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Section A

A sounding rocket payload for X-ray astronomy employing high-resolution microcalorimeters

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Abstract

We have completed a sounding rocket payload that will use a 36 element array of microcalorimeters to obtain a high-resolution spectrum of the diffuse X-ray background between 0.1 and 1 keV. This experiment uses only mechanical collimation of the incoming X-rays, but the cryostat and detector assembly have been designed to be placed at the focus of a conical foil imaging mirror which will be employed on subsequent flights to do spatially resolved spectroscopy of supernova remnants and other extended objects. The detector system is a monolithic array of silicon calorimeters with ion-implanted thermometers and HgTe X-ray absorbers. The 1 mm^2 pixels achieve a resolution of about 8 eV FWHM operating at 60 mK.

The soft X-ray diffuse background was discovered almost 25 years ago [1], but it remains poorly understood. The very bright diffuse flux observed at 0.2 keV appears to originate largely from within our galaxy, and is assumed to be thermal radiation from a component of the interstellar gas that must then be a temperature near 10^6 K. If such material is as common throughout the disk of the galaxy as it appears to be locally, it would have a profound effect on our understanding of the interstellar medium, star formation, and galactic evolution.

A major difficulty with this interpretation is that we are currently unable to come up with a place to put the hot gas that is consistent with all of the observations: some data appear to require that all of the emission originate quite close to the sun [2], while others show that at least half must come from much further away [3,4]. Distances are inferred by looking for the effects of absorption by cooler gas whose distance has been determined by other means. At the low spectral resolution now available, this process is complicated by the confusion of effects of varying absorption column and varying emission temperature.

In the 0.5–1 keV range, the interstellar medium is still opaque within about $\pm 10°$ from the galactic plane, so emission seen there must originate within the galaxy, and is presumably thermal (although this may be only a lack of imagination in finding viable alternatives). The required gas temperatures are $2–4 \times 10^6$ K, and the emission should be essentially all in the characteristic lines of the partially-ionized heavy elements. At high latitudes, on the other hand, deep exposures with ROSAT have shown that at least 45% of the observed flux can be resolved into distant quasars [5]. Maps of the sky at this energy show no change in intensity between high latitudes and the galactic plane, however, and the broad-band spectrum appears the same at all latitudes [6]. This is a most bothersome coincidence, but could be confirmed with high spectral resolution observations: the galactic emission should be entirely resolved into lines, while the cosmological contribution must be at least quasi-continuous due to smearing by the large redshifts.

Fig. 1 shows existing spectral data in the 0.1–1.0 keV range from a gas proportional counter on ROSAT. Predictions for a two-temperature thermal emission model that fits this observed spectrum are shown for a CCD detector and for a microcalorimeter with 5 eV FWHM resolution. The model also includes a continuum component based on the assumption that about half the observed 0.5–1 keV flux is cosmological. The CUBIC CCD experiment will be flown in the near future by the Penn State X-ray group on the Argentinean satellite SAC-B. The CCD has only ~2 e$^-$ readout noise, so this spectrum represents very nearly the fano-limited theoretical resolving power of silicon. This is a major improvement on the proportional counter, but the calorimeter spectrum reveals much more of the detailed information available. It can resolve a large number of individual lines, whose relative intensities can be used to deduce elemental abundances, electron temperatures, and

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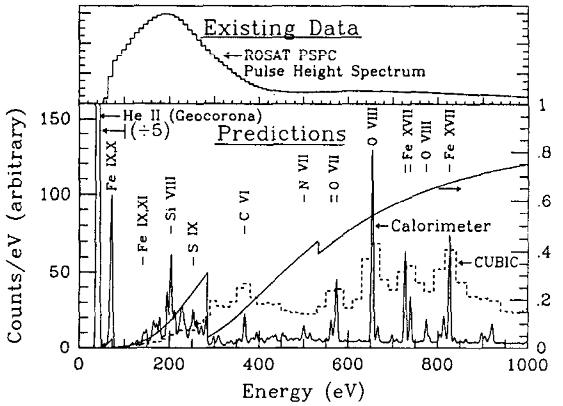

Fig. 1. Existing spectral data on the diffuse X-ray background and predictions for the Penn State CUBIC experiment, employing a state-of-the-art CCD, and for a 5 eV FWHM microcalorimeter. The predictions use a two-temperature thermal emission plus $11E^{-1.4}$ keV/(cm^{2}s sr keV) continuum model that is consistent with the ROSAT proportional counter spectrum.

ionization states in the hot gas. There is sufficient redundancy to allow detection of multiple temperatures along a line of sight. The past history of the gas is also accessible: at interstellar densities, the time required to reach equilibrium between ionization state and electron temperature is 10^6 years or more – longer than the evolution time of the interstellar medium. By comparing these quantities, it can be determined whether the gas is in the process of heating or cooling, or how long ago it was heated. Examination of individual line ratios in different directions can disentangle the effects of absorption and temperature variation, and the presumably extragalactic continuum level can be measured readily by looking between the lines. If there is no extragalactic flux, the lines above 0.5 keV would be twice as bright, and there would be no counts between them.

The present experiment uses a 36-element array of 1 mm^2 pixels with HgTe X-ray absorbers and ion-implanted silicon thermistors, operating at ~50 mK. The detector array is described in detail elsewhere in this volume [7]. Its field of view on the sky is limited by a 1 sr mechanical stop. Since the X-rays of interest will travel only a millimeter or so in air, the instrument must be above most of the atmosphere in order to observe them. We decided to fly it on a sounding rocket instead of a satellite because a) we can do it now instead of 10 or 15 years from now, and b) it is more fun.

The sounding rocket is about 44 cm in diameter and 15 m long, and is fired almost straight up. It reaches an altitude of ~250 km, then falls back down, giving ~300 s of observing time above 160 km. The data are returned by a telemetry link. A cross section of the rocket cryostat is shown in Fig. 2. It has a 4 l liquid helium container with two vapor-cooled shields, and weighs a total of 22 kg. The adiabatic demagnetization unit consists of a 50 g iron-alum salt pill with a Kevlar fiber suspension, and a 4 T, 8 A superconducting magnet. The complete ADR insert, which bolts into a hole in the helium can, weighs about 1.8 kg. The magnet leads have a high-T_c superconducting link between the helium can and the 30 K vapor-cooled shield, which greatly reduces the heat load on the liquid helium. Silicon JFET source followers operated at 125 K and low-noise room temperature preamps give an overall system noise of 3 nV/$\sqrt{\text{Hz}}$, flat down to 5 Hz, for each detector element.

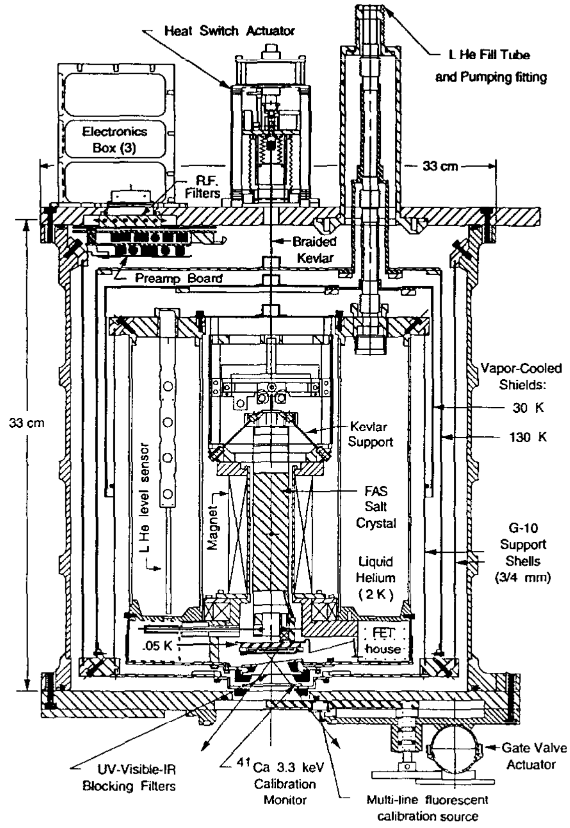

Fig. 2. A cross section view of the sounding rocket cryostat.

We pump on the LHe bath through a port in the rocket skin up to ~2 m before launch. A motor-driven valve in the port is then closed, and the rocket flies away from the vacuum connection. The valve is reopened at 70 km, and is closed again before reentry. A gate valve is opened above 160 km to allow observations. An attitude control system with nitrogen gas jets and a gyroscope reference aims the instrument in the desired directions.

Everything in the cryostat is designed to withstand 200 g on any axis, so there is a substantial safety margin for launch loads (13 g static plus 17 g rms vibration), and about a 90% chance or surviving the parachute recovery. The high vibration levels during motor burn create an additional problem that would not exist for a satellite experiment, however. There is not time to cycle the ADR in flight, so the detectors must be cooled down before launch, and there is then only a limited amount of cooling energy available before it would need to be cycled again. The heat input to a mass suspended from a surface driven by a flat vibration spectrum turns out to be independent of both resonant frequency and damping, and is proportional to the mass with a magical constant of nature equal to 13 W kg^{-1} g^{-2} Hz^{-1}. With a cold stage mass of 100 g, the rocket vibration level of ~0.1 g^2/Hz (5–2000 Hz) would produce a heat input of about 130 mW, compared to the normal parasitic heat load of 200 nW. This would almost immediately exhaust the cooling capacity of the salt pill. A very careful mechanical design (largely due to Jiahong Zhang) employs staggered resonant frequencies at different levels culminating in the ~500 Hz resonant frequency of the Kevlar cold stage suspension. This provides sufficient isolation to reduce the vibrational heat input to ~85 μW, which uses up only ~20% of the cooling capacity in the 43 s of powered flight.

The coldstage is demagnetized to 50 mK before the launch, then the superconducting magnet terminal voltage is held at zero volts, keeping the magnet current constant, during the powered flight. Vibrational heat input raises the coldplate temperature to ~80 mK, and 10 s after burnout, control of the magnet terminal voltage is switched to a simple analog PID controller that uses an NTD germanium resistance thermometer on the coldplate to control the temperature. The primary coldplate-salt pill thermal time constant has been kept down to ~1 s, and the GRT readout has a bandwidth of 3 Hz. This allows the 50 mK temperature regulation to be recovered to better than 1 μK in ~20 s, leaving ~50 s to look at the multi-line low-energy fluorescent source on the inside of the gate valve before the minimum observing altitude of 160 km is reached and the gate valve opened. Fig. 3 shows the temperature error as a function of time during a simulated flight.

Another difficulty for any low-energy X-ray observation of sources outside the cryostat is that room-temperature infrared radiation must be attenuated by about ten orders of magnitude or else shot noise from infrared photons will contribute significantly to detector noise. Since no material has a sufficiently large ratio of infrared to soft X-ray absorption to allow usable sensitivity at 150 eV and below, we have made use of the large real part of the refractive index of aluminum in the infrared to attenuate the infrared largely by reflection. (There is very little surface loss in the X-ray region.) Four filters with 200 Å of aluminum supported on 1000 Å of Parylene are tilted by 3° to minimize multiple reflections. A Monte Carlo ray-tracing program shows that this stack provides the required infrared attenuation, and the measured X-ray transmission is shown in Fig. 1 (and has been included in the predicted response).

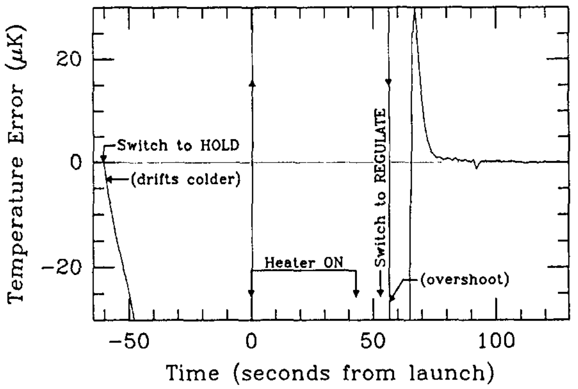

Fig. 3. Coldplate temperature error as a function of time during a simulated launch. The vertical scale is expanded to show the final recovery to the 50 mK regulating point. Launch vibration is simulated by applying an electrical heat load equal to the heat input measured during a vibration test at launch levels.

The rocket payload is on its way to integration, and we expect to launch it by the end of the year.

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