SSC18-WKIX-01

HaloSat: a search for missing baryons with a CubeSat

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ABSTRACT

HaloSat is the first mission utilizing the CubeSat platform funded by NASA's Astrophysics division. Its scientific goal is to constrain the mass and spatial distribution of the hot gas that surrounds our Milky Way galaxy. HaloSat's scientific payload is made of 3 independent X-ray detectors and associated electronics that will detect line emission from highly ionized oxygen in the soft X-ray band. The payload is carried onboard a Blue Canyon Technologies 6U spacecraft bus. Using the CubeSat platform enables an observing strategy that maximizes the scientific outcome of the mission. A variety of environmental tests performed on the HaloSat payload and spacecraft show that the mission is capable of surviving launch and fulfilling its scientific objectives during the expected mission lifetime. Here we describe the mission concept, its implementation, and plans for archiving and distribution of the data.

INTRODUCTION

Baryonic matter makes up almost 5% of the total mass-energy of the Universe today.[1] However, observations of luminous matter fail to locate a substantial fraction of the predicted baryons.[2] One of the possible reservoirs of the missing baryons may be halos of hot gas surrounding galaxies. The closest such hot halo is the one extending around our Milky Way galaxy.[3] The gas within this halo is at a temperature of ~10^6 K.[4, 5] Thus, it should readily emit in the X-ray band.

Line emission and absorption from highly ionized species present in the gaseous halo is the primary diagnostics to study such hot gas. Using absorption lines as the diagnostic tool can only probe the properties of the halo along a limited number of lines of sight simply because the number of X-ray bright extragalactic sources is limited. In contrast, emission lines can be measured in any direction and thus provide a means to study the full geometry of the halo. In particular, emission from highly ionized oxygen, O^{+6} (OVII) and O^{+7} (OVIII), can be used as a diagnostic tool for studying the properties of the hot galactic halo. The scientific goal of the HaloSat mission is to constrain the mass and spatial distribution of the hot gas that surrounds our Milky Way by mapping the emission from OVII (561 eV) and OVIII (653 eV).

This paper describes the HaloSat instrument design, observing strategy, and plans for archiving and distribution of the data.

SCIENCE INSTRUMENT

In order to achieve the scientific goals of the mission, a science instrument that meets the following requirements had to be built:

- be equipped with X-ray detector(s) sensitive in an energy band of 0.3 – 2 keV with an energy resolution (defined as full width at half maximum) of ≤100 eV near 600 eV;
- achieve a statistical accuracy of ±0.5 LU (LU = photons/cm^2/s/ster) for a field with an oxygen line strength of 5 LU by:
  - using detectors with sufficient effective area;
  - operating for 6-12 months;
  - viewing large part of the sky at a time (have field of view with a diameter of 10°);
- be able to observe the whole sky.

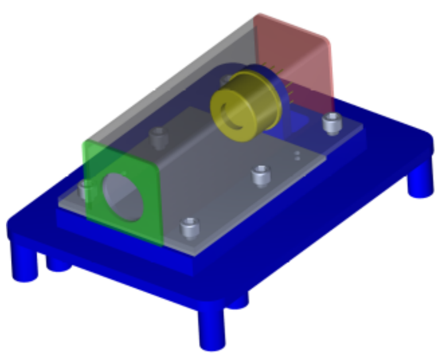

Figure 1: X-ray detector assembly. SDD detector, passive shield and baseplate are indicated with yellow, semi-transparent gray and blue color, respectively.

X-ray Detector

The FAST SDD silicon drift detectors (SDD) from Amptek , Inc., are used by the HaloSat instrument to detect X-rays. The radiation sensing element with its multilayer collimator and 2-stage thermoelectric cooler is encapsulated in a TO-8 package. The detector has an active area of 17 mm^2. The entrance window is a *C-Series* C1 window made of Si_3N_4 covered with a thin layer of aluminum. The C1 window has good transmission properties around 600 eV (transmission is around 40% for 600 eV X-rays) and provides sensitivity down to 0.3 keV.

Passive Shielding

In order to minimize the background from events resulting from cosmic ray interactions and the diffuse X-ray background, the SDD detector is surrounded on 5 sides by a passive shield made of copper-tungsten alloy electroplated with a thin layer of gold (see Figure 1). The sixth side of the shield has a circular cutout to provide an unobstructed path for the X-rays from the source to reach the detector (green element in Figure 1).

Signal Processing Electronics

An X-ray impinging on the detector chip is converted into an electron cloud with a charge that is proportional to the energy of that X-ray. The liberated charge is then drifted down a field gradient applied between the drift rings towards centrally located anode.[6,7] The charge that accumulates at the anode is converted to a voltage signal by the FET preamplifier. The signal then goes through a preamplifier and a shaping amplifier circuit, followed by lower and upper level discriminators and a resettable peak hold circuit. In the next step, the signal from the detector is digitized and sent to the spacecraft bus. The silicon drift detector, due to its method of operation, has no imaging capabilities, however, its main advantage is low noise and thus good energy resolution.

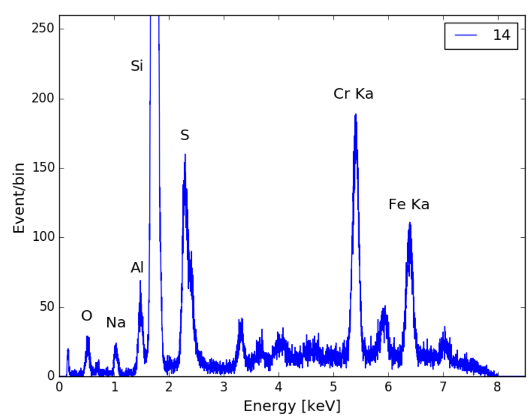

Figure 2: Spectrum obtained with HaloSat detector in its flight-like configuration. Emission lines were produced by scattering X-rays off of borosilicate glass. The tests were performed in vacuum.

A detector unit in its flight configuration is sensitive to X-rays with energies between ≈230 eV and 8000 eV. And is characterized by an energy resolution of ≈80 eV and ≈85 eV at 526 eV (O Kα) and 677 eV (F Kα), respectively. Figure 2 shows a spectrum obtained with a flight-like detector unit during tests performed under vacuum.

Science Payload

Three identical detector units (X-ray detector assembly and signal processing electronics) comprise the HaloSat science payload. Each of the detector units can be operated independent of each other – a solution that allows to avoid single point failures.

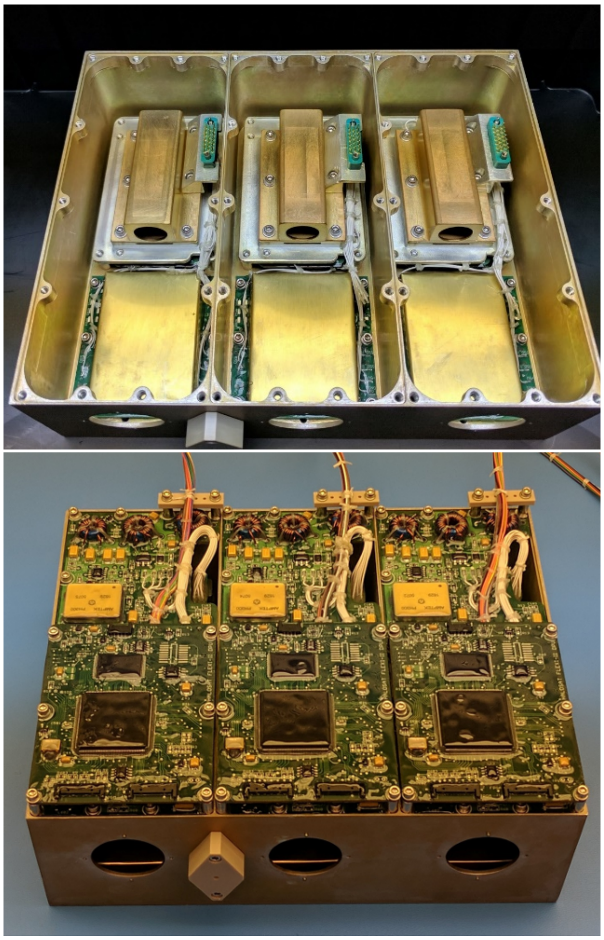

Figure 3: Science payload assembly. Top: three detector units mounted in a flight chassis in their respective compartments. The detector/shield assembly is mounted towards the back of the compartment, while the high voltage power supply is mounted towards the front. Bottom: Same as top, but each of the compartments is closed off by detector's readout electronics (analog and DPU boards).

The top panel of Figure 3 shows the detector units mounted inside the flight chassis. The chassis is machined out of aluminum and its dimensions are 87 mm × 220 mm × 170 mm. Each of the detector units is mounted in an individual compartment. The detector baseplate (the detector itself is not visible in this figure) and the passive shield are mounted towards the back of each compartment. Each detector's signal processing electronics is mounted under the baseplate. A high voltage power supply, providing drift field for the SDD detector, is mounted in front of the baseplate, such that it does not obstruct the detector's field of view. Each compartment is closed off by analog and digital processing unit (DPU) boards visible in bottom panel of Figure 3.

Three circular apertures are visible on the front wall of the flight chassis. The size of the field of view (FOV) of each of the three detectors is controlled by an aluminum washer that is mounted onto the circular aperture (FOV washer is not shown in Figure 3). The FOV was measured for all three detector units – the measured full response radius and zero response radius are 5.62° and 7.03°, respectively.

Spacecraft

A spacecraft bus from Blue Canyon Technologies, Inc. (BCT) is used to carry the science payload. The bus has a 6U format (i.e. dimensions of 10.5 cm × 22.5 cm × 36.5 cm) with a 4U volume allocated for the science payload, a 1.5U volume allocated for the spacecraft avionics and a 0.5U volume allocated for the payload-to-spacecraft interface. The top panel of Figure 4 shows the spacecraft bus with the science payload already integrated with the bus (right hand side of the bus; top cover still removed). The 2U volume harboring the avionics and payload-to-spacecraft interface is the volume to the left of the science payload.

Power to the spacecraft is provided by the deployable solar panels (bottom panel of Figure 4) that charge the on-board batteries during the day side of the orbit. The spacecraft has pointing capabilities. It can be slewed at a 3°/sec rate, and has a pointing accuracy of ±0.002°.

CALIBRATION AND ENVIRONMENTAL TESTS

A series of calibration and environmental tests on the payload and spacecraft level were performed in order to understand and characterize the instrument performance under various conditions, and to verify system stability, robustness and survival under flight-like conditions.

On-Ground Instrument Calibration

In order to study payload performance as a function of instrument temperature, the science payload was placed in a thermal-vacuum (TVAC) chamber, where the payload temperature was controlled via use of a thermal plate. In that configuration each of the three detector units was illuminated with an X-ray beam scattered off of a teflon target mounted on an aluminum holder. This X-ray source configuration allowed for production of fluorescence emission lines across the HaloSat energy range, including a low energy line from F Kα (677 eV) that probes the detector performance in the energy band where the oxygen OVII and OVIII emission is expected. The payload temperature was varied between -25°C and +40°C, with each of the three SDD detectors always cooled down to -30°C. Spectra obtained in these TVAC tests allowed for determining how:

- energy calibration of each detector unit depends on the instrument temperature,
- energy resolution and electronic noise of each detector unit depend on the instrument temperature,
- energy resolution of each detector varies as a function of energy,

which in turn allowed for determination of instrument response for each of the detectors.

Environmental Tests

In order to verify that the science payload and the spacecraft will survive the launch and operate properly in the flight conditions the following tests were performed:

- vibration test at the science payload level (see Figure 5). The science instrument was mounted to a shake cube in 3 different orientations and subject to the NanoRacks vibration levels. The test was performed at NASA Wallops Flight Facility.
- vibration test at the spacecraft level. Once the science instrument was integrated with the spacecraft, the spacecraft was placed inside a double-wide NanoRacks container, i.e. the configuration in which the spacecraft was to be launched onboard the Cygnus spacecraft. The container was then mounted to a shake table in 3 different orientations and subject to the NanoRacks vibration levels. The test was performed at Element Materials Technology (Longmont, CO).
- Day-in-the-Life (DITL) test in which the spacecraft was placed in a TVAC chamber and where thermal conditions were varied to simulate one day in orbit. Spacecraft and payload operations in flight-like conditions, including communication via radio, were tested during DITL. The test was performed at BCT (Boulder, CO).
- end-to-end communication test that verified uplink and downlink paths between the ground station (NASA WFF), the mission operations center (BCT) and the spacecraft/payload. The test was performed at NASA Wallops Flight Facility.

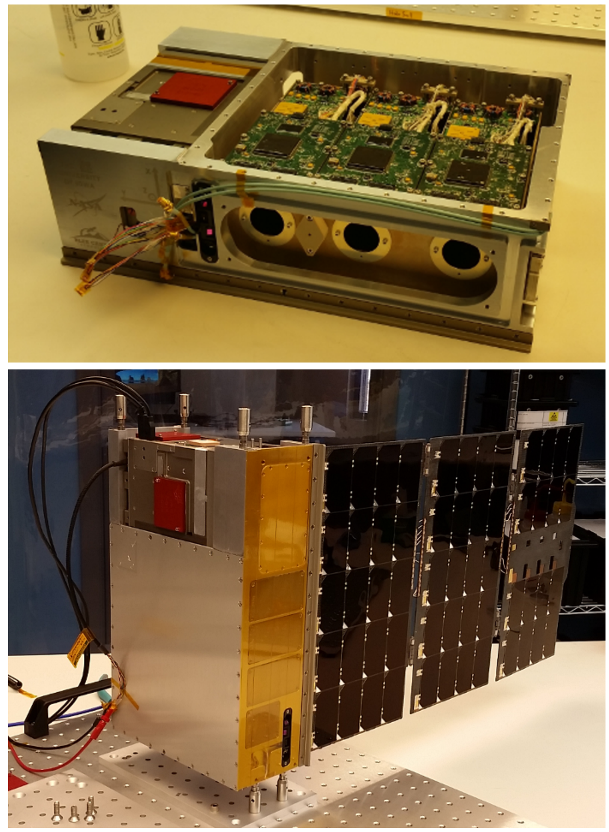

Figure 4: Spacecraft assembly. Top: science payload being integrated with the spacecraft. Bottom: spacecraft (after payload integration) with fully extended solar panels.

OBSERVING STRATEGY

HaloSat has been delivered to the International Space Station (ISS) and will be deployed into an orbit with an altitude of about 400 km, an inclination of about 52° and an orbital period of about 90 min. During the day-side of the orbit (~45 min) the science payload will be switched off and the spacecraft will point the solar panels towards the Sun in order to charge the batteries. Once the spacecraft crosses the dusk terminator, the science payload will be turned on and pointed towards selected target. The science payload will be switched off right before the spacecraft crosses the dawn terminator. Per each orbit, during its night-side, two science targets will be observed with approximately

1300 seconds of exposure time devoted to each target. The selected pair of the targets will be observed for ten consecutive orbits after which a new pair of targets will be selected. There are 330 HaloSat targets that are evenly spread across the sky. The targets cover 98.5% of the sky. A minimum of 8000 detector-seconds will be accumulated for each target.

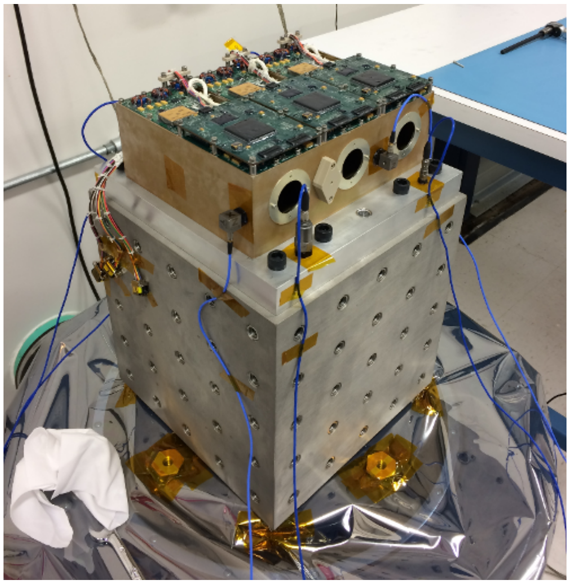

Figure 5: Science payload mounted to the shake cube during vibration test performed at NASA Wallops Flight Facility.

MISSION OPERATIONS

The CADET radio onboard the HaloSat spacecraft will be used to downlink telemetry and receive commands. The NASA Wallops Flight Facility ground station will be used to communicate with the spacecraft. Blue Canyon Technologies will run the Mission Operation Center, while the Science Operation Center will be run at the University of Iowa.

ARCHIVING AND DISTRIBUTION OF DATA

All the telemetry (including X-ray event data, housekeeping, spacecraft pointing and attitude) will be captured and converted to FITS (Flexible Image Transport System) format. The data will be then archived at the High Energy Astrophysics Science Archive Research Center (HEASARC) and made publicly available within 5 months from mission completion. In addition to the telemetry data, calibration files and software required for analysis of the instrument science data will also be archived at the HEASARC.

SUMMARY

HaloSat was successfully built and tested under flight-like conditions. At 4:44am Eastern time on May 21, 2018, HaloSat, onboard a Cygnus cargo spacecraft, was launched on an Antares rocket as a part of the OA-9 resupply mission to the ISS. On May 24, 2018, the Cygnus spacecraft successfully docked to the ISS. HaloSat is scheduled to be deployed from the ISS in late July to mid-August 2018 and start collecting science data one month later.

Acknowledgments

We acknowledge support from NASA grant NNX15AU57G. D. Koutroumpa acknowledges financial support through the program "Soleil Heliosphere Magnetosphere" of the French space agency CNES.

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