EXCLAIM: The EXperiment for Cryogenic Large-Aperture Intensity Mapping

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ABSTRACT

The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) will constrain star formation over cosmic time by carrying out a blind and complete census of redshifted carbon monoxide (CO) and ionized carbon ([CII]) emission in cross-correlation with galaxy survey data in redshift windows from the present to z=3.5 with a fully cryogenic, balloon-borne telescope. EXCLAIM will carry out extragalactic and Galactic surveys in a conventional balloon flight planned for 2023. EXCLAIM will be the first instrument to deploy µ-Spec silicon integrated spectrometers with a spectral resolving power R=512 covering 420-540 GHz. We summarize the design, science goals, and status of EXCLAIM.

Keywords: Line intensity mapping, on-chip spectrometer, kinetic inductance detectors, balloon, star formation

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1. INTRODUCTION

After the first stars formed within ≈ 200 million years after the big bang, the star formation rate in the universe steadily increased until it peaked approximately 10 billion years ago at redshift $z \approx 2$. Since that time, the star formation rate has declined by a factor of $\sim 10$, despite the dark matter continuing to cluster. A number of feedback mechanisms likely contributed to this decline, including winds from massive stars, supernovae, and active galactic nuclei. Measurements of the total gas reservoirs available for star formation and of the average conditions of the interstellar medium (ISM) are required to shed light on the dynamics of galaxy evolution during this time.

Line intensity mapping is a complementary approach to traditional galaxy surveys that maps the unresolved, integral surface brightness of redshifted line emission from galaxies over cosmologically large volumes. The emission from a given atomic or molecular line maps onto a unique redshift, allowing three-dimensional tomography of gas species. The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) targets measurements of the ladder of rotational emission lines from carbon monoxide (CO) at rest frame frequency $\nu = (115 \text{ GHz}) \cdot J$ for $J = 4 - 7$ at redshifts $z < 1$ and ionized carbon emission ([CII], $\nu = 1.889 \text{ THz}$) at $z = 2.5 - 3.5$. The EXCLAIM survey will consist of a 320 deg$^2$ extragalactic (EG) survey and several 100 deg$^2$ Galactic plane (GP) survey regions. The GP survey will map the $J = 4$ CO line and neutral carbon ([CI]). The [CI] survey will assess the CO-H$_2$ ratio to inform the higher-redshift survey, as [CI] traces H$_2$ in regions where CO is photodissociated. The EG survey will be cross-correlated with galaxies and quasars in the Baryon Oscillation Spectroscopic Survey (BOSS) to map EXCLAIM observations in redshift space.

For a full description of the EXCLAIM design, please see Ref. 4. In these proceedings, we briefly summarize the EXCLAIM science goals and instrument design, noting any recent changes to the design and giving an update on the current project status.

2. SURVEY AND SCIENCE GOALS

EXCLAIM will perform $\sim 7^\circ$ peak-to-peak azimuth scans at a constant 45$^\circ$ elevation during a conventional North American balloon flight, currently planned to be from Ft. Sumner, NM, USA, in the fall of 2023. This scan allows the survey to overlap with a number of galaxy redshift surveys for cross-correlation to isolate the target line emission from Galactic foregrounds and interloper lines. The primary science target for EXCLAIM is cross-correlation with the BOSS spectroscopic redshift catalog within the Stripe 82 (S82) region, but the survey strategy also provides access to Hyper Suprime-Cam (HSC) photometric redshifts. Due to the lack of pressure broadening at high altitude, observing from a stratospheric platform with a moderate-resolving-power ($R > 300$) spectrometer provides access to dark windows between narrow atmospheric lines with photon loading within a factor $\sim 6$ of the radiation background of space. Optics at ambient temperature would dominate photon loading in these dark windows, so EXCLAIM employs an all-cryogenic instrument (See Sections 3 and 4).

Intensity mapping efforts aimed at CO have provided constraints on the total Poisson variance of emission. Interpretation of this line autopower requires a model for emission in the CO ladder at all redshifts and ruling out other sources of variance in the emission. Cross-correlation is critical to enabling the isolation of emission from a single line at a target redshift. An initial intensity mapping detection of [CII] at $z \approx 2.6$ in cross-correlation between Planck 545 GHz data and the Baryon Oscillation Spectroscopic Survey (BOSS) quasar redshift sample suggests cumulative [CII] emission considerably higher than many models. Current models at these redshifts are anchored by or comparable to observations of relatively few individual galaxies, often among the brightest of the population. There is considerable uncertainty within models based on the range of their assumptions and between models, especially at the low-mass end of the population.

The EXCLAIM intensity mapping survey will help rule out selection function and sample variance effects and unambiguously tie the CO and [CII] line emission to target redshifts through a large-area, intensity-mapping survey in cross-correlation with well-defined spectroscopic galaxy redshift samples. EXCLAIM also acts as a pathfinder for the intensity mapping approach and integrated spectrometer design for future space mission applications.

A typical observing plan, the details of which will depend upon exact launch location and date, includes an elective daytime field using an antisolar scan, covering $\sim 200 \text{ deg}^2$ in a stripe across the Galactic plane. After
nightfall, another Galactic field can be observed until the primary science field rises to our elevation. Later in the flight, this primary field can also be observed setting, or another Galactic field can be observed, or a combination of both. We have identified a catalog of bright, nearby galaxies that can be observed in dedicated scans that slew out of the survey fields and will be planned before the flight. A typical scan strategy would be able to target the primary science field on the S82 extragalactic region for 6 hr rising and up to 10.5 hr when adding observations while setting.

3. PAYLOAD OVERVIEW

EXCLAIM consists of a completely cryogenic telescope in an open liquid-helium bucket dewar with a cold inner volume approximately 1.5 m in diameter and 2.0 m deep. At target float altitudes above 27 km, the ambient pressure of less than 10 Torr pumps on the helium bath, lowering its temperature below its superfluid transition to approximately 1.7 K. Superfluid helium pumps demonstrated on the ARCADE2 and PIPER payloads\textsuperscript{18–20} efficiently cool the full optical chain to below 5 K.

Figure 2 provides an overview of the mission and its technical approach. EXCLAIM maintains a fully cryogenic telescope and receiver in a 3000 liter open bucket dewar with LHe, which has an interior 2 m deep and 1.5 m in diameter, following an approach from the ARCADE2 and PIPER instruments. This is the maximum dewar size that stays within total payload mass limits of 3400 kg. Superfluid fountain effect pumps\textsuperscript{23} cool the optics to <5 K and maintain the receiver at ≈1.7 K.

The EXCLAIM gondola design, attitude determination and control system, and flight electronics are based on those of PIPER with modest modifications and improvements. A reaction wheel executes the azimuth scan and is a large rolled brass hoop in a spoked-wheel configuration, which is driven by a brushless direct-drive DC motor. In-flight pointing requirements are relatively modest (∼1° error), whereas post-flight pointing reconstruction must be accurate to a few percent of the optical FWHM (∼4 arcmin). In-flight pointing is...
provided by a Kalman-filter control system that uses gyroscope and magnetometer sensors for velocity and position reconstruction. Post-flight reconstruction will incorporate star-camera pointings at scan turn-arounds and an additional clinometer to establish tilts. An additional solar sensor determines the Sun’s position to within 0.5 deg during daytime operations, when the payload will be pointed in an anti-solar direction.

Thermal simulations have been carried out that model each system component as isothermal nodes connected by conductive and radiative links, with the exception of extended radiator panels that are allowed to have a gradient. Foam panels covered with multi-layer insulation (MLI) blankets provide shielding from radiation from the Sun and the Earth. The simulations include ground, daytime flight, and nighttime flight operations. Survival heaters are employed where electronics would fall below the required minimum temperature of −20\degree C.

4. INSTRUMENT OVERVIEW

The EXCLAIM optics consist of a two-mirror, off-axis Gregorian telescope with a 90-cm parabolic primary mirror and a 10-cm parabolic secondary mirror. A folding flat between the primary and secondary allows the telescope to fit within the dewar volume. Baffling around the intermediate focus controls stray light and houses an aerogel scattering filter for rejection of IR radiation.24 The rays are collimated after the secondary mirror and pass through a meta-material anti-reflection (AR) coated silicon vacuum window into the receiver cryostat. See an overview of the optics and receiver in Figure 3.

The receiver houses additional stray-light baffling, aerogel scattering and band-defining metal-mesh filters,25 an AR-coated silicon lens,26 and six integrated silicon spectrometers (\(\mu\)-Spec).27–30 The receiver is enclosed in a superfluid-tight shell31 with a diameter constrained by the size of a flight-like LHe test system. The overall height is limited by the dewar bottom when the receiver is in its flight optical configuration in the telescope. The collimated optical input provided by the optics allows significant flexibility in the optical baffling and magnetic shielding design. This versatility means that the telescope could also accommodate other receiver designs in the future.

The receiver provides 900 mK and 100 mK cold stages using by a \(^4\)He adsorption cooler and custom adiabatic demagnetization refrigerator (ADR).32 The ADR and sorption cooler can operate from a liquid helium (LHe) bath at \(\sim 4\) K during ground operations and are estimated to provide > 12 hr hold time when operating from
Figure 3. Overview of the EXCLAIM optics within the open helium bucket dewar with an expanded view of the receiver, showing the major optical elements, including the mirrors, silicon lens, silicon vacuum window, filters, and in-situ calibrator. Note that the calibrator is tilted into the page in this figure, such that it is in the sidelobes of the lenslet beams.

the 1.7 K bath at float altitudes. The ADR can provide threshold (> 4 hr) operation from a 1.7 K bath in the event that the sorption cooler fails. A two-layer, high-permeability magnetic shield (Amuneal A4K) with a ~ 3:1 aspect ratio around the optics tube and spectrometer package provides an estimated shielding factor of greater than 1000 to reduce the sensitivity of the detectors to magnetic fields from the Earth and the ADR. Note that the ADR is integrated with magnetic shielding to reduce stray fields at the spectrometer chips to the same order of magnitude as the Earth’s field (requirement is < 5 G). The receiver also houses the cryogenic segment of the spectrometer readout.

The µ-Spec spectrometers combine all the elements of a traditional diffraction-grating spectrometer in a compact package using planar transmission lines on a silicon chip. The grating is replaced by a niobium microstrip delay line network that launches signals into a 2D parallel-plate waveguide region with emitting and receiving feeds arranged in a Rowland configuration. EXCLAIM will operate at the second grating order selected by an on-chip filter along with the free-space band-defining filters. A set of 355 microwave kinetic inductance detectors (MKIDs) made from 20-nm-thick aluminum (Al) half-wave resonators will detect the signal. A dipole slot antenna coupled to a hyper-hemispherical AR-coated silicon lenslet forms the spectrometer beam and couples the light to the on-chip circuitry. The combination of quasi-optical metal-mesh filters, on-chip filters, and spectrometer design defines the EXCLAIM observing band of 420–540 GHz. The MKID arrays for the six spectrometers use a microwave multiplexing readout scheme with heritage from The Next Generation Balloon-borne Large Aperture Submillimeter Telescope (BLAST-TNG)\textsuperscript{33} and the Far Infrared Observatory Mounted on a Pointed Balloon (OLIMPO).\textsuperscript{34}

5. CURRENT STATUS

EXCLAIM completed a mission-level critical design review (CDR) in May 2022 and has entered its final fabrication, assembly, and test phase in preparation for a flight currently planned for fall 2023. The EXCLAIM mission mass allocation is under the maximum allowable mass set by the NASA Balloon Program Office with sufficient
marginal to allow for current design uncertainties. The battery allocation provides at least 18 hours of operation at altitude, sufficient to allow for science operations during a single-night flight.

Fabrication is currently underway on EXCLAIM flight µ-Spec spectrometers, with the first devices expected to be tested in a dedicated cryogenic facility later this year. Prototype spectrometer readout electronics have been completed and will be tested with flight devices. Component-level tests of ADR stages are underway, with system-level testing to be carried out by the end of summer 2022. Production will begin shortly on other items with long fabrication times, including the payload dewar, telescope mirrors, lens, and vacuum window.

6. CONCLUSIONS
EXCLAIM is an experiment to improve our understanding of star formation over cosmic time through measurements of the integrated emission from galaxies using the technique of line intensity mapping. By cross-correlating with galaxy redshift surveys, notably SDSS-BOSS, EXCLAIM can unambiguously isolate the redshift of the line emission from galaxies to carry out three-dimensional tomography of carbon monoxide and ionized carbon, which are key tracers of star formation and the gas reservoirs that seed it. EXCLAIM will field novel integrated silicon spectrometers in a fully-cryogenic telescope to provide sensitivities approaching those of a space mission between narrow stratospheric emission lines.

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