The Balloon-Borne Cryogenic Telescope Testbed Mission:
Bulk Cryogen Transfer at 40 km Altitude

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Abstract

The Balloon-Borne Cryogenic Telescope Testbed (BOBCAT) is a stratospheric balloon payload to develop technology for a future cryogenic suborbital observatory. A series of flights are intended to establish ultra-light dewar performance and open-aperture observing techniques for large (3–5 meter diameter) cryogenic telescopes at infrared wavelengths. An initial flight in 2019 demonstrated bulk transfer of liquid nitrogen and liquid helium at stratospheric altitudes. An 827 kg payload carried 14 liters of liquid nitrogen (LN2) and 268 liters of liquid helium (LHe) in pressurized storage dewars to an altitude of 39.7 km. Once at float altitude, liquid nitrogen transfer cooled a separate, unpressurized bucket dewar to a temperature of 65 K, followed by the transfer of 32 liters of liquid helium from the storage dewar into the bucket dewar. Calorimetric tests measured the total heat leak to the LHe bath within bucket dewar. A subsequent flight will replace the receiving bucket dewar with an ultra-light dewar of similar size to compare the performance of the ultra-light design to conventional superinsulated dewars.
I. INTRODUCTION

Cryogenic telescopes flown at altitudes above 30 km offer compelling astrophysical returns. By reducing emission from both the atmosphere and warm elements of the optics, a cryogenic telescope can improve sensitivity to astrophysical sources by over two orders of magnitude compared to observations from ground-based or aircraft platforms. Achieving such sensitivity gains requires fully cryogenic optics. Thermal emission from optical elements at 250 K is 300 times brighter than the deepest atmospheric windows (Figure 1). Reducing emission from the telescope to levels below the atmospheric emission requires maintaining the beam-forming optics at temperatures 10 K or colder. This in turn presents a problem for balloon payloads. Obtaining sufficient signal and/or angular resolution requires a large collecting area (cf Herschel’s 3.5 m primary mirror diameter). A dewar large enough to accommodate such large optics would exceed balloon lift capability. For example, the ARCADE-2 and PIPER missions flew cryogenic telescopes with 1 m clear aperture [1, 2]. The dewar alone weighed over 800 kg. Scaled to 3 m aperture, the resulting payload mass of 5000 kg easily exceeds the 2800 kg balloon lift capability.

FIG. 1. Atmospheric emission dominates the diffuse sky brightness even from airborne platforms such as SOFIA (thin red curve). Observations from a balloon platform (thick blue curve) reduce atmospheric emission by 2-3 orders of magnitude, but require cryogenic optics in order to take advantage of the lower emission.
The Balloon-Borne Cryogenic Telescope Testbed (BOBCAT) develops technology for large, lightweight dewars at balloon altitudes. We describe the BOBCAT program and provide results from the first of several planned demonstration flights.

II. BOBCAT MISSION

A dewar has two functional requirements. It must store a volume of cryogen and isolate the cryogen from environmental heat. The heat load is typically minimized by surrounding the storage volume with multiple layers of reflective material (superinsulation) maintained in a vacuum to eliminate gas conduction. Conventional superinsulated dewars routinely achieve an areal heat load below 1 W m$^{-2}$.

The dewar mass is dominated by the pressure walls required to maintain the superinsulation in vacuum. The pressure walls must be thick to prevent catastrophic buckling against the one-atmosphere pressure gradient at sea level. The ambient pressure at 35 km altitude, though, is less than 0.3% of the pressure at sea level. A thin-wall dewar optimized for operation at balloon altitudes could achieve significant mass savings provided that it never hold cryogen at sea level. Figure 2 shows the concept. BOBCAT consists of a dewar with

FIG. 2. Concept of the BOBCAT mission. A thin-wall bucket dewar launches empty (left panel) with the vacuum space vented so there is no pressure gradient across the walls. Once at float altitude (right) the vent is closed to isolate the vacuum space. Cryogens are then transferred from a compact storage dewar into the ultra-light dewar. The dewar walls need only be thick enough to support the small pressure gradient at float altitude, allowing significant mass savings. Dewars as large as 4–5 m diameter could be flown with existing balloon lift capability.
thin (0.5 mm) stainless steel walls. The dewar launches warm with its vacuum space vented continuously during ascent, thereby eliminating any pressure gradient across the walls. Once float altitude is reached, the valve is closed to seal the ultra-light dewar’s vacuum space. A separate (standard construction) storage dewar maintains a reservoir of liquid helium with minimal parasitic mass. It launches with the payload, connected to the ultra-light dewar by a vacuum-insulated transfer line. Once the valve closes to seal off the vacuum space, cryogens (LN2 and LHe) may be transferred from the storage dewar into the ultra-light dewar. Cryopumping of the residual gas within the vacuum space efficiently eliminates direct gas conduction between the radiative shields, allowing the ultra-light dewar to function normally. The cold boiloff gas from the ultra-light bucket dewar forms a barrier between the cryogenic optics and the atmosphere: there are no warm windows to overwhelm the sky signal. As demonstrated by ARCADE, helium gas below 20 K is denser than the ambient atmosphere at float and forms a stable “pool” within the bucket dewar to prevent nitrogen condensation on the cold optics below\cite{1,3}.

A key requirement is the ability to efficiently transfer large volumes of cryogenic liquid from a storage dewar to the ultra-light dewar while at float altitude. Pressure gradients between the storage dewar and the ambient environment provide a simple means for such transfer, requiring only a remotely-controllable valve to initiate and terminate cryogen flow. Unlike the Superfluid Helium On-Orbit Transfer mission\cite{4}, which demonstrated superfluid LHe transfer between two vessels both maintained at near-vacuum pressure, the gradient between the high-pressure storage dewar and low-pressure ultra-light receiving dewar presents two potential complications. Liquid nitrogen is commonly used to pre-cool instrumentation prior to helium transfer. The 1–2 Torr ambient pressure at float altitude is well below the 94 Torr triple point of nitrogen. Liquid nitrogen exiting the transfer line will thus freeze into a nitrogen “snow,” potentially clogging the transfer line. Liquid helium undergoes a superfluid phase transition as the pressure falls below 38 Torr. Back pressure from the resulting boiloff can create standing waves (thermal-acoustic oscillations) within the transfer line to reduce or stop liquid transfer.

The BOBCAT program develops technology for a future balloon-borne observatory. It validates the required fabrication and operational techniques while demonstrating key performance parameters (heat leak, hold time) for a thin-walled bucket dewar. It proceeds in several phases. A first phase (BOBCAT-1) flew in August 2019 to demonstrate the nec-
essential cryogen transfer and flow control at altitude using a standard superinsulated dewar with 25 cm aperture. A second phase (BOBCAT-2) will fly at a later date, replacing the standard superinsulated dewar with an ultra-light dewar of identical size to demonstrate the thermal performance of the ultra-light concept. For simplicity, both BOBCAT-1 and BOBCAT-2 seal the top of the receiving bucket dewar with a foam lid to isolate the liquid space from the ambient atmosphere; there is no “pool” of cold helium gas for either flight. Additional flights will characterize the helium gas pool above an open-aperture dewar to quantify the astronomical seeing through the gas column. Results from the full program can then inform the design and operation of future large (3–5 m aperture) cryogenic missions at balloon altitudes.

III. BOBCAT-1 INSTRUMENTATION

Figure 3 shows the BOBCAT-1 payload. It consists of a 500-liter LHe storage dewar, an 80-liter LN2 dewar, and an electronics module on a simple aluminum gondola frame. A conventional superinsulated stainless-steel bucket dewar with liquid storage volume 59 liters

![Schematic drawing of the BOBCAT-1 payload.](image)
TABLE I. Payload Mass Budget

| Subsystem               | Dry Mass (kg) |
|-------------------------|---------------|
| LN2 Storage Dewar       | 75            |
| LHe Storage Dewar       | 320           |
| LN2 Transfer Line       | 3             |
| LHe Transfer Line       | 20            |
| Bucket Dewar            | 70            |
| Avionics                | 114           |
| Telemetry               | 30            |
| Frame                   | 150           |
| **Total**               | **782**       |

stands in for the ultra-light dewar and receives cryogens from the two storage dewars. A video camera provides real-time visual feedback. Telemetry boards copied from PIPER [2, 5] provide temperature and pressure readout from multiple locations. Table 1 summarizes the mass budget for the BOBCAT-1 payload.

The payload includes 2 conventional storage dewars, modified for use on a high-altitude payload. An 80-liter dewar (Cryofab model CLPB-80) holds liquid nitrogen to pre-cool the test dewar. It has been modified to include an American Magnetics capacitive level sensor, a 50 W pressure builder, and a separate telemetry port for pressure sensors. A 500-liter dewar (International Cryogenics model IC-500) holds liquid helium. It has been modified to replace the standard neck assembly with a conflat flange, which contains a liquid withdrawal line, vent line, temperature and pressure sensors, two redundant American Magnetics superconducting level sensors, and two redundant 52 W heaters / pressure builders which also allow rapid boiloff of residual cryogen at the end of the flight. Custom-installed pressure relief valves on each storage dewar maintain the cryogen at one atmosphere above ambient pressure, allowing each dewar to vent as needed during ascent.

A standard stainless steel transfer line (McMaster-Carr model 54935K61) connects the LN2 storage dewar to the receiving test dewar. A DC gearmotor (Midwest Motion Products
model MMP D22-376H-24V GP52-1140 E5-032) couples to the handle of the storage dewar’s liquid withdrawal valve to control LN2 flow to the test dewar. A vacuum-insulated transfer line (International Cryogenics model 92-9552) with 4.77 mm inner diameter connects the LHe storage dewar to the receiving dewar. A separate, identical DC gearmotor turns a cryogenic globe valve built into the helium transfer line to control LHe flow to the test dewar. A shaft encoder, tachometer, current monitor, and voltage monitor provide real-time telemetry for each valve motor. Each motor includes a thermometer and heater for thermal control; the LN2 valve also has a heater/thermometer pair.

Figure 4 shows the receiving dewar. It consists of a conventional bucket dewar 132 cm tall and 35.6 cm outer diameter, using multi-layer superinsulation within stainless steel vacuum walls to enclose a 59-liter cylindrical liquid space with 25.4 cm diameter. The vacuum space remains sealed throughout the flight. A lid made from extruded polystyrene foam (Dow blue Styrofoam™ sheet) prevents atmospheric ingress and supports the two cryogen fill lines, a telemetry port, and an open vent. A set of 8 silicon diodes (Lakeshore DT-670) and 6 ruthenium oxide thermometers (Lakeshore RX-103) monitor temperatures throughout the dewar liquid space. Two redundant American Magnetics superconducting level sensors 91 cm tall monitor the LHe level. A discrete level sensor mounts a set of heaters and resistive ruthenium oxide thermometers at heights 2.5, 7.5, 13, 23, 38, and 58 cm above the

![FIG. 4. Schematic drawing of the receiving dewar. Temperatures and liquid helium level are monitored through a telemetry port.](image)
dewar bottom. When powered, each 2 W heater will heat the thermometer, decreasing its resistance from 38 kΩ to 11 kΩ if the thermometer is not immersed in LHe. As with the LHe storage dewar, separate heaters (14 W and 72 W) on the dewar bottom can be powered to rapidly boil off any cryogens remaining at the end of the flight, with the two sizes intended to provide fine and coarse control if needed.

IV. BOBCAT-1 FLIGHT

BOBCAT-1 launched at 13:59 UT on 22 Aug 2019 from NASA’s Columbia Scientific Balloon Facility in Ft Sumner, NM (elevation 1200 m) carrying 14 liters of liquid nitrogen and 268 liters of liquid helium. The LHe storage dewar was vented to atmosphere several hours prior to launch so that its internal pressure at launch (810 Torr) was only modestly above the ambient 656 Torr. A 0.84 million cubic meter balloon carried the payload, reaching float altitude of 39.7 km at 16:52 UT. During ascent, temperatures within the 500 liter storage dewar remained steady until the ambient pressure dropped below 80 Torr, after which the temperature fell steadily from 4.3 K to 3 K, below the 4.2 K value expected for the one-atmosphere overpressure relief valve but consistent with a slow leak in the neck assembly or a stuck / frozen pressure relief valve. Figure 5 shows the pressure, temperature, and altitude during the flight. At 16:20 UT a 52 W heater within the 500-liter storage dewar was turned on for 3 minutes to increase the pressure and maintain LHe temperature well above the superfluid transition. The temperature of the LHe bath within the dewar stabilized at 3.2 K after the heater turned on, consistent with a pressure of 300 Torr inside the dewar compared to 1.2 Torr ambient pressure at float.

Cryogen transfer began at 16:38 UT using LN2 to pre-cool the receiving dewar. To minimize collection of frozen nitrogen within the receiving dewar, the LN2 liquid withdrawal valve was only opened to 6% of its full-open position (i.e. barely open), using the 1000 Torr pressure gradient between the LN2 storage dewar and the receiving dewar to force LN2 through the transfer line. The valve opened three times for a six-minute duration each time, and then closed for ten minutes to allow temperatures within the receiving dewar to stabilize before opening the valve again. Figure 6 shows selected temperatures during the nitrogen precooling operation. During each nitrogen transfer, the LN2 liquid withdrawal valve cooled rapidly, reaching temperatures below 260 K before the valve was closed each time. A 24 W
heater on the valve raised the temperature once the valve closed, but proved unable to maintain a constant temperature during nitrogen transfer. During the third and final nitrogen transfer, the valve temperature continued to fall after the valve was commanded to the closed position. Temperatures within the receiving dewar also continued to fall, consistent with the continued flow of nitrogen through the valve into the receiving dewar. It is probable that frozen nitrogen held the valve slightly open despite several commands to close. By 17:30 UT the bottom of the receiving dewar reached 63 K, indicating a layer of frozen nitrogen. Both boiloff heaters on the dewar bottom were then turned on for 3 minutes to sublimate the frozen nitrogen, after which temperatures at the dewar bottom stabilized near 100 K.

FIG. 5. Temperature and pressure within the 500-liter storage dewar throughout flight. The ambient pressure and payload altitude are also shown. Telemetry within the storage dewar is unreliable during active LHe transfer. Pressure within the storage dewar fell below the 1 atmosphere design goal but remained well above the superfluid transition.
Once the boiloff heaters turned on, the LN2 valve temperature recovered and we were able to fully close the valve.

Liquid helium transfer began at 17:46 UT. To achieve some additional cooling from the helium gas enthalpy, the LHe valve was only commanded to 15% of the full open position, minimizing the initial transfer rate. Figure 7 shows temperatures within the receiving bucket dewar during LHe operations. Temperatures within the receiving dewar fell rapidly, reaching the LHe boiling temperature of 1.3 K at 17:57 UT. By 18:09 UT the receiving dewar held

![Image of temperature graphs]

**FIG. 6.** Selected temperatures during the LN2 pre-cooling operation. The top panel shows the LN2 valve and motor temperatures while the bottom panel shows temperatures within the receiving bucket dewar. Vertical gray bars show periods when the LN2 valve was commanded open. Falling temperatures after the third and final LN2 transfer indicate a stuck or frozen valve. Dashed vertical lines indicate additional commands to close the valve while the vertical red bar shows the period with the two boiloff heaters turned on.
32 liters of LHe, at which point the valve on the LHe transfer line was closed and cryogen transfer terminated.

The primary goal of the 2019 flight was a demonstration of cryogen transfer at float altitude. A secondary goal was the calorimetric measurement of the total heat leak to the receiving dewar, which will be compared in a follow-up flight to a similar measurement using an ultra-light receiving dewar of identical dimensions. This test proceeded in two stages. We paused for 20 minutes after the LHe transfer to allow temperatures to settle in the receiving dewar, after which both continuous level sensors were turned on. Figure 8 shows the subsequent LHe volume as a function of time. From 18:30 to 18:50 UT we measure a LHe loss rate of $5.4 \pm 0.2 \text{ l hr}^{-1}$, corresponding to a total heat leak of $4.7 \pm 0.2$ W. The power dissipated by the level sensors depends on the liquid level. We monitor the current and voltage in each sensor to correct for the dissipated power. During the continuous level test, sensor 1 dissipated average power 0.76 W while sensor 2 dissipated average power 1.07 W. Correcting for the LHe loss due to sensor power dissipation yields a corrected heat leak of $2.8 \pm 0.2$ W for the dewar.

The second half of the test monitors the LHe level intermittently, limiting the duty cycle of the two level sensors to reduce their dissipated power. From 19:00 to 19:40 UT each

![Temperature Graph](image)

FIG. 7. Selected temperatures within the receiving bucket dewar during LHe operations. The vertical gray bars show the periods when the LHe valve was commanded open. The dashed vertical line indicates an additional command to close the valve.
sensor was powered 5 times for approximately 40 seconds each time, for a total combined dissipation of 285 joules. After correction for this minor dissipation, the measured loss rate of \(3.2 \pm 0.3 \text{ l hr}^{-1}\) corresponds to a heat leak \(2.7 \pm 0.2 \text{ W}\).

The calorimetric tests are both consistent with a heat leak of \(2.7 \pm 0.2 \text{ W}\) to the interior of the receiving dewar. This includes heat conduction through the 1.2 m\(^2\) superinsulation as well as conduction down the interior wall and along the insert holding the transfer lines and level sensors. Stratification of boiloff gas within the dewar during these tests could affect the latter two terms, but the effect should be nearly constant over the limited change of LHe level during calorimetric testing. Figure 9 shows the temperature at the top of the dewar (just beneath the lid) during calorimetric testing, as a function of the distance to the liquid below. Conductive heat flow from the top of the dewar to the liquid should scale linearly with the temperature gradient and inversely with the lid–liquid distance. Throughout calorimetric testing, the ratio \(\Delta T/L\) varies by only 11%.

![Figure 8](image_url)

**FIG. 8.** Liquid helium volume within the receiving dewar during passive calorimetric testing. Two redundant level sensors monitored the liquid level continuously for the first half of the test, then were intermittently powered during the second half to minimize their dissipated power.
At 19:54 UT preparations began to terminate the flight. The LHe valve was opened again to remove helium from the 500-liter storage dewar, transferring an additional 20 liters to the receiving dewar. At the same time, heaters in both the 500-liter storage dewar and the receiving dewar were turned on to boil off all remaining cryogen. By 20:28 UT both LHe dewars were empty. The nitrogen storage dewar was not emptied, and was left with 11 liters LN2 at one atmosphere overpressure.

Pressure within the 500-liter storage dewar remained at 380 Torr, well below both the one-atmosphere design and the ambient pressure at landing. To prevent potential buckling of the storage dewar from internal underpressure during descent, the LHe valve between the 500-liter storage dewar and the receiving dewar was left in the full open position so that the

![Graph](image.png)

**FIG. 9.** The temperature underneath the receiving dewar lid during calorimetric testing is shown as a function of the distance to the liquid below. The reduced duty cycle of the continuous LHe level sensors during the second half of the test causes the break in slope at distances above 56 cm. Heat flow from the lid to the liquid depends on the temperature gradient and the lid–liquid distance; the higher temperatures are compensated by longer distances so that the conducted heat during calorimetric testing is constant within 11%.
storage dewar would remain at ambient pressure throughout descent. The flight ended at 21:28 UT; the payload was subsequently recovered undamaged.

The BOBCAT instrument package included a real-time video link with the camera focused on the vent line exiting the receiving dewar. At no time throughout the flight was any plume of condensation visible. This includes the initial LN2 cooldown, the LHe transfer for calorimetric testing, and the final LHe transfer and boiloff prior to termination. Figure 10 shows the dewar and exhaust vent during the initial LHe fill. Both the initial LHe fill and the final boiloff reduced the temperature of the vent exhaust gas below 30 K but produced no visible plume into the ambient atmosphere. Additional instrumentation to determine the extent (if any) of atmospheric condensation from cryogenic operations at 39 km altitude is planned for a future flight.

![Image of dewar and exhaust vent](image.png)

**FIG. 10.** In-flight video still showing the receiving dewar exhaust vent during LHe transfer. Although the vent is at 30 K, no condensation plume is visible.
V. DISCUSSION

Cryogen expenditure and transfer efficiencies during BOBCAT-1 flight agreed with pre-flight ground tests at Ft Sumner. The nitrogen transfer at float consumed 3 liters of LN2 while cooling the bucket dewar liquid volume from initial temperature 297 K to 100 K at the dewar bottom and 200 K at the top. Ground tests also required 3 liters of LN2 to achieve similar cooling. The 500-liter storage dewar launched with 268 liters LHe, of which 168 liters remained once float altitude was reached. Cooling the bucket dewar to 1.3 K and transferring 32 liters LHe required a total LHe usage of 61 liters, including the losses to the superfluid phase transition. By comparison, ground tests required 35 liters LHe to transfer 9 liters into the bucket dewar. Once the transfer line and receiving dewar are cooled to LHe temperatures, additional parasitic losses are a small fraction of the transferred helium volume. Ground tests thus required some 26 liters of LHe to cool the transfer line and receiving dewar, compared to 29 liters required at float. The measured values agree with the estimated LHe volume needed to cool the ∼10 kg of stainless steel in the transfer line and dewar inner walls. The helium volume required to cool future missions using much larger dewars can thus be estimated from the total thermal mass to be cooled.

The total heat leak of 2.7 ± 0.2 W measured in flight is larger than the 1–2 W measured using the same dewar in ideal laboratory configurations. From the measured top-bottom temperature gradient (Fig 9) the parasitic heat flow down the dewar wall will be of order 0.4 W (neglecting cooling through the gas) and should be comparable for both ground and flight operations. Laboratory configurations include a longer (20 cm) set of radiative baffles between the lid and the liquid, and did not include the fixed transfer lines and sensor suite. Sensors within the storage dewars and receiving bucket dewar are designed for ruggedness, not to minimize parasitic heat leaks. In particular, the copper wire leads to the thermometers and heaters inside the dewars have diameters of 0.32 mm and 0.80 mm, respectively. Prior experience with balloon payloads has shown that the 0.13 mm wire more typical of laboratory dewars tended to develop shorts or breaks during cross-country shipping to the launch site. Thermal conduction through the wires could contribute as much as 0.65 W during calorimetric tests if cooling through the gas column can be neglected. Solar heating of the dewar during flight creates an additional potential source of heat. The BOBCAT-1 flight took place in daylight. The temperature of the unpainted stainless steel dewar walls
was not recorded during flight, but nearby unpainted aluminum boxes warmed to 342 K, well above the 300 K temperatures typical for ground testing. If the dewar exterior wall reached comparable temperatures, heat flow through the dewar superinsulation would be expected to increase by 10–50%, depending on the ratio of conductive to radiative transport within the superinsulation. Other sources of heat in flight are small. Direct thermal radiative from the 70 K lid contributes less than 60 mW to the total load.

The BOBCAT project develops technology and operational techniques for a future large (3–4 meter) cryogenic telescope on a balloon platform. The BOBCAT-1 flight provides a baseline to compare the performance of a standard-construction superinsulated dewar to an ultra-light dewar of comparable dimensions. A second flight will compare the cryogenic performance of an ultra-light dewar to the standard-construction superinsulated dewar described here. The liquid space of the BOBCAT-2 ultra-light dewar will have identical dimensions as the BOBCAT-1 superinsulated dewar and will re-fly the same transfer lines, lid assembly, and sensor suite so that any differences in the calorimetric heat leak between the BOBCAT-1 and BOBCAT-2 flights can be attributed to the dewar design and not the instrumentation.

The BOBCAT-1 flight shows that bulk cryogen transfer at float altitude can proceed on time scales and with cryogen losses comparable to ground operations, despite the low operating pressure at float. We find no significant differences between flight and ground tests for the cryogen volume required to cool the dewar and instrument package, or for the time required for cryogen transfer. Several simple modifications to the BOBCAT-1 payload would facilitate future operations. The heater on the nitrogen valve was unable to maintain stable temperatures during active LN2 transfer. While a larger heater could mitigate this problem, use of a custom LN2 transfer line with a built-in valve (comparable to the LHe transfer line and valve) would provide physical separation between the cryogen flow and the valve motor, eliminating the problem. The largest cryogen loss from the low operating pressure (a 30% loss of helium mass from the storage dewar at the superfluid transition) could be avoided in future large missions using a storage dewar pumped below the superfluid transition prior to flight. Use of a pumped storage dewar would additionally eliminate the need to backfill the dewar prior to descent, removing the possibility of ice plugs forming in the storage dewar during descent.
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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

[1] J. Singal, D. J. Fixsen, A. Kogut, S. Levin, M. Limon, P. Lubin, P. Mirel, M. Seiffert, T. Villela, E. Wollack, and C. A. Wuensche, The Astrophysical Journal 730, 138 (2011), arXiv:0901.0546 [astro-ph.IM].

[2] S. Pawlyk, P. A. R. Ade, D. Benford, C. L. Bennett, D. T. Chuss, R. Datta, J. L. Dotson, J. R. Eimer, D. J. Fixsen, N. N. Gandilo, T. M. Essinger-Hileman, M. Halpern, G. Hilton, G. F. Hinshaw, K. Irwin, C. Jhabvala, M. Kimball, A. Kogut, L. Lowe, J. J. McMahon, T. M. Miller, P. Mirel, S. H. Moseley, S. Rodriguez, E. Sharp, P. Shirron, J. G. Staguhn, D. F. Sullivan, E. R. Switzer, P. Taraschi, C. E. Tucker, A. Walts, and E. J. Wollack (2018) p. 1070806.

[3] D. J. Fixsen, A. Kogut, S. Levin, M. Limon, P. Lubin, P. Mirel, M. Seiffert, J. Singal, E. Wollack, T. Villela, and C. A. Wuensche, The Astrophysical Journal 734, 5 (2011), arXiv:0901.0555 [astro-ph.CO].

[4] M. DiPirro and S. Castles, Cryogenics 26, 84 (1986).

[5] J. Lazear, P. A. R. Ade, D. Benford, C. L. Bennett, D. T. Chuss, J. L. Dotson, J. R. Eimer, D. J. Fixsen, M. Halpern, G. Hilton, J. Hinderks, G. F. Hinshaw, K. Irwin, C. Jhabvala, B. Johnson, A. Kogut, L. Lowe, J. J. McMahon, T. M. Miller, P. Mirel, S. H. Moseley, S. Rodriguez, E. Sharp, J. G. Staguhn, E. R. Switzer, C. E. Tucker, A. Weston, and E. J. Wollack, “The Primordial Inflation Polarization Explorer (PIPER),” (2014) p. 91531L.