EUV Astrophysics with *ALEXIS*: The Wide View

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The *Array of Low Energy X-ray Imaging Sensors* (*ALEXIS*) satellite is Los Alamos' pathfinding small space mission achieving low cost and rapid development time for its technology demonstration and science goals. The *ALEXIS* satellite contains the *ALEXIS* telescope array, which consists of six EUV/ultrasoft X-ray telescopes utilizing normal incidence multilayer mirrors, microchannel plate detectors, and thin UV rejecting filters. Each telescope is tuned to a relatively narrow bandpass centered at either 130, 171, or 186 angstroms. Each telescope has a 33° field-of-view, and a resolution of $\sim 0.25°$. With each 50 s rotation of the satellite, the telescopes scan most of the anti-solar hemisphere of the sky. The spacecraft is controlled exclusively from a ground station located at Los Alamos.

This paper discusses the characteristics and performance of the *ALEXIS* telescopes and the results from the mission in spite of the damage incurred to the spacecraft at launch.

1. Introduction

The *ALEXIS* small satellite contains an ultrasoft X-ray or extreme ultraviolet (EUV) monitor experiment that consists of six compact normal-incidence telescopes operating in narrow bands centered on 66, 71, and 93 eV (186, 176, and 130 Å). The satellite also contains a VHF broadband ionospheric survey experiment called BLACKBEARD. Los Alamos National Laboratory (LANL) is the project lead and where the experiments were built and integrated with the spacecraft bus. Sandia National Laboratory (SNL) provided the payload data processors and detector high voltage supplies, and the University of California Space Sciences Laboratory (UCB SSL) built and calibrated the detectors. The spacecraft bus, built by AeroAstro, Inc., is a custom, low-cost, miniature satellite, made to be compatible with several expendable launch vehicles. The Air Force Space Test Program provided the launch for *ALEXIS* via a Pegasus air-launched booster into a 400 × 450 nautical mile orbit on April 25, 1993. The satellite and experiments are controlled entirely from a small groundstation at LANL. The project, excluding launch, was funded entirely by the Department of Energy (DOE) Office of Non-proliferation and National Security as part of an advanced technology development program for potential future uses in Comprehensive Test Ban Treaty (CTBT) monitoring.

The *ALEXIS* experiment takes up 100 pounds of the 242 pound total satellite mass, draws 45 watts, and produces an orbit average of 10 kbits s^{-1} of data. Position and time of arrival are recorded for each detected photon. The satellite is spin stabilized, with magnetic torque coils providing attitude control authority. *ALEXIS* is always in a survey-monitor mode, with no individual source pointings. It is well-suited for simultaneous observations with ground-based observers who prefer to observe sources at opposition. Coordinated observations need not be arranged before the fact, because most sources in the anti-Sun hemisphere will be observed and archived. A single ground station in Los Alamos tracks and controls *ALEXIS*. Between ground station passes, experiment and spacecraft data are stored in 78 Megabytes of solid state memory in the spacecraft bus.

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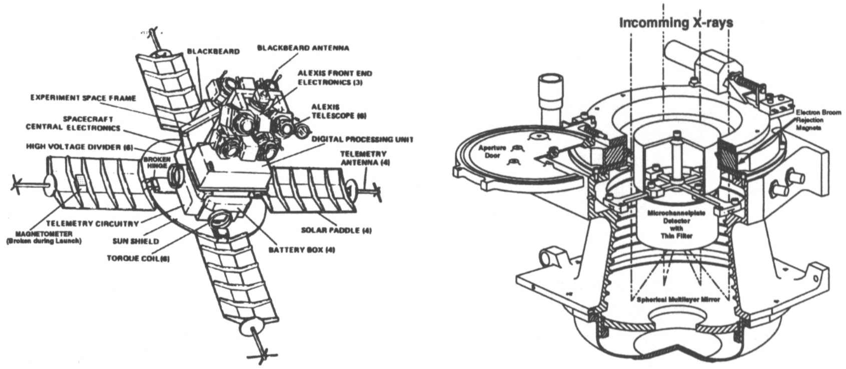

FIGURE 1. Left: The *ALEXIS* satellite in its on-orbit configuration. The damaged solar panel hinge and magnetometer are indicated. Right: Cross sectional view of one of the six *ALEXIS* telescopes.

2. Telescope Design

Normal incidence multilayer X-ray/EUV telescopes have been used for solar observations, but *ALEXIS* is the first time that they have been used successfully on-orbit for non-solar cosmic ultrasoft X-ray/EUV measurements. Figure 1 shows a cross sectional view of an *ALEXIS* telescope. It is an extremely simple $f/1$ optical design, consisting of an annular entrance aperture, a spherical mirror, an optical and UV rejecting filter, and a curved, microchannel plate detector with wedge and strip anode readout. The curved front of the microchannel plate follows the curvature of the focal surface so that the spatial resolution of the system is approximately constant over the entire 33° field-of-view. Spherical aberration limits the system's spatial resolution to about 0.25°.

As shown in Figure 1, the six EUV telescopes are arranged in three co-aligned pairs and cover three overlapping 33° fields-of-view. During each 50 s rotation of the satellite, *ALEXIS* scans most of the anti-solar hemisphere (see Figure 2). The geometric collecting area of each telescope is about 25 cm^2. Analysis of the preflight X-ray throughput calibration data indicates that the peak on-axis effective collecting area for each telescope's response function ranges from 0.25 to 0.05 cm^2. The peak area-solid angle product response function of each telescope ranges from 0.04 to 0.015 cm^2-sr. In one twelve hour data collection period, the brightest EUV sources in the sky can be detected (see Figure 3).

The spacing of the molybdenum and silicon layers on each telescope's mirror is the primary determinant of the telescope's photon energy response function. The *ALEXIS* multilayer mirrors also employ a "wavetrap" feature to significantly reduce the mirror's reflectance for He II 304 angstrom geocoronal radiation which can be a significant background source for space borne EUV telescopes. These mirrors, produced by Ovonyx, Inc., are highly curved yet have been shown to have very uniform multilayer coatings and hence have very uniform EUV reflecting properties over their entire surfaces. Our efforts in designing, producing and calibrating the *ALEXIS* telescope mirrors have been previously described in Smith et al. (1990), and Smith et al. (1989).

The left portion of Figure 3 represents an estimate of each telescope's on-axis effective area vs. input photon energy. These curves are currently being refined based on actual count rates observed from different EUV bright white dwarfs whose spectra have been measured with the *EUVE* spectrometers.

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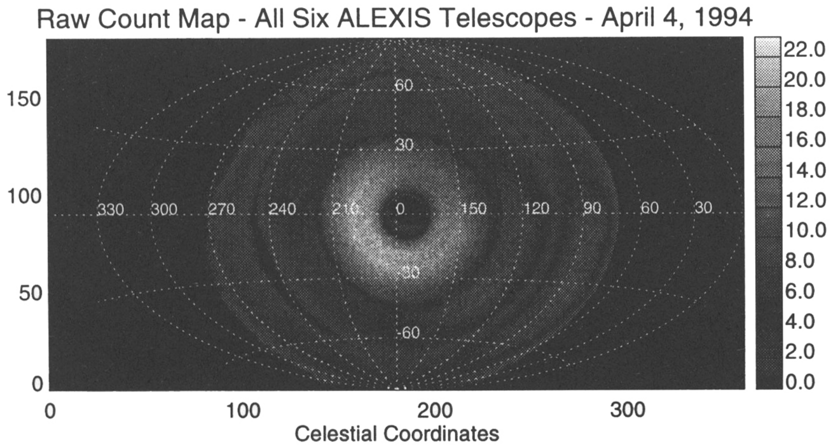

FIGURE 2. Raw count sky map (0.25 degree pixels) summing the data from all six *ALEXIS* telescopes demonstrating the wide area coverage that *ALEXIS* affords. The apparent variations in signal are entirely due to exposure and vignetting effects. The scanning motion of each telescope pair produced each of the annular ring regions on the map.

TABLE 1. Filter and photocathode makeup for each of the six *ALEXIS* telescopes.

Telescope	Look Direction Offset to Spin Axis (°)	Multilayer Mirror Bandpass	Filter	Photocathode
1A	87.5	93 eV / 130 Å	Lexan/boron	MgF_2
1B	87.5	71 eV / 172 Å	Al/Si/C	NaBr
2A	56	93 eV / 130 Å	Lexan/boron	MgF_2
2B	56	66 eV / 186 Å	Al/Si/C	NaBr
3A	31.5	71 eV / 172 Å	Al/Si/C	NaBr
3B	31.5	66 eV / 186 Å	Al/Si/C	NaBr

Table 2 describes the makeup of each of the telescopes' filters and detector photocathodes. Mechanically, each of the telescopes are identical.

3. Launch, Loss, and Scientific Recovery

ALEXIS was launched by a Pegasus booster on 1993 April 25 into a 844 × 749 km orbit with an inclination of 70°. The Pegasus dropped from the wing of a B-52 bomber at 13:56 UT. Initial reports from the launch site indicated a perfect, nominal launch. Initial attempts to contact the *ALEXIS* satellite after the launch were unsuccessful. Video taken

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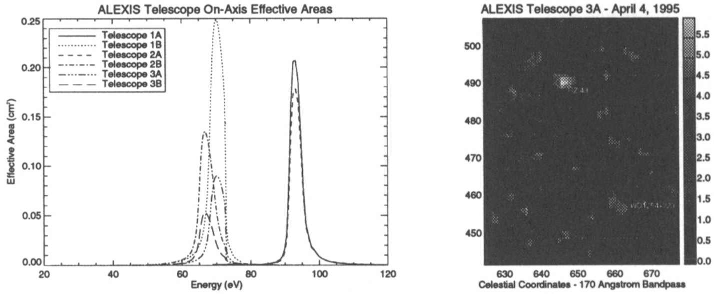

FIGURE 3. Left: Preflight on-axis effective area estimates for each *ALEXIS* telescope. Right: Detection significance map constructed from a 12 hour dataset from Telescope 3A (176 angstroms) on April 4, 1995. The scale is minus the base 10 log of the probability that the number of counts in a given source region is a fluctuation above the surrounding background. The bright source HZ 43 is unambiguously detected and a second white dwarf (WD1254+223) to the south is marginally detected. The horizontal grid lines are 10 degrees apart in Declination.

from the second stage of the Pegasus booster showed the *ALEXIS* +Y solar paddle to have prematurely unstowed.

During the weeks after launch, data gathered from external assets indicated that all four solar paddles had deployed. This implied that *ALEXIS* was not dead on arrival in orbit, but turned on and stayed on long enough to deploy the three undamaged solar paddles. After a 15 s transmission on June 2, on June 30, 1993 *ALEXIS* transmitted a strong signal and stayed in contact for 4 minutes. The telemetry data showed that *ALEXIS* was spinning about an axis nearly 90° from the Sun. All systems appeared functional except the magnetometer, which had failed. By July 5, 1993, commands had been successfully sent to *ALEXIS* to conserve power usage and the batteries became fully charged. Once regular contact with *ALEXIS* had been established, we devised a manual method of controlling the magnetic torque coils that did not depend on the broken magnetometer to control the orientation of the satellite spin axis (see Bloch et al. (1994a) for more details). By the end of July 1993, the solar panels were finally facing the Sun. Telescope doors were opened, and scientific operations began with the telescopes.

For several months that followed, telescope data were collected blindly in the hope that we could eventually devise an attitude solution algorithm that took into account the modified mass properties of the spinning satellite, the missing magnetometer, and the possible motion of the broken solar paddle. The first significant success with a new algorithm (a Kalman filter/backsmoother dynamics estimator) was achieved in April of 1994, when it was used to produce an image of the Moon and the EUV bright white dwarf HZ43 (Bloch et al. (1994b)). This first version appeared to have pointing accuracy of about one degree, still short of the desired 0.25° original goal. By November of 1994, a new revision of the attitude solution software was producing solutions with accuracies less than 0.5°, at which time three months of archival data were co-added to show the detection of several bright EUV sources, as well as the Cataclysmic Variable VW Hyi in super outburst from a dataset collected in late May and early June of 1994. These and subsequent source detections are detailed in Roussel-Dupré et al. (1995a). A further refinement of the attitude solution software became available in February of 1995 which allowed for solutions to be generated during spacecraft maneuvers which had not been possible previously. Since we have to perform maneuvers to correct for the drift away from the Sun of the spacecraft spin axis every 2 – 5 days (which would last up to 8 hours), we can now recover a significant additional portion of the data for analysis.

4. Science Goals

As an astronomical instrument, *ALEXIS* is like a set of wide-angle fish-eye lens cameras with narrow bandpass filters as opposed to observatory-class telescopes. With its wide fields-of-view and well-defined wavelength bands, it complements the scanners on *EUVE* and the *Rosat* WFC, which are sensitive, narrow field-of-view, broad-band survey experiments. The 66 and 71 eV *ALEXIS* bandpasses are tuned to the Fe IX–XII emission line complex, characteristic of million degree optically thin plasmas which exist in the coronae of stars and which are thought to fill a large fraction of interstellar space around the sun, creating the soft X-ray background. While the maximum effective areas are small compared to *EUVE* or WFC (which have peak effective areas of several cm^2), each *ALEXIS* telescope has a significant area-solid angle product, which is the true figure of merit for sky survey/monitor experiments. As a result of the telescopes' fast optics, *ALEXIS* can also excel in diffuse background studies, where large area-solid angle products are needed. Now that we know about the instrument's on-orbit performance, we can comment in detail on the status of the preflight science goals.

4.1. *The Diffuse EUV Background*

Measurements of the diffuse EUV cosmic background on degree angular scales would produce valuable information about the structure of the million degree gas that produces the soft X-ray background. Comparisons of *ALEXIS* data with the *Rosat* 0.25 keV sky maps would help set limits on low neutral column density structures that may exist in the local cavity, due to the large difference in photon absorption cross sections between the *Rosat* soft X-ray and *ALEXIS* bandpasses. The absolute fluxes observed in the *ALEXIS* 176 and 186 angstrom bandpasses could help set limits on the Fe abundance in the hot phase of the local interstellar medium (Bloch et al. (1991)).

We have only recently undertaken the first efforts at understanding the diffuse EUV cosmic flux in the *ALEXIS* data (Smith et al. (1995)). The analysis is very dependent on understanding all of the non-cosmic background sources. Despite great efforts in the design of the telescopes to reduce or eliminate a variety of on-orbit backgrounds, several unwanted diffuse signals are apparent in the *ALEXIS* data. These must be carefully cataloged and modeled before any diffuse maps with believable structure can be produced. In particular, an intense anomalous background is seen in the data that appears to be correlated (when it is present), with the spacecraft velocity direction vector ((Roussel-Dupré et al. 1995d),Bloch et al. (1994b)). This background may be similar to a background seen with the *Rosat* WFC (West et al. (1994)). There are other background trends that are related to high energy particle populations at different orbital positions, as well as geocoronal contributions. In spite of these non-cosmic background issues, *ALEXIS* can already place interesting upper limits on the flux from Fe lines in the million degree gas that is supposed to produce the soft X-ray background (Smith et al. (1995)) by looking at the difference between Earth and sky pointing counting rates.

4.2. *Narrow Band Source Survey*

Over 18 steady EUV sources have been detected in the first attempt at analyzing a year's worth of *ALEXIS* archival data (Roussel-Dupré et al. (1995a)) These sources, mostly white dwarfs, have been cataloged already by WFC and *EUVE* and for most have had detailed EUV spectra obtained with the *EUVE* spectrometers. In this regard, *ALEXIS* can add little to what is known about these sources, save that they provide convenient on-orbit calibration lamps to check for on-orbit instrument sensitivity changes. In addition, the *ALEXIS* telescopes and individual components (detectors, filters, and mirrors) underwent extensive calibrations prior to flight, so that when the final versions of *ALEXIS* preflight responses are available, an independent absolute calibration check can be performed with other EUV instruments.

4.3. *Transient Phenomena*

Bright transient EUV source detections have turned out to be the most significant science topic that *ALEXIS* can immediately address in the first months after the scientific mission recovery. The interest in this area of study intensified after the serendipitous discovery by the WFC of an extremely bright EUV transient that brightened by more than a factor of 4000 from its quiescent state (Dahlem et al. (1995)).

Several EUV outbursts from cataclysmic variables (CVs) have been observed with *ALEXIS*, namely VW Hyi, U Gem, and AR Ursae Majoris (=1ES1113+432) (Remillard et al. 1994). In addition, *ALEXIS* has detected at least two bright EUV transients lasting 24 hrs or less with (at the time of this writing), no obvious counterparts (Roussel-Dupré et al. 1995b), (Roussel-Dupré et al. 1995c). An *EUVE* target of opportunity observation was performed for each of these transients, but preliminary indications are that the sources had faded completely away by the time *EUVE* was pointed at the source location.

Before launch, it was hoped that *ALEXIS* would be able to gather statistics on the frequency of flare star outbursts using the 130 angstrom bandpass telescopes that include the intense Fe XX–XXIII lines, as seen in *EUVE* observations of AU Mic (Cully et al. (1994)). It is not clear as of this writing how much this goal can be achieved due to the fact that *ALEXIS'* actual observing efficiency is somewhat less than predicted preflight.

Since January 1995, we have been operating an automated software procedure to notify the *ALEXIS* team by e-mail if there are any sources or transients in the last 12, 24, or 48 hrs of telescope data. This procedure is usually completed within 2 hrs of the time that the data is downloaded to Los Alamos groundstation from the satellite.

4.4. *Gamma Ray Bursts*

Current theories to explain the isotropic distribution of Gamma Ray Bursts (GRBs) over the sky as seen with the Compton Gamma Ray Observatory (CGRO) now tend to put their source locations at cosmological distances. Because *ALEXIS* scans over such a wide area of the sky with every 50 s rotation of the satellite, it is natural to look for possible EUV counterparts to GRBs. If such a counterpart emission is observed, the source would have to be within $\approx$ 100 pc of the earth due to the opacity of the ISM at EUV wavelengths. Such an observation would be extremely significant to the study of GRBs.

We have begun to search the archival *ALEXIS* data for good datasets to use for this GRB study. For the 39 GRBs examined thus far, 10 were not in any *ALEXIS* telescope scan area, 12 occurred behind the earth from *ALEXIS'* vantage point, and 3 occurred during satellite shutdown periods. The remaining 14 bursts are good candidates to search for pre- or post-event EUV emission, and 4 of these events are good candidates for near-simultaneous observations, i.e., an *ALEXIS* telescope may have been scanning over the GRB error box at the exact moment that the GRB occurred.

4.5. *Lunar EUV Observations*

ALEXIS has collected a significant number of Lunar EUV flux measurements in the last two years. In fact, back in November of 1993, before we had developed any real spacecraft attitude solution capability, the Moon was the first celestial object identified in the *ALEXIS* data using the first rough analysis tools. These observations are useful for Solar EUV variability measurements, as well as Lunar surface composition studies (Edwards et al. (1995)).

5. Current Status

As of this writing (May, 1995), the *ALEXIS* satellite and payloads continue to function nominally. The difficulties caused by the launch damage have been mostly overcome through new procedures and software. The telescopes appear not to have lost any significant sensitivity over the two years that they have spent on orbit (Roussel-Dupré et al. 1995a).

ALEXIS would not have been possible without the dedication of a great many people over the last six years. We would like to particularly thank those who lent their hearts and minds to the launch and rescue, and those that continue to work tirelessly on flight operations and data analysis tasks. Past and present, these include Ron Aguilar, Frank Ameduri, Tom Armstrong, Mark Bibeault, Doug Ciskowski, Don Cobb, Jim Devenport, Bryan Dunne, Brad Edwards, Don Enemark, John Gustafson, Amy Hodapp, Mark Hodgson, Dan Holden, Irma Gonzales, Dave Guenther, Meg Kennison, Phil Klingner, Cindy Little, Lisa May, Carter Munson, Greg Nunz, Greg Obbink, Tim Pfafman, Mick Piotrowski, Bill Priedhorsky, Keri Ramsey, Diane Roussel-Dupré, Sean Ryan, Ernie Serna, April Smith, Barry Smith, Steve Smoogen, Steve Stem, Ralph Stiglich, and Steve Wallin of Los Alamos; Bob Dill, Frank McLoughlin, Robert Miller, Mark Psiaki, Richard Warner, and Chris Wright of AeroAstro; David Bullington, Jim Griffee, Jim Klarkowski and Harvey Temple of Sandia National Laboratories; David Hastman and Jean Floyd of Orbital Sciences, Inc.; Lt. Frank Dement and Capt. Kurt Hall of the United States Air Force, and the staff of the Vandenberg Tracking Site. The *ALEXIS* detectors were built and calibrated at the University of California-Berkeley Space Sciences Laboratory by Oswald H. Siegmund, Scott Cully, and John Warren. This work was supported by the US Department of Energy.

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