron observations
  - Suitable for studying small spectral bands for large objects
- Sensitive Polarimetry with SXRP
  - Study both galactic and extragalactic systems
  - For galactic X-ray binaries as a function of pulse and binary phase

The science objectives derived from these capabilities by the US SXGCF staff were presented in talks by Terekhov and Wells at the Joint European and National Astronomical Meeting in Moscow, Russia (29 May - 3 June 2000). These include:

- understanding the accretion dynamics and the importance of reprocessing, upscattering, and disk viscosity around black holes
- studying cluster mergers (see Fig. 1 which graphically illustrates the power of SXG)
- spatially resolving cluster cooling flows to detect cooling gas

- detecting cool gas in cluster outskirts in absorption
- mapping gas in filaments around clusters
- finding the "missing" baryons in the Universe
- determining the activity history of the black hole in the Galactic Center i.e., "astroarchaeology" of our own central black hole
- determining pulsar beam geometry (fan vs. pencil beam)
- Searching for the Lense-Thirring effect in black hole sources
- Constraining emission mechanisms and accretion geometry in AGN

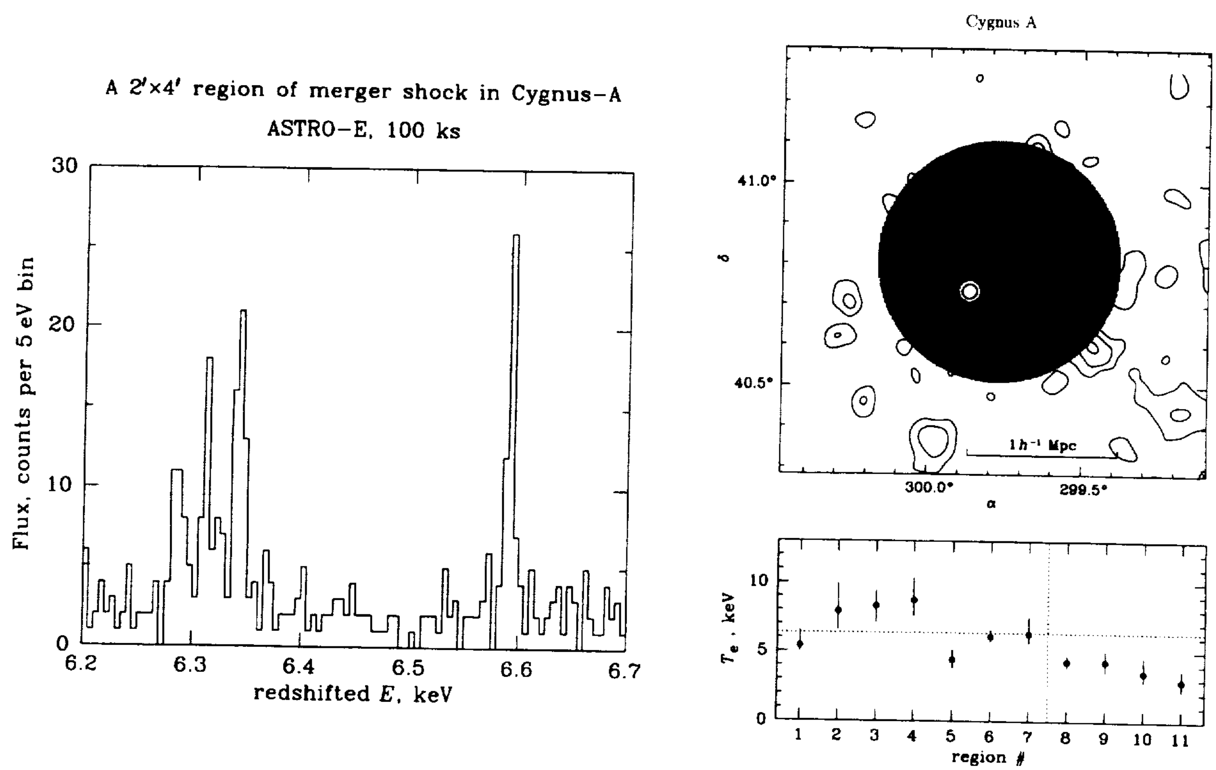

Figure 1: Major cluster mergers dissipate up to 10^{63-64} ergs and hence are the most energetic events in the Universe since the Big Bang. SXG with its Objective Crystal Spectrometer (OXS) is uniquely able to study such mergers since the OXS provides high energy resolution for extended sources over a large FOV. SXG is more efficient at studying such phenomena than any other current or planned observatory.

The study of cluster mergers is a particularly informative objective to consider in detail since it illustrates the complementarity of SXG compared to other missions and fully utilizes the OXS capability to perform detailed emission line diagnostics at very high energy resolution over a large field of view. While some clusters appear dynamically relaxed, many show evidence of ongoing formation and a few show evidence of spectacular major mergers where nearly equal mass components are combining to form a single cluster. These massive mergers are the most energetic events in the Universe since the Big Bang, involving up to 10^{63-64} ergs (exceeding gamma ray bursts by 10 orders of magnitude!) and can best be studied in X-rays. Shock structures, entropy distributions, and electron-ion temperature diagnostics provide otherwise unavailable information about details of the virialization process.

Fig. 1 shows the merger event for the Cygnus A cluster, named for the very bright radio source that lies at the center of one of the merging components (white spot on map). The contours are derived from the ROSAT PSPC image and show the bright peak around the Cygnus A galaxy itself (point source + cooling flow) plus the secondary peak (centered near the number 6) which is merging with the main cluster. As the two components merge, the gas between them is shock heated (red regions). The quantitative temperatures are shown in the lower figure (1 sigma error bars). Note that the region in white located at Cygnus A has a multi-component spectrum and has no single characteristic temperature.

The key feature of SXG is that, unlike XMM-Newton and Chandra, the OXS allows spatially resolved, high energy resolution. While a mission like ASTRO-E (spectrum in Fig. 1 at left) can also obtain spatially resolved high resolution spectroscopy, the planned mission had a small field of view and a limited cryogenic lifetime. Thus, over a limited energy range, the SXG OXS could map the iron line distribution in Cygnus A in about 2 weeks of observing, a small part of the expected observatory lifetime. To cover the same FOV with an ASTRO-E like mission would require 30% of the detector lifetime. For all large objects where the scientific goals can be achieved by studying a limited range of energy around prominent lines - nearby supernova remnants, galactic interstellar features, and clusters of galaxies - SXG has a unique and important contribution to make.

As part of our planned activities, we drafted the Project Data Management Plan. This detailed plan includes:

- an overview of the mission and instruments
- a description of the expected data and products
- data archive plans
- plans for interacting with HEASARC and NSSDC

All this material is available on the WWW at:

`http://hea-www.harvard.edu/SXG/pdmp.html)`

We maintained our own WWW page and made appropriate additions. For example, comparisons of SXG to other missions was added as was the the SODART Observatory Guide see

`http://hea-www.harvard.edu/SXG/obsguide/obsguide.html`

We supported the development of a WWW site to be mirrored by all the international partners showing the science capabilities of SXG and the hardware progress. As part of this effort we supported preparation of a booklet summarizing SXG's capabilities.

In collaboration with other partners, we supported the development of a presentation to the European Space Agency (ESA). The material developed for NASA's Structure & Evolution of the Universe advisory committee was updated and made available to ESA (see science objectives above).

We attended the meeting at the European Space Agency (ESA) in Paris on April 19-20, 2001 to review the ESA requirements for participation in the SXG mission. We presented science arguments showing the continued relevance and importance of SXG. We presented the SAO-developed tools showing the existing data analysus capabilities for all FITS-based data. We discussed possible organizations of data centers suitable for SXG data processing.

3 Unifying X-ray Astronomy Capabilities

We have taken advantage of powerful existing software tools to provide a unifying approach to X-ray data analysis tasks. Our recent focus has been on combining the ZHTOOLS (tool package developed by A. Vikhlinin at IKI for JET-X) with SAO-developed image display (SAOIMAGE/DS9) and new FITS tools to facilitate all X-ray astronomy mission research. This approach shows that proper design of software and tools with use of standard FITS format will provide extensive tools for X-ray astronomy data analysis.

3.1 FUNTOOLS

We contributed to the development of a suite of easily mastered tools to promote initial quantitative understanding of SXG data before moving on to more complex traditional analysis systems. Our "Funtools" suite of analysis programs is based on the Funtools library (developed at SAO) that offers fast FITS access without the complexity of existing libraries. This library contains sophisticated region filtering capabilities (compatible with SAOIMAGE/DS9 and IRAF regions) to filter images and tables using boolean operations between geometric shapes and to support world coordinates.

Our Funtools library consists of a small number of flexible routines that make development of SXG analysis programs far easier than other FITS-based libraries. It especially is tailored to programs that process photon events using a standard "get-next-photon" loop, the key FITS format utilized throughout X-ray astronomy and planned for SXG. The input events are retrieved into an array of user structs, which can be accessed serially.

A key requirement in X-ray astronomy and a foundation of the Funtools library, is the ability to filter/select events in FITS Binary tables and raw event files. A flexible set of user-specified criteria that allows column values to be compared with numeric values, header parameters, functions, or other column values is incorporated into Funtools.

In addition to filtering columns of binary tables, our funtools library also can filter both events and images using spatial regions specifiers. Spatial region filtering allows a program to select regions of an image or event list to process using simple geometric shapes and boolean combinations of shapes. When an image is filtered, only pixels found within these shapes are processed. When an event list is filtered, only events found within these shapes are processed. Spatial region filtering for images and events is accomplished by defining geometric shapes which can be combined according to the rules of boolean algebra. Available regions include annulus, box, circle, ellipse, line, panda (pie and annulus), pie, and polygon. Available boolean operators are "not", "and", and both inclusive and exclusive "or".

While other schemes to carry out these filtering tasks exist, the large size of X-ray data sets from current and future missions demands speed. We have solved this problem by implementing event and spatial region filtering, by converting the desired operations into a small C program, which is compiled and linked automatically. The power of the technique lies in 1) the generated filter program is very small, containing approximately 200 lines of code, so that it compiles and links in about one second or less on most modern machines 2) The filter specification itself becomes a hard-wired part of this program, so that filter checking is performed as part of compiled code, not in the usual interpreted mode. This use of a compiled filter results in a speed-up factor of 4-5 over previous techniques, even after the program compilation time is added. and 3) All C syntax and C operators become valid parts of the filter syntax, making available a much wider range of filter possibilities than previously.

Using our library and its filter/region capabilities, we have developed a number of analysis tools. The most important of these is funcnts, which counts photons in the specified source regions. Other programs that we have developed using the Funtools library include: 1) fundisp - display data in a Funtools data file, 2) funevents - copy selected events from a Funtools event file to a FITS binary table, 3) funhead - display a header in a Funtools file, 4) funimage - create a FITS image from a Funtools data file.

3.2 Combining ZHTOOLS and FUNTOOLS with SAOIMAGE/DS9

We have used the scripting language Tcl/Tk to interface the SXG Jet-X ZHTOOLS analysis package for several particularly popular applications. These include imexam, imsmo and wvdecomp which respectively carry out simple image statistical analysis, image smoothing, and wavelet decomposition (searching for emission at different scales. The interface and use of the ZHTOOLS package is illustrated in Fig. 2.

In an identical manner, we have used Tcl/Tk to interface FUNTOOLS tasks described above to the SAO-developed display program SAOIMAGE/DS9. As an example, Fig. 3 shows the extraction of counts in a complex region defined graphically.

What is most important about these software systems which are interfaced to SAOIMAGE/DS9 is that they are universally applicable to X-ray data that follow the FITS conventions. Hence, a single set of tools are applicable to *ALL* X-ray astronomy data. These tools which we have tested on Chandra X-ray data will be applicable to archival ROSAT and ASCA data as well as new observations from XMM-Newton and SXG.

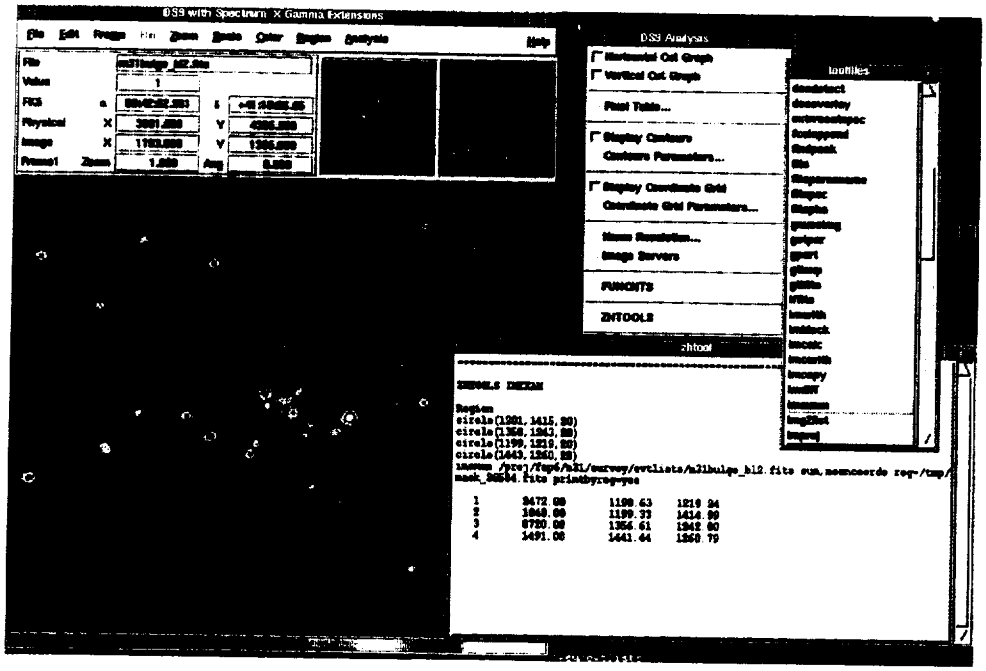

Figure 2: SXG images displayed with the popular SAOimage DS9 image display program may be analyzed with SXG Jet-X analysis tools (ZHTOOLS), using an interactive graphical user interface developed by the SXGCF. In this example, four circular regions are defined in DS9 and analyzed using the Jet-X tool imexam. The Jet-X tools are incorporated into the DS9 analysis menu under the ZHTOOLS sub-menu.

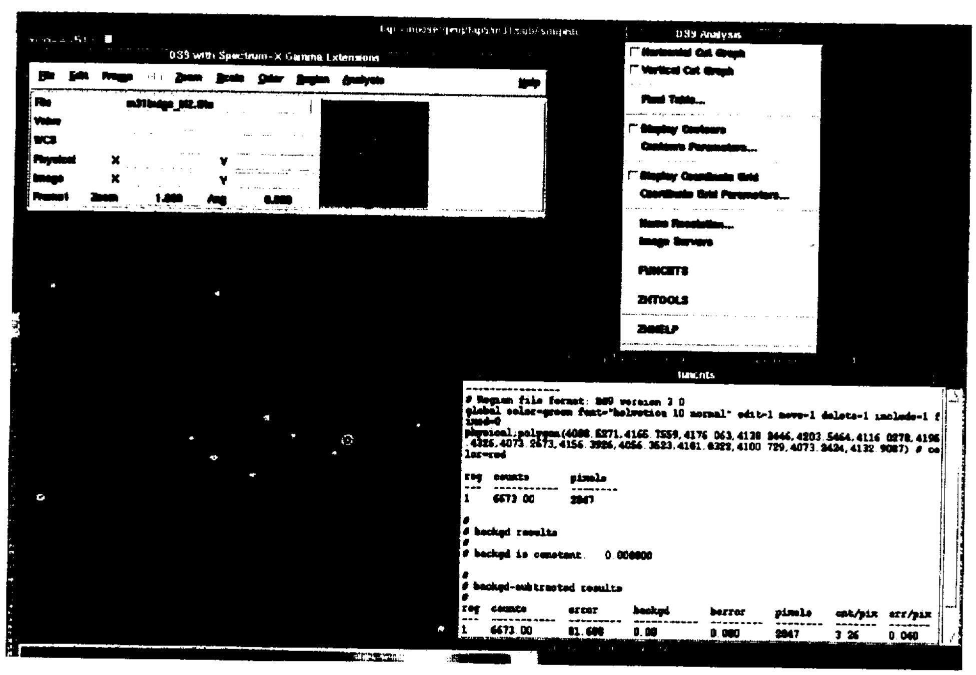

Figure 3: A similar graphical user interface to DS9 has been developed for funtools. In this example, a complex, polygonal region defined by DS9 is analyzed by the funtool funcnts.

4 Science Research and Support to the Community

F. Primini chaired the Local Organizing Committee for the Tenth Annual Conference on Astronomical Data Analysis Software and Systems (ADASS X). The ADASS Conference Series provides a forum for scientists and computer specialists concerned with algorithms, software and operating systems in the acquisition, reduction and analysis of astronomical data. Its goal is to encourage communication between software specialists and users, and to stimulate further development of astronomical software and systems.

We supported the development of the Chandra data analysis tools. One particular example of note is the cleaning of cosmic ray hot spots in the Chandra CCD's. This tasks utilized the FUNTOOLS libraries.

4.1 Scientific Research

Below is a list of papers which utilized support from this grant.

Churazov, E., Bruggen, M., Kaiser, C., Forman, W. Evolution of the buoyant bubbles in M87, submitted to ApJ (astroph 0008215)

Kraft et al. 2000, A Chandra High-Resolution X-Ray Image of Centaurus A ApJ Letters, volume 531, page L9.

Garcia et al. 2000 A First Look at the Nuclear Region of M31 with Chandra ApJ Letters, volume 537, page L23.

Talk at workshop on ISM in M31 and M33 and authored paper for Conference Proceedings: Primini et al. 2000, Chandra Observations of M31 and their Implications for its ISM

Nevalainen, J., Markevitch, M., Forman, W. 2000, X-Ray Total Mass Estimate for the Nearby Relaxed Cluster A3571, ApJ, 536, 73

McNamara, B. et al. 2000, Chandra X-Ray Observations of the Hydra A Cluster: An Interaction between the Radio Source and the X-ray Emitting Gas, ApJ, 534 L135

Markevitch et al. 2000 Chandra Observation of Abell 2142: Survival of Dense Subcluster Cores in a Merger, ApJ in press (astroph 001269)

Nevalainen, J., Markevitch, M., Forman, W. 2000, The Cluster M-T Relation from Temperature Profiles Observed with ASCA and ROSAT, ApJ, 532, 694

Harris, D. E. et al. 2000 Chandra X-Ray Detection of the Radio Hot Spots of 3C 295, ApJ, 530, L81

Churazov, E., Forman, W., Jones, C., Bohringer, H. 2000, Asymmetric, arc minute scale structures around NGC 1275, A&A, 356, 788

Markevitch, M. et al. 1999, Mass Profiles of the Typical Relaxed Galaxy Clusters A2199 and A496, ApJ, 527, 545

Nevalainen, J., Markevitch, M., Forman, W. 2000, The Baryonic and Dark Matter Distributions in Abell 401, ApJ, 526, 1

Vikhlinin, A., Forman, W., Jones, C. 1999, Outer Regions of the Cluster Gaseous Atmospheres, ApJ, 525, 47