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Submitted to:

TITLE
ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR**
EDITORS

Limits on the Emission from Fe VIII – XII in the Hot Local Interstellar Medium

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Abstract. The majority of the emitted power from an optically thin million degree plasma (such as the one thought to produce the soft x-ray background) originates in the EUV band at wavelengths longer than 170Å. Lines from Fe VIII - Fe XII dominate the emission in this wavelength region. This paper describes work in progress on the analysis of three years of data from the ALEXIS mission in search of this flux.

1. Introduction

In the 30 years since the discovery of the diffuse Soft X-Ray Background (SXRB) (Bowyer, Field, & Mack 1968; Henry et al. 1968; Bunner et al. 1969), a consensus has developed that much (although not all) of this $^1/_4$keV background is a signature of hot interstellar gas in the Local Interstellar Medium (LISM) inside the so called "Local Bubble". (See Sanders & McCammon 1990 for a review). Understanding the origin and dynamics of this gas is an important part of understanding the lifecycle of matter in our Galaxy. Until recently there were only broad energy band measurements of the x-ray and EUV flux from this gas, and the existing atomic plasma emission models could correctly fit the observed emission (Mccammon et al 1983; Marshall and Clark 1984; Bloch et al. 1986; Juda et al 1991). These broad band measurements ($\Delta E/E \approx 1$) were performed with proportional counters, microchannel plate detectors, and x-ray/EUV filters. Even with the poor spectral resolution of these devices, some difficulty with the detailed spectral fits had become apparent at very low energies (Bloch 1988; Bloch et al 1990). Indeed, as more detailed spectral measurements of this diffuse low energy x-ray and EUV emission became available, inconsistencies with existing emission models have become even more apparent prompting questions about the physical state and composition of this hot phase of the LISM. Most notably, the Diffuse X-ray Spectrometer (DXS) (Sanders et al 2001), Extreme Ultraviolet Explorer (EUVE) Medium Wavelength Spectrometer (Jelinsky et al 1995; Vallerga and Slavin 1998), the Wisconsin microcalorimeter rocket experiment (Kelly et al 2000), and the ROSAT Wide Field Camera (West et al 1995) have all shown results that significantly depart from emission models that assume cosmic abundances and ionization equilibrium for the hot gas that fit the other broad band measurements.

Plasma emission models (Raymond & Smith 1977; Mewe et al 1986; Kaastra 1992) show a dramatic increase in the number and strength of emission lines

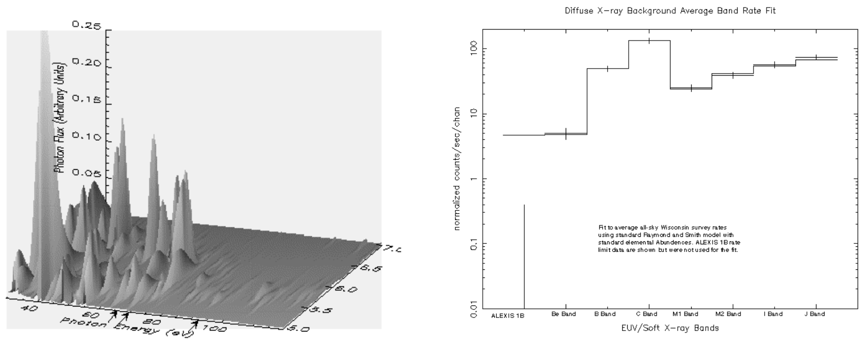


Figure 1. Left: Photon spectrum from an optically thin hot plasma as a function of temperature (Raymond & Smith 1977). The arrows indicate the energy centers of the three ALEXIS telescope bandpasses. Right: XSPEC model fit to the average all sky count rates from the various bands in the Wisconsin Sky Survey including the Be Band. The energy of the bands represented by the channels increases from left to right. The leftmost channel is the ALEXIS 1B Band. The fit does not include the ALEXIS upper limit found in this paper and predicts that the ALEXIS Telescope 1B average all sky count rate should be about 5 counts per second using a Raymond & Smith (1977) model described in Table 1. The one sigma upper limit for ALEXIS telescope 1B found with this work is also indicated.

at wavelengths longer than 170Åfor optically thin plasmas with temperature ranges from 10^5 to 10^7 K temperature range and standard cosmic abundances (see Figure 1). A particularly strong set of lines appears around 170Åfor plasmas with cosmic abundances and equilibrium conditions around 10^6 K. This temperature plasma has adequately fit the broad band SXRB data. The lines at 170Åare from $\delta n = 0$ transitions from Fe VIII through Fe XII ions. These lines provide a surprisingly large fraction (up to $\approx$ 34%, Bloch 1990) of the cooling power for such a plasma. The detection and mapping of this radiation from the hot LISM was one of the scientific objectives of the Array of Low Energy X-ray Imaging Sensors (ALEXIS) satellite experiment.

Table 1. Description of average all-sky emission model and fit parameters used in Figure 1, from nearest to farthest components. The ALEXIS Telescope 1B upper limit was not used in the fit.

Component and Description	Parameter	Units
NH absorber - Local "Fluff"	2×10^{18} (fixed)	cm^{-2}
Hot LISM Plasma Emission Temperature	0.0904 ± 0.0143	keV
Hot LISM Emission Measure	0.0036 ± 0.0005	$cm^{-6} - pc$
NH Galactic Slab Absorber	2×10^{20} (fixed)	cm^{-2}
Hot Extragalactic ISM Temperature	0.250 ± 0.039	keV
Hot Extragalactic ISM Emission Measure	0.0045 ± 0.0012	$cm^{-6} - pc$
Extragalactic Power Law Index	-1.4 (fixed)	
Extragalactic Power Law Normalization	11 (fixed)	$photons - cm^{-2} - keV$

2. The ALEXIS Mission and Instrument

The ALEXIS satellite (Priedhorsky et. al. 1991; Bloch et. al. 1992) contains six compact normal-incidence telescopes operating in narrow energy bands centered on 66, 71, and 93 eV (186Å, 172Å, and 130Å). ALEXIS was launched using a Pegasus air-launched booster into a 70° inclination, 400 x 450 nautical mile orbit on April 25, 1993. Although a serious incident occurred at launch in which one of the solar panel hinge brackets broke, the mission was fully recovered (Bloch et al. 1994) and continues to operate on orbit.

The six ALEXIS EUV telescopes are arranged in three co-aligned pairs and cover three overlapping 33° fields-of-view. The telescopes scan almost all of anti-solar hemisphere during each rotation of the satellite. Each telescope consists of electron rejection magnets at the telescope aperture, a spherical mirror with a Mo-Si multilayer coating, a UV background-rejecting filter in front of a curved profile microchannel plate detector located at the telescope's prime focus, and image processing readout electronics. The on-axis geometric collecting area of each telescope is $\approx 25 cm^2$, with spherical aberration limiting spatial resolution to about 0.25°.

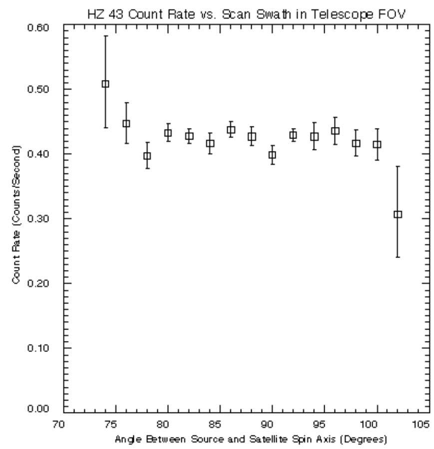
The narrow band responses ($\Delta E/E \approx 5\%$) enabled by the normal incidence multilayer mirrors in the fast optics of the ALEXIS telescopes provided a unique opportunity to measure this flux and map it across the sky because of the relatively large area-solid angle response for measuring diffuse emission. This is a uniquely powerful diagnostic measurement because the telescopes can measure radiation that is primarily from one element and a narrow range of ionic species. This same technique has been used successfully by the Solar EIT experiment on the SOHO satellite (Delaboudiniere et al 1995).

ALEXIS is always in a survey-monitor mode, rotating approximately once every 50 seconds so that the same portion of the sky is scanned repeatedly during each orbit and for different local orbital background conditions. ALEXIS is tracked and controlled from a single small ground station located at Los Alamos.

For this ongoing study, we are using the data from ALEXIS Telescope Pair 1, containing the telescopes designated 1A and 1B. This pair of co-aligned telescopes points approximately 90° away from the satellite spin axis. Thus this telescope pair scans a full 180° which often includes the earth as well as the sky in a time period ($\approx$ 50 seconds) short enough that the orbital environment background conditions change relatively little. Thus the same parts of the sky are scanned 30 or more times during orbit eclipse (when data are collected) but with slowly varying environmental conditions. This is in marked contrast to the orbital operations during the scanning phases of the EUVE or ROSAT missions in which the scanning period was close to the orbital period so that different parts of the sky were scanned only once per orbit and were correlated with different orbital environment parameters.

Telescope 1B's narrow response function is centered at 175Åon the intense Fe line emission from the hot ISM. This work reports initial results from the analysis of Telescope 1B in looking for a signal from the SXRB.

For this study it was critical to verify the response of the instrument to diffuse radiation. This effort proceeded in several steps. This was done indirectly



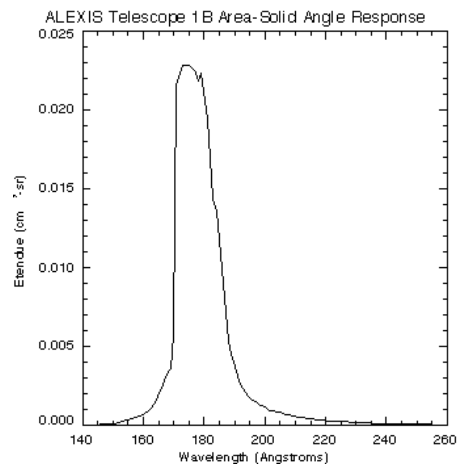


Figure 2. Left: Count rate for HZ 43 in ALEXIS Telescope 1B vs. scan angle in the telescope field-of-view. Right: Validated ALEXIS Telescope 1B area-solid angle product response curve.

as a monochromatic, calibrated, diffuse source of EUV radiation was not available in the laboratory prior to launch. First, the individual calibrations for each component of the telescope (telescope geometry, mirror, filter, and detector) were combined into a single end-to-end simulation model of the telescope's operation. With this model, photons of any wavelength can be traced through the entire system. This software can generate simulated data files that look just like real pre-flight calibration or in-flight data. The software was then used to generate data files that corresponded to actual monochromatic absolute throughput pencil beam tests. Simulation and telescope geometry parameters were modified until the best correspondence between simulation and actual calibration run were obtained. Overall normalization factors were fit for each calibration run and a wavelength dependent correction factor plot was generated. These wavelength dependent normalization factors were fit to an ad-hoc empirical function. We then used the resulting instrument model to generate an on axis effective area function, used for point source studies.

The vignetting function, or off-axis efficiency function of the ALEXIS telescopes has a very steep radial dependence in the field of view. This function was adjusted in a relative way using on orbit data from the bright white dwarf source HZ 43. These corrections to the vignetting function were all of a relative nature with respect to the maximum throughput on axis. This effort produced a vignetting function that yielded a constant count rate for HZ 43 over all telescope scan swath angles as shown in Figure 2. The final area-solid angle response curve shown in Figure 2 was created by combining the on axis effective area response curve with the integration of the effective solid angle response implied by the final vignetting function. As a final consistency check, we can compare the count rate for HZ 43 predicted for telescope 1B by folding the EUVE spectral atlas spectrum with the effective area curve. This comparison is shown in Table 2. The comparison with Alpha Cen is particularly important as it is a coronal source of the same Fe lines that we are trying to detect from the ISM. Also importantly (but not shown), the count rate observed from HZ 43 (and therefore the relative response of ALEXIS Telescope 1B) did not change significantly over the three year period for the analysis presented here.

Table 2. Telescope 1B EUV source count rates.

EUV Source	Predicted Rate	Observed Rate
HZ 43 :	0.478	0.436 ± 0.03
Alpha Cen :	0.0186	0.012 ± 0.004
G191 B2B :	0.063	0.066 ± 0.002

3. The Data

For the analysis presented here, ALEXIS Telescope 1B was treated as a "light bucket" in the sense that the event count rate over the entire detector area was considered without further regard to the spatial imaging information. The half-second sampled count rate records generated by the front end electronics form the basis of the dataset that we analyzed. During the standard science data pipeline processing, each count rate record is tagged with the look direction of the telescope at that time interval, the L value of the magnetic field line on which the satellite was located, the satellite's location, and the angle of the telescope look direction to the satellite velocity vector.

3.1. Modelling the Non-cosmic Background

The count rate time history for the ALEXIS data proved to be extremely complex once regular data collection operations commenced. A multi-component model was constructed to explain the non-cosmic signal sources.

As reported in Bloch 1994 and Roussel-Dupre' et al 1996, ALEXIS telescope data show large count rate variations over a satellite rotation. The high count rates were not associated with the Earth. After correlating the count rates with all possible attitude related system parameters, the most consistent correlations arise from plots of count rate vs. telescope look direction angle to the velocity or ram direction. It appears that the low count rates all occur for ram angles higher than 110° on all six telescopes, i.e. when the ram flow can no longer get into the telescope aperture.

The exact nature of the background is still unknown but for the purpose of the work presented here, selecting data based on the angle between the telescope look direction and the velocity ram vector very effectively removes this background, regardless of its source.

The microchannel plate detectors used for ALEXIS are similar to those used in many other space missions such as EUVE. Residual radioactive Potassium in the glass material within the detector generates a baseline dark count rate of a few counts per second. These intrinsic rates were observed during ground calibration runs. This intrinsic rate can increase during orbital operations as high energy radiation gradually activates the detector material causing even more intrinsic radioactivity.

High energy electrons and protons that could penetrate the bodies of the ALEXIS telescopes on orbit and cause secondary electron generation in the microchannel plate detectors were expected prior to launch. To monitor each telescope's intrinsic detector and penetrating particle count rates a small aluminum mask was placed at the edge of the active area of each ALEXIS telescope detector. Events underneath the small circular mask can only originate as dark counts or penetrating particle events. The events collected under these shadow masks during 1995 were analyzed. For L values less than 3, the dependence of the count rate on L is fairly linear. This linear dependence on L for the penetrating particle count rate forms an important component of the non-cosmic background model used for this analysis. In addition to the linear L value dependence, the model terms for penetrating radiation allowed for a periodic dependence on the magnetic longitude of the satellite's location, as well as a linear time dependence of the L value count rate dependence over the typical 5 day period of a single data set analysis.

Cosmic measurements in the EUV band always have to contend with large geocoronal backgrounds that can swamp the measurement of interest if these off band fluxes are not dealt with properly. Despite the measures taken to reduce the response of the telescopes to He II 304 Åflux, ground calibration indicated that up to 1 detector count/second per Rayleigh of 30.4 nm diffuse radiation would be observed as an out of band pass light leak in telescope 1B. A qualitative model of this emission was constructed based on Gladstone (1992), and references therein. In the fit we make to the total background, only the overall normalization factor is varied. This accounts for potentially varying solar source function intensity as well as global He^{+} density variations.

Other geocoronal backgrounds, such as 121.6 nm, 83.4 nm, and 25.6 nm were considered to be well suppressed by the telescope filter design.

3.2. Data Analysis

We used the spectral modeling software package XSPEC (version 10.0) for determining the expected count rate to be seen with ALEXIS and fitting various models to the results of the analysis. A set of virtual pulse height bins were created for the analysis by having the ALEXIS telescope 1B count rate represented by the lowest pulse height bin, then having the following seven pulse height bins represent the Wisconsin Sky Survey Be, B, C, M1, M2, I, and J bands. An average all sky model outlined in Mccammon and Sanders 1990 was put into XSPEC and fits the previous data quite well (see table 1. This model predicts a count rate of 5 counts/second in ALEXIS telescope 1B, a very detectable signal. Bloch et al. (1986) showed that the low energy Be band rate correlated very well with the higher energy B band count rate. Models show that a major fraction of the counts in the Be Band should come from the Fe lines around 175Åinside the 1B response, so we might expect the spatial variation of the 1B measured flux to follow the Wisconsin B band sky map.

The 0.5 second sampled count rate data from Telescope 1B were fit to the cosmic and non-cosmic model components in 5 day segments. Two types of cosmic fits were performed where possible. First, a fit where the cosmic component is a scaled version of the Wisconsin B band map. The second, a fit to a fixed cosmic background count rate using those 5 day datasets where both

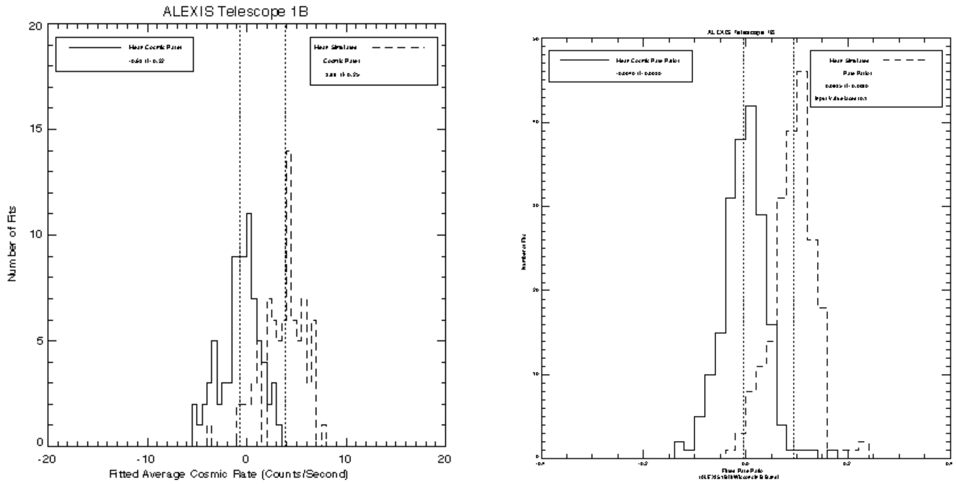


Figure 3. Left: Summary of 5 day fits to a constant cosmic excess flux. Right: Summary of 5 day fits to a cosmic ratio of cosmic ALEXIS excess flux to Wisconsin B-Band count rate map. In both plots, the dashed histograms represent the fits with the expected counts from the sky artificially injected into the data with proper poisson statistics based on the expected count rate ratio from the Wisconsin B band map.

earth looking and sky looking data are present. The results of the cosmic count rate ratio (ALEXIS 1B rate to Wisconsin B band rate) and fixed cosmic rate fits are shown as the histograms in Figure 3. The Histograms are consistent with zero cosmic flux. As a consistency check, we injected simulated counts from the sky with poisson statistics into the real data at the expected count rates and re-fit the data. The resulting histograms for both fitting methods are shown as the dashed lines. These results are consistent with the input sky parameters and thus our procedure would have pulled out a true sky flux had it been present. The one sigma upper limits compared to the sky average predicted flux is shown in Figure 1. Thus, the Fe lines are absent by at least a factor of 10 from what is expected from plasma emission models with normal cosmic abundance and ionization equilibrium.

4. Summary and Conclusions

The ALEXIS analysis presented here is consistent with (but over a much broader area of the sky) the results obtained with the EUVE Medium Wavelength Spectrometer (Jelinsky et al 1995; Vallerga and Slavin 1998) searching for the Fe lines. It is beyond the scope of the limited space in this paper to discuss all the possible alternatives for the missing Fe line flux from the hot phase of the LISM. ALEXIS data must be combined with other spectroscopic datasets at different wavelengths to constrain such modified abundance or non-equilibrium (Breitschwerdt et al 1998; Breitschwerdt and Schmutzler 1994) alternatives. This ongoing work suggests that the new clues about the origin and nature of the hot LISM may be found in the explanation of these spectral discrepancies.

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