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ABSTRACT

We present the CODEX sounding rocket payload, a soft x-ray (0.1-1.0 keV) spectrometer designed to observe diffuse high-surface brightness astronomical sources. The payload is composed of two modules, each with a 3.25° x 3.25° field of view defined by a stack of wire grids that block light not coming to a 3.0 m focus and admit only nearly-collimated light onto an array of 67 diffraction gratings in an off-plane mount. After a 2.0 m throw, the spectrum is detected by offset large-format gaseous electron multiplier (GEM) detectors. CODEX will target the Vela supernova remnant later this year to measure the temperature and abundances and to determine the contributions of various soft x-ray emission mechanisms to the remnant's energy budget; resulting spectra will have resolution ($E/\Delta E$) ranging from 50 to 100 across the band. CODEX is the third-generation of similar payloads from the University of Colorado, with an increased bandpass, higher throughput, and a more robust mechanical structure than its predecessors.

Keywords: x-ray spectroscopy, Vela supernova remnant, sounding rocket, off-plane gratings, GEM detectors

INTRODUCTION

The soft x-ray (0.1-1.0 keV) sky is poorly understood on large angular scales. Spectrometers with high spectral resolution have tiny fields of view, while ones with large fields of view have low spectral resolution. Large angular scale spectroscopy is necessary to understand the energy budgets of supernova remnants and features in the soft x-ray background (SXRB), instead of focusing on bright emission features or absorption lines in front of bright point sources as is necessary with the small fields of view of the *Chandra* and *XMM-Newton* orbiting observatories. Small fields of view can be mosaicked into large fields of view, but such observations are expensive.

The standard for large-angle soft x-ray observations is set by the *Roentgen Satellite* (ROSAT), providing excellent spatial coverage, moderate spatial resolution, and dismal spectral resolution ($E/\Delta E \approx 1$). The proportional counters divided the soft x-ray bandpass into two bands (110-400 eV and 400-900 eV). They provided an efficient and deep all-sky survey, identifying several bright, extended features in the soft x-ray sky against a ubiquitous but non-uniform soft x-ray background. Prominent amongst the bright features are the Cygnus Loop and the Vela supernova remnants (SNRs), with surface brightnesses a factor of ~50 above the SXRB. Additional features, most notably the North Polar Spur, have surface brightnesses a factor of a few above the SXRB.

We have built a sounding rocket payload optimized to access the large-angle, high-resolution void of astronomical soft x-ray spectroscopy. Named CODEX, the payload carries an optical configuration identical to that of the *Cygnus X-ray Emission Spectroscopic Survey* (CyXESS [1,2]) and *Extended X-ray Off-plane Spectrometer* (EXOS [3]) payloads, both of which targeted the Cygnus Loop SNR. The payload carries two nearly-identical spectrographs, each of which uses a stack of wire grids to create pseudo-collimated light paths by blocking most

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non-parallel light though each channel. An array of off-plane diffraction gratings forms the heart of the spectrograph at a distance of 2.0 m from the detectors, dispersing the spectrum to a resolution of 50-100. The spectrum is recorded by gaseous electron multiplier (GEM) detectors, with their positioning relative to the spectrum being the only significant difference between the spectrographs.

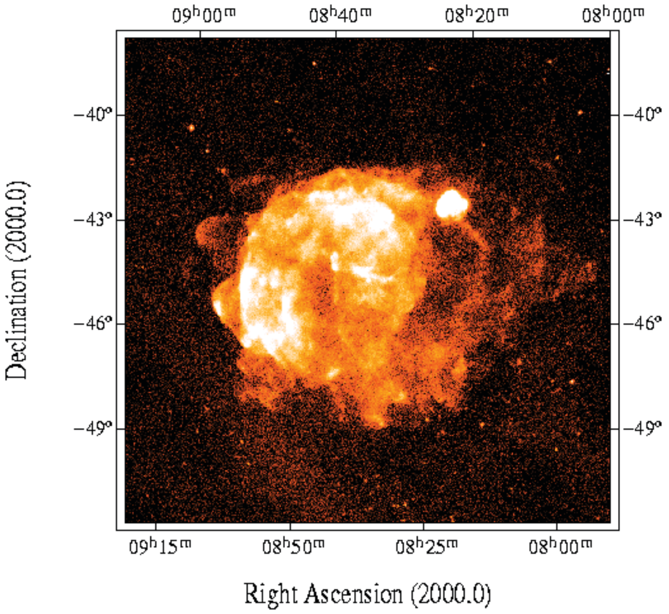

Figure 1: The Vela and Puppis SNRs, imaged with the 400-900 eV proportional counter on the ROSAT satellite. Puppis is the bright spot to the upper right of the much-larger Vela SNR. (*ROSAT* image)

We have extensively remodeled the CyXESS/EXOS mechanical design to make it more robust and modular, allowing for easier future improvements to sensitivity or for using the layout to piggyback on satellite missions. The CODEX payload will target the Vela SNR $08^{h}41^{m}40.0^{s}$ RA, -44°$08^{m}00^{s}$ Dec) with a launch from White Sands Missile Range. In terms of visibility, the Vela SNR is a diffuse, high-surface brightness soft x-ray source. Astronomically, it is a middle-aged (12 kyr) supernova remnant with soft x-ray emission from all regions and minor edge-brightening where the SNR plows into the interstellar medium (ISM), as seen in Figure 1. It lies at a distance of 250 pc in the constellation of Vela, spanning 5°x8° and lying along the same line of sight as the younger and smaller Puppis SNR. The Vela SNR has a known pulsar with a wind nebula, but these features are insignificant in the large field of view of the CODEX payload. In targeting the Vela SNR, we hope to determine both the dominant emission mechanism in the soft x-ray bandpass and the equilibrium state of the plasma.

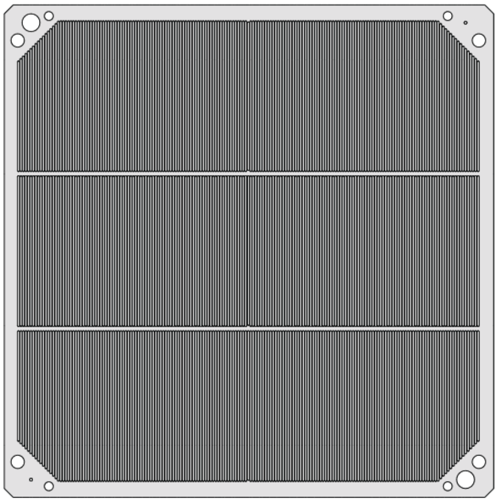

Figure 2: The top wire grid from one of the CODEX spectrometers. Each of three sections has 184 wires with 165 μm width separated by 724 μm gaps. The plate is 125 μm thick electroformed nickel. The 500 μm alignment edge is to the right, and the laser alignment holes are in the bottom right and top left.

This paper focuses on the instrument design, following photons through the optical path. The wire grid stacks (Section 2.1) precede the diffraction grating arrays (Section 2.2) and the GEM detectors (Section 2.3). Support electronics and gas system are briefly discussed (Section 2.4). We also present the nominal flight plan of the rocket, including calibration (Section 3), and the expected science return (Section 4).

2. PAYLOAD DESIGN

2.1 Wire grid stack design

Science requirements call for an optical system capable of producing a line focus at 3.0 m. Additionally, the light must be collimated at 1.0 m (2.0 m from the detectors) where the diffraction gratings mount. Due to the strenuous conditions of rocket flight, the system must also be light and robust. We achieve these goals via a series of 24 wire grids spaced unevenly along a 0.9 m stack. Each grid is made of 125 μm-thick electroformed nickel, manufactured by Thin Metal Parts, Inc., and epoxied to an aluminum frame for support. The thinness of the grids causes them to behave as knife edges in an effort to minimize internally-scattered light. The wires themselves begin at 165 μm in width and spaced at 889 μm intervals, spanning a 165 mm x 165 mm area with 184 parallel wires; horizontal support bars divide this into three sections (Fig. 2). Wire widths and spaces decrease proportionally along the stack to match the separation of light for a 3.0 m focus (Fig. 3), resulting in a final wire width of 114 μm and a spacing of 500 μm. When assembled, these parameters produce a line focus with a full-width half-maximum of 1.7 mm (1.8-2.4 mm across the bandpass after diffraction from the gratings).

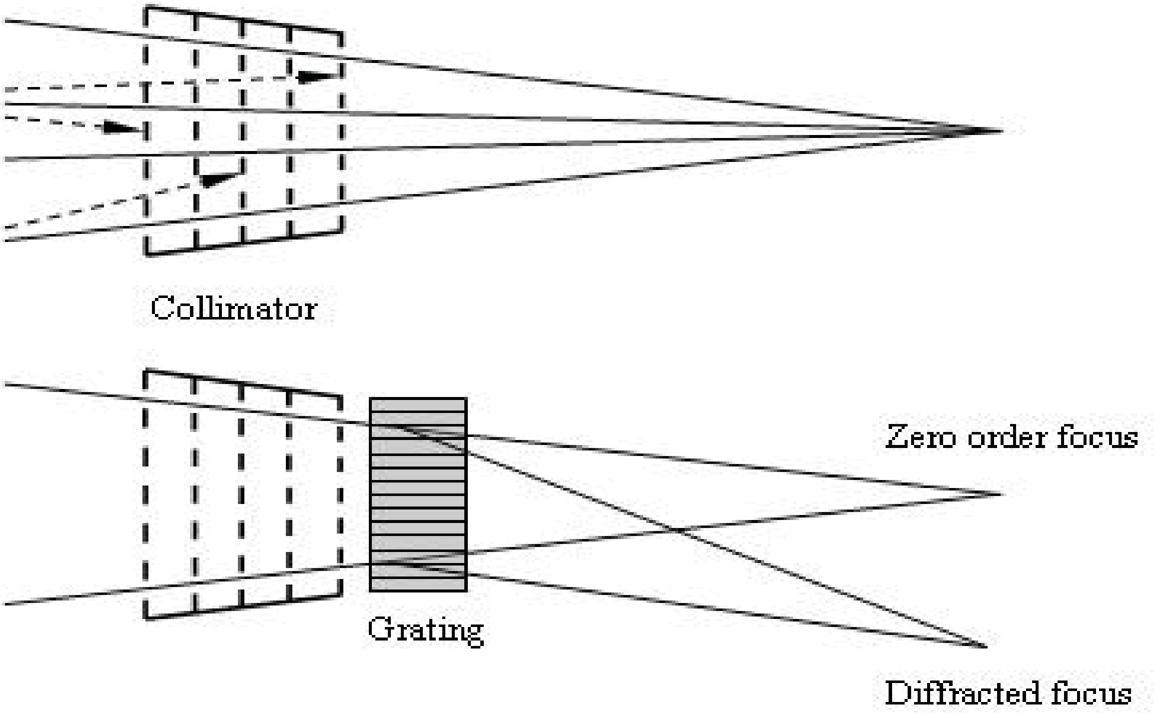

Figure 3: Schematic of the wire grid stacks ("Collimator") creating a 3.0 m focus (top) and the placement of the gratings and spectrum (bottom).

The spacing of the wires is determined by ray traces to minimize stray light while requiring only components that can be feasibly manufactured and assembled. By carefully spacing the 24 grids we can reduce stray light (light that would pass through the stack but not come to a 3.0 m focus) to under a few percent. The wire grid method, although inefficient and more of a “photon destroyer” than a focusing telescope, is preferable to optics (e.g., Wolter or Kirkpatrick-Baez configurations) because of the limited budget of sounding rocket payloads. Additionally, the wire grids have shown themselves to be very robust under the stresses of sounding rocket flights.

The challenge presented by the wire grids is that they must all be aligned relative to each other to high precision: a single grid displaced perpendicularly to the wire direction by 70 μm costs CODEX 10% of its throughput (relative to an ideal ray trace) and increasing stray light through the payload. A displacement parallel to the wire direction is less catastrophic, with a 5 mm displacement only decreasing throughput by 3%. We set our tolerances in these directions as 50 μm and 500 μm, respectively, to make construction feasible while maintaining the payload’s scientific viability. Rotations relative to the rest of the stack are also severely unhealthy. A 500 μm edge was added to the grids parallel to the wires (Fig. 2); the edge protrudes from the Al frame after bonding to create an alignment edge. By aligning the edge to two precision rods that are flat and aligned to each other to under 50 μm over their 1.0 m length and aligning the frame to a third rod along one of the sides perpendicular to the alignment edge, the specified tolerances were met when building the wire stacks. The alignment was crudely checked by shining a HeNe laser through two 1 mm holes drilled through the edges of the plates.

The structure for holding the grids in place within the payload is discussed in detail in Shipley, Zeiger, & Rogers 2011[4]. The paper also includes finite element modeling of the wire grid support structure and of other mechanical components throughout the rocket that are improvements over previous designs.

Diffraction grating array design

Since an individual photon can travel along only one of the 185 slits in the wire grids (~98% of light crossing from one slit to another is vignetted by design), light arrives at the gratings in nearly parallel paths across the 100 mm x 100 mm area of the last wire grid. To diffract the photons in an efficient manner, we use a 104 mm x 104 mm array of 67 diffraction gratings mounted at a 4.4° angle relative to the direct path parallel to a slit in the wire grid (admitting light at angles of ~4.4°±2.0°) in an off-plane mount. The gratings, manufactured by HORIBA Jobin-Yvon, were holographically recorded with 5670 grooves/mm. Each grating is 20 mm deep, presenting a 1.53 mm x 104 mm cross section to incident light. Parameters are set to achieve a resolution of 50-100 across the CODEX bandpass.

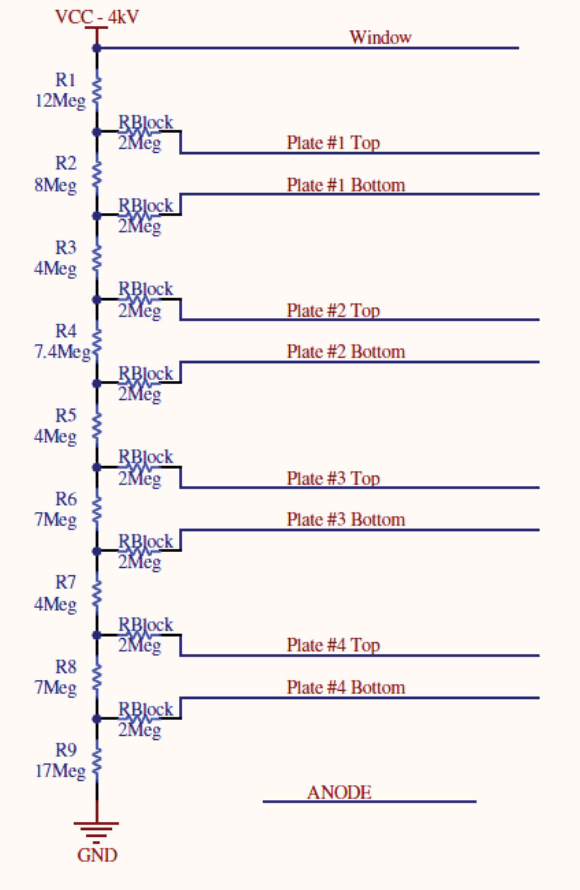

Figure 4: Electrical schematic of the CODEX GEM detectors. The 2 MΩ resistors on each plate reduce the load on other plates if one plate fails by shorting between top and bottom.

The gratings are mounted on 125 μm electroformed Ni substrates (again made by Thin Metal Parts). Replication was done in an epoxy resist layer followed by an electroless nickel plating process. Maintaining flatness of the thin, closely-spaced gratings under launch vibrations requires them to be held under tension; they are held with 22 N of tension per grating in a titanium flexure mount. The same gratings and mount flew on both the CyXESS and EXOS payloads, demonstrating the robustness of the design.

GEM detector design and placement

Light diffracted at the gratings travels 2.0 m farther along the payload before encountering the gaseous electron multiplier detectors. GEMs are a relatively new hybrid of proportional counters and microchannel plates, providing a large-format, low-power, high-quantum efficiency, low-noise (~5x10^{-3} Hz cm^{-2}) detector for a low price. Light penetrates a 105 mm x 105 mm Luxel Corp. window composed of 100 Å carbon and 5000 Å polyimide (supported by a stainless steel mesh, reducing the active area by 42%), which contains a 75% argon/25% carbon dioxide gas in the detector at ~10^{5} Pa from the vacuum of space within the payload. The C coating is necessary to make the window conductive. The window is held at -4 kV above ground, and a series of four GEM plates consisting of a copper surface on either side of an insulating liquid-crystal polymer sheet create a cascade of voltage drops toward a cross-delay-line resistive anode. Each plate is perforated with 70 μm laser-etched holes to allow an electron cascade to travel and be accelerated through the plates. Voltage drops are ~800 from the window to the first plate, 310-500 V across the plates, ~250 V in the spaces between the plates, and 1000 V from the last plate to the anode. The anode provides a resolution of ~200 µm along both axes.

Argon gas provides the source of electrons that produce the detector gain. An incident photon will ionize an Ar atom, with the freed electron being accelerated by the electric field. The accelerated electron initiates a cascade of electrons via collisions as it travels through the pores of the GEM plates toward the anode, creating a gain of ~1.5-2.5x10^4 across the bandpass. The 25% CO_2 balance in the detector neutralizes the Ar ions via charge exchange.

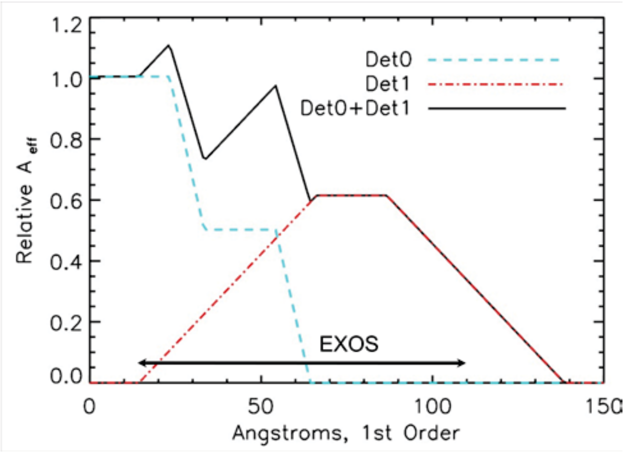

Figure 5: Effective area of the CODEX payload (two spectrometers) relative to two overlapping detectors. The EXOS bandpass is indicated by the arrow.

The CODEX GEMs were designed, assembled, and tested at the University of Iowa, using GEM plates manufactured by SciEnergy, Inc.

Detector placement is crucial to the scientific yield of the payload. Previous flights of this design[1,3] had detectors placed so that the spectrographs were perfectly redundant, giving an 89 Å bandpass. The CODEX payload sacrifices sensitivity while increasing the calibration accuracy and the bandpass by reducing the overlap of the detectors (Fig. 5). The bandpass stretches from 0-order to 144 Å, with a strong carbon edge (44.7 Å) in the effective area due to the carbon coating of the detector windows (Fig. 6).

Electronics and gas system design

The polyimide windows on the GEM detectors have an intrinsic leak rate. To ensure that CODEX has a constant gain during flight, it carries a gas delivery system with a high-pressure bottle regulated to the ~10^5 Pa nominal pressure of the detectors. Onboard proportional valves give independent remote control of gas pressure seen by each detector, allowing one to be shut off in the event of a window leak (a continued leak would disable both detectors because of the gas leak into the payload).

The details of the electronics system do not differ appreciably from other sounding rocket flights. All data is sent down via telemetry; none is stored onboard. The maximum readout rate is 10 kHz, which is well above any astronomical source aside from the Sun.

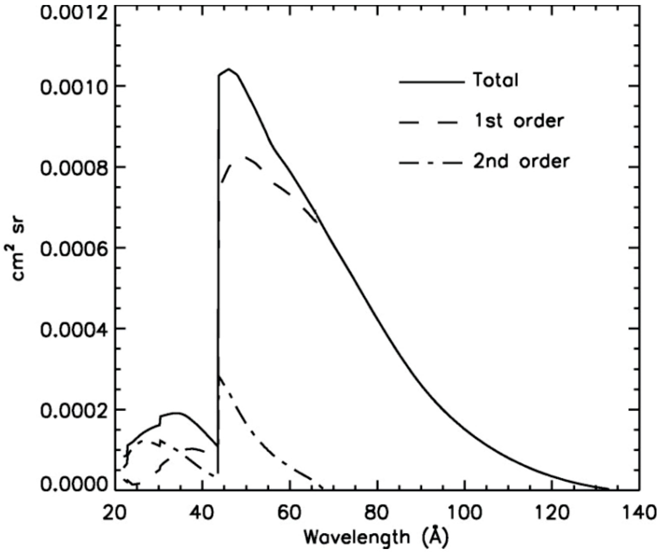

Figure 6: Effective area of the CODEX payload as a function of wavelength[1].

FLIGHT PLAN

Although not strictly pertinent to an instrument paper, the flight plan is instrumental in knowing whether the instrument worked correctly in flight. CODEX will fly for ~300 s. It will be calibrated on the ground before and after flight for throughput and gain, but then the full system will go through 12.7 g_{rms} (nominal) launch load and turn on the high voltage detectors with no warm-up time. Measuring the functionality of the detectors in flight requires some of the 300 s to be devoted to calibration, at a cost of ~30 s slew time plus integration. Calibration of a soft x-ray spectrograph with a 3.25° x 3.25° field of view and no spatial resolution is hampered by the celestial sphere: the only target comparable to the Vela SNR in surface brightness is the Cygnus Loop, which is not visible at the same time as Vela. However, if a noise rate can be measured we can be assured (within statistical limitations) that counts above that are real even though in-flight gain (incident photons per count on the detectors) cannot be measured. We will begin off-target on a patch of empty (except for the SXRB) sky 5° N of the Vela SNR, slew on-target (presumably showing a strong rise in the count rate), and repeat that cycle once. Detectors will remain on after the shutter door closes, creating a dark exposure for several seconds before the gas pressure in the payload climbs too high for the detectors to operate without arcing.

EXPECTED SCIENCE RETURN

The Vela SNR is a much softer source than the Cygnus Loop SNR targeted by the CyXESS and EXOS payloads. Models and images from the *ROSAT* proportional counters suggest that, with ~150 s on-source, we should expect a spectrum with ~2000 counts across the CODEX bandpass, with ~75% of the photons in the 110-400 eV range. Higher energy flux is likely dominated by O VII and O VIII emission lines, with Fe and Ne also contributing[5]. These strong lines, 0-order light, and the C edge of the detectors provide a convenient wavelength calibration.

A high-resolution spectrum of the Vela SNR will provide elemental abundances and thermometry, particularly by comparing the ionization states of oxygen. The soft x-ray bandpass is also a crucial piece of the energy budget of the heavily-studied remnant, and measuring the contribution of various emission mechanisms will help to understand the cooling of supernova remnants generally and, conversely, the heating of the ISM.

SUMMARY

The CODEX payload will target the Vela supernova remnant when NASA resumes sounding rocket launches from the White Sands Missile Range. Using two wire grid stacks to block any uncollimated light before diffracting the collimated light from off-plane grating arrays, CODEX will produce a high sensitivity, large solid angle spectrum with a resolution of 50-100 across the soft x-ray (0.1-1.0 keV) bandpass. The payload has been redesigned with higher throughput and more robust mechanical, electronics, and gas systems. The new modular design will ease future improvements in sensitivity by adding more modules, with the ultimate goal of obtaining a spectrum of the soft x-ray background during a future flight.

ACKNOWLEDGEMENTS

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