Cryocooling technologies for the Origins Space Telescope

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Abstract. The Origins Space Telescope's (Origins) significant improvement over the scientific capabilities of prior infrared missions is based on its cold telescope (4.5 K) combined with low-noise far-IR detectors and ultrastable mid-IR detectors. A small number of new technologies will enable Origins to approach the fundamental sensitivity limit imposed by the natural sky background and deliver groundbreaking science. This paper describes a robust plan to mature the Origins mission, enabling cryocooler technology from current state-of-the-art (SOA) to Technology Readiness Level (TRL) 5 by 2025 and to TRL 6 by mission Preliminary Design Review. Entry TRLs corresponding to today's SOA are 4 or 5, depending on the technology in question. [DOI: 10.1117/1.JATIS.7.1.011008]

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1 Introduction

To achieve the orders of magnitude improvements over the current state of the art spectroscopic sensitivity in the far infrared, Origins uses a cold, 4.5 K telescope and extremely sensitive detectors operating at 50 mK (see Fig. 1 and accompanying articles in this volume and the Origins Study Report).[1]

Taking advantage of radiation to deep space can enable achieving low temperatures. However, due to the T^4 decrease in cooling power per area—and parasitic heat from the spacecraft, Earth, and Sun—radiators colder than ~30 K are not practical. In the past, the InfraRed Astronomy Satellite, the Cosmic Background Explorer (COBE), the Infrared Space Observatory (ISO), Spitzer, and the Herschel instruments used liquid helium to cool to <6 K and the Midcourse Space eXperiment, and the Wide-field Infrared Survey Explorer (WISE) used solid hydrogen to cool telescopes to <12 K. Stored cryogens have limited life, are bulky, and drive ground testing and on-orbit operations. For these reasons, mechanical cryocoolers have been developed over the last several decades to replace stored cryogens.

Cryocooler advancement is needed to cool the telescope to 4.5 K and the detectors in the far-infrared instruments to sub-Kelvin temperatures. Cooling the entire observatory reduces its self- emission. Cooling the far-infrared detectors reduces their noise. Both are required to reach astronomical background-limited performance. Origins requires 4.5 K mechanical coolers for all instruments and telescope, and sub-Kelvin coolers for the Origins Survey Spectrometer (OSS) and Far IR Imaging Polarimeter (FIP) instruments.

Origins is designed with high thermal conductance materials in low-temperature regions. Consequently, the 4.5 K, 20 K, and 35 K regions are all nearly isothermal. Cooling these areas at one location produces only small gradients. Therefore, concepts such as broad area cooling are

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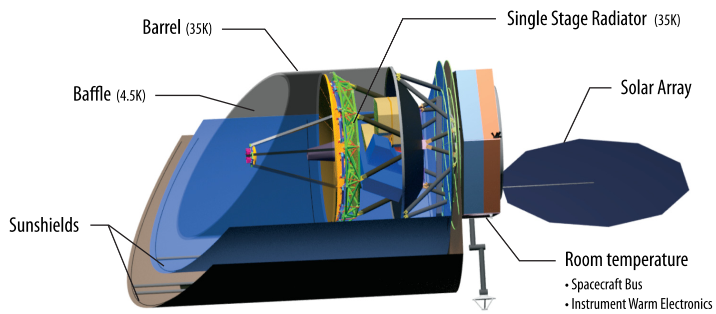

Fig. 1 Origins temperature zones are designed to maximize cryocooling efficiency while ensuring a 4.5 K environment for the telescope and instruments. The instruments are housed in the 4.5 K zone beneath the primary mirror.

not required. What is required, however, is a scheme to transfer relatively cold fluid where it is produced (e.g., at the spacecraft) to where it is needed at the telescope, instruments, and surrounding structure. Fortunately, the scheme used by the James Webb Space Telescope (JWST)/mid-infrared instrument (MIRI) cooler also works for Origins, and the Origins system has been modeled after it. Two of the five cooler concepts need some method to mimic this (e.g., by providing a separate circulating loop). Soft mounted compressors of the type for the MIRI cooler have been shown to produce exported vibration ~0.1 N. Origins performed a rough simulation of the effect on the telescope, using four simultaneously operating coolers each producing this level of vibration. The results indicated that the stability requirements for the most sensitive instrument were met by a factor of more than 5.

2 Mechanical Cryocoolers at 4.5 K

2.1 *Origins Requirements*

The baseline Origins design assumes high-reliability, relatively low-vibration mechanical cryocoolers. Four such cryocoolers will each provide 50 mW of cooling power at 4.5 K, 100 mW of cooling at 20 K, and 5 W of cooling at 70 K, all with an input power (bus power) of 450 W or less. These requirements were derived to be straightforward extensions on present-day cryocoolers. The requirements are somewhat flexible to allow more qualified cryocooler vendors to participate. Therefore, while the total cooling power at 4.5 K is fixed at $4 \times 50 = 200$ mW, and the total input power is fixed at $4 \times 450 = 1800$ W, the number of cryocoolers and the intermediate stage temperatures can vary. 4.5 K was chosen as the base temperature to limit the in-band emission from the telescope. While a temperature of lower than the cosmic microwave background at 2.7 K provides the least noise, for low emissivity optics, 4.5 K represents a reasonable compromise, allowing the use of some existing cryocoolers, as well as limiting input power to the cryocoolers (see Fig. 2 for a comparison of telescope emission for various temperatures and sky background).

2.2 *State-of-the-Art*

State-of-the-art mechanical cryocoolers at Technology Readiness Level (TRL) 7+ include Planck,[2] JWST/MIRI,[3] and Hitomi (ASTRO-H).[4] It is worth noting that while the quoted performance of the Joule/Thomson (JT) cryocooler on Hitomi was 4.5 K, the actual cooler temperature under full load was 4.3 K to 4.4 K, so a considerable margin exists on achieving the telescope temperature of 4.5 K. Domestic coolers that could achieve 4.5 K are considered to be TRL 4-5, having been demonstrated as a system in a laboratory environment under NASA's Advanced Cryocooler Technology Development Program (ACTDP)[5] (Fig. 3) or are a variant of a high TRL cooler (JWST/MIRI). The JWST/MIRI cryocooler engineering unit was tested with a simple substitution of the rare isotope ^{3}He for the typical ^{4}He, which produced significant cooling at temperatures below 4.5 K.[6] Mechanical cryocoolers for higher

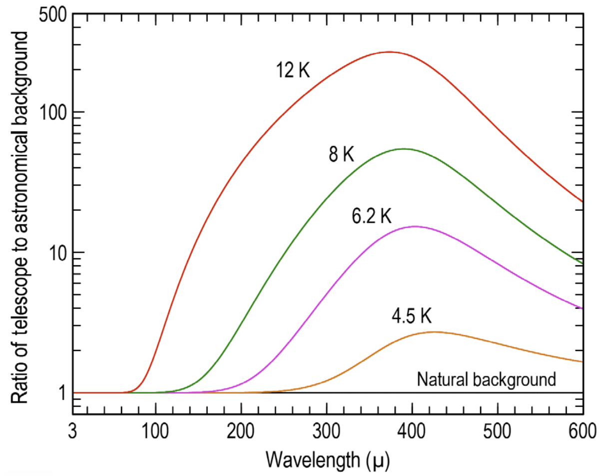

Fig. 2 A comparison of telescope emission (effective emissivity = 0.05) compared to the sky background in the mid to far infrared.

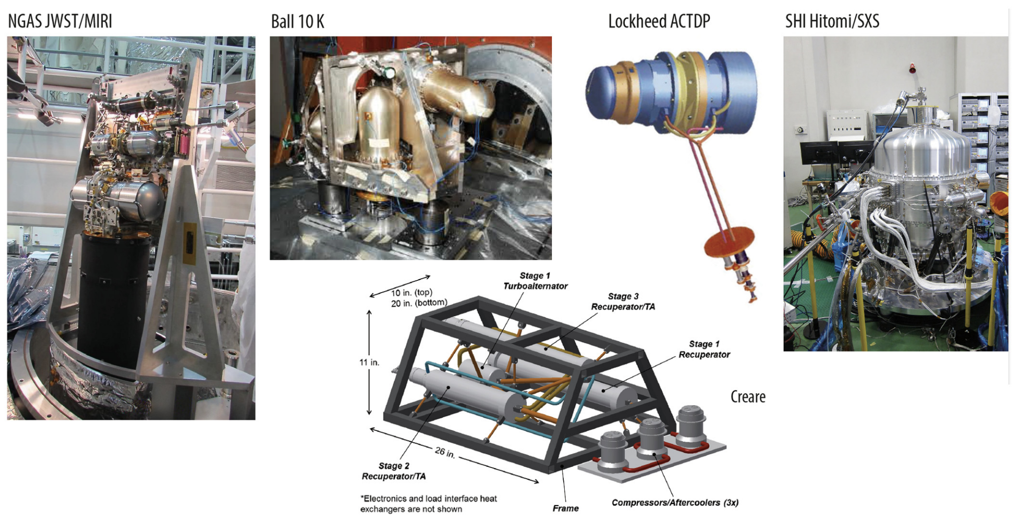

Fig. 3 Five vendors have developed cryocoolers that have reached TRL 4+ and need only small improvements to meet the Origins's requirements.

temperatures have already demonstrated impressive on-orbit reliability,[7] with updated space flight operating experience as shown in Fig. 4. The moving components of a 4.5 K cooler are similar (expanders) or are exactly the same (compressors) as those that have flown. Further development of these coolers to maximize cooling power per input power (<9000 W/W at 4.5 K) for small cooling loads (50 to 200 mW) while minimizing mass is desired. There is also a need to minimize the exported vibration from the cooler system. The miniature reverse-Brayton cryocoolers in development at Creare[8] are examples of high efficiency, reliable coolers with negligible exported vibration. These coolers are at TRL 6 for 80 K, TRL 4-5 for 10 K, and TRL 3 for 4 K operation.

2.3 *Mechanical Cryocooler Advancements Planned to Reach TRL 5 and 6*

The TRL 7 JWST/MIRI cryocooler is designed to cool a primary load at 6.2 K and an intercept load at 18 K. It does this using a precooled helium Joule Thomson loop that compresses ^{4}He from 4 to 12 bar, precools it to 18 K with a three-stage pulse tube cryocooler, then circulates it to a remote heat intercept at 18 K and an isenthalpic expander that provides cooling at 6.2 K. The only change required to lower the temperature to 4.5 K is to lower the return pressure from 4 to 1 bar. To maintain the required mass flow, the compressor swept volume must be increased to

Recent Long-Life Space Cryocooler Flight Operating Experience as of May 2016

Cooler/Mission	Hours/Unit	Comments
Air Liquide Turbo Brayton (ISS MELFI 190K)	85,600	Turn on 7/06, Ongoing, No degradation
Ball Aerospace Stirling		
HIRDLS (60K 1-stage Stirling)	83,800	8/04 thru 3/14, Instr. failed 2009; Data turned off 3/14
TIRS cooler (35K two-stag Stirling)	27,900	Turn on 3/6/13, Ongoing, No degradation
Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
Fujitsu Stirling (ASTER 80K TIR system(	141,700	Turn on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	27,500	FM1 (8/10-10/13 EOM); FM2 failed at 10,500 h
Mitsubishi Stirling (ASTER 77K SWIR system)	137,500	Turn on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Coolers		
CX (150K Mini PT (2 units))	161,600	Turn on 2/98, Ongoing, No degradation
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission End, No degradation
MTI (60K 6020 10cc PT)	141,600	Turn on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	133,600	Turn on 12/00, Ongoing, No degradation
SABER on TIMED (75 Mini PT)	129,600	Turn on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	121,600	Turn on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	102,600	Turn on 8/04, Ongoing, No degradation
JAMI (65K HEC PT (2 units))	91,000	4/05 to 12/15, Mission End, No degradation
GOSAT/IBUKI (60K HEC PT)	63,300	Turn on 2/09, Ongoing, No degradation
STSS (Mini PT (4 units))	52,800	Turn on 4/10, Ongoing, No degradation
OCO-2 (HEC PT)	14,900	Turn on 8/14, Ongoing, No degradation
Himawari-8 (65K HEC PT (2 units))	12,800	Turn on 12/14, Ongoign, No degradation
Oxford/BAe/MMS/Astrium/Airbus Stirling		
ISAMS (80K Oxford/RAL)	15,800	10/91 thru 7/92, Instrument failed
HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, Mission End, No degradation
MOPITT (50-80K BAe (2 units))	138,600	Turn on 3/00, lost one disp. at 10,300 h
ODIN (50-80K Astrium (1 unit))	132,600	Turn on 3/01, Ongoing, No degradation
AATSR on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No degradation, Satellite failed
MIPAS on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No degradation, Satellite failed
INTEGRAL (50-80K Astrium (4 units))	118,700	Turn on 10/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	96,600	Turn on 4/05, Ongoing, No degradation
Helios 2B (50-80K Astrium (2 units))	58,800	Turn on 4/10, Ongoing, No degradation
SLSTR (50-80K Airbus (2 units))	1,400	Turn on 3/16, Ongoing, No degradation
Planck (4K JT using 2 Astrium Comp.)	38,500	5/09 thru 10/13, Mission End, No degradation
Raytheon ISSC Stirling (STSS (2 units))	52,800	Turn on 4/10, Ongoing, No degradation
Rutherford Appleton Lab (RAL)		
ASTR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
ASTR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	59,300	7/05 thru 4/12, Mission End, No degradation
Akari (20K 2-stg (2 units))	39,000	2/06 to 11/11 EOM, 1 Degr., 2nd failed at 13 kh
Kaguya GRS (70K 1-stg)	14,600	10/07 thru 6/09, Mission End, No degradation
JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
Sunpower Stirling		
RHESSI (75K Cryotel)	124,600	Turn on 2/02, Ongoing, Modest degradation
CHIRP (CryoTel CT-F)	19,700	9/11 to 12/13, Mission End, No degradation

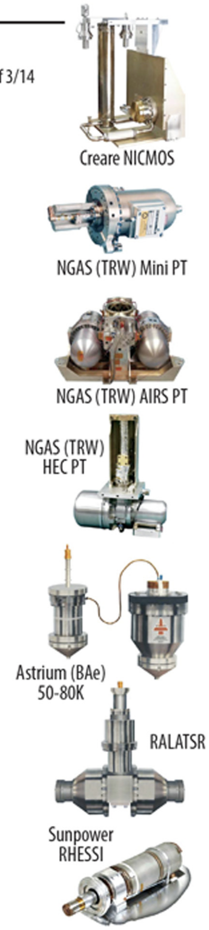

Fig. 4 On-orbit mechanical cooler lifetimes. Almost all cryocoolers have continued to operate normally until turned off at the end of instrument life. [Ross, 2007, updated 2016]. It is worth noting that there are 8766 h in one year.

accommodate the lower density of the lower pressure helium, and the pressure ratio must be increased to maintain the pressure drop. This can be achieved by upgrading the JT compressor used in the MIRI cooler. One way this can be done is by augmenting the existing MIRI JT compressor with a second JT compressor of the same design but with larger pistons to act as the first stage in a two-stage compressor.

The Lockheed four-stage pulse tube cryocooler has demonstrated the required heat removal at the temperatures required for Origins in a TRL 4 design.[9] However, for Origins, 4.5 K is required in a location, i.e., remote from the compressor. This will require development of a separate 4.5 K cooling loop. This could be realized using a Hubble Space Telescope/Near Infrared Camera and Multi-Object Spectrometer (HST/NICMOS) cooling loop driven by a fan.

The Ball Aerospace (Ball) 4.5 K cooler design uses a similar architecture to the Northrop-Grumman Aerospace Systems (NGAS) JWST/MIRI cryocooler with a stirling-type displacer (rather than a pulse tube) and a JT with a long loop for remote cooling. The Ball design lacks a system-level demonstration to reach TRL 5.[10]

Creare is developing a 4.5 K stage for its miniature turbine reverse-Brayton cryocoolers under Small Business Innovative Research (SBIR) funding. This expansion stage is similar to the one used for a single stage cooler flown on HST/NICMOS and the two-stage 10 K design currently at TRL 5.

The Sumitomo Heavy Industries (SHI) 4.5 K cryocooler flown on Hitomi had a lifetime goal of 5 years. Lifetime is expected to be limited by bearing friction and contamination. Reliability and lifetime will be improved by using a noncontacting suspension system (similar to displacers) and by improving the cleanliness of the critical internal parts and working fluid. The improved suspension system will extend expected life from 5 to 10 or more years. This development is in progress at SHI.

3 Sub-Kelvin Cooling

3.1 *Sub-Kelvin Cooling Requirements*

The FIP instrument requires 3 μW of cooling at 50 mK plus 125 μW at 0.6 K for a heat rejection temperature at 4.5 K with a heat rejected of 4 mW average.

The OSS instrument requires 3 μW of cooling at 50 mK, plus 125 μW at 0.6 K, plus 500 μW at 1.6 K for a heat rejection temperature of 4.5 K and a heat reject power of <8 mW average. These cooling powers are the current best estimates (CBE) from the up-scoped design for these instruments (Origins Study Report, Volume 1, Sec. 3). The cooling required is over and above any internal sub-Kelvin cooler requirements and inefficiencies. For the baseline designs (Origins Study Report, Volume 1, Sec. 3), the requirement for low temperature heat lift will be lowered by almost a factor of 2. It is also required that the sub-Kelvin cooler capability would provide a factor of 2 margin for the baseline design. In other words, the sub-Kelvin coolers must be capable of providing 6 μW of cooling at 50 mK and 250 μW of cooling at 0.6 K. Superconducting detectors and their readout systems are very sensitive to small/time varying magnetic fields. Typically, a detector package will provide its own shielding to deal with external fields on the order of 30 μT, so the magnetic field generated by the sub-Kelvin cooler must be <30 μT.

3.2 *Sub-Kelvin State-of-the-Art*

For detector cooling to 50 mK, adiabatic demagnetization refrigerators (ADRs) are currently the only proven technology, although some work has been funded by European Space Agency to develop a continuously recirculating dilution refrigerator (DR). A single shot DR flown on Planck produced 0.1 μW of cooling at 100 mK for ~1.5 years,[2,11] while a three-stage ADR used on Hitomi produced 0.4 μW of cooling at 50 mK with an indefinite lifetime.[12] The Origins temperature stability requirement at the 50-mK stage (2.5 μK rms over 10 min) is similar to that of Hitomi. The Hitomi design and temperature readout system easily meet (<0.4 μK rms) this requirement (Fig. 5).

3.3 *Advancements Planned to Reach TRL 5 and 6*

In contrast, a TRL 4 Continuous ADR (CADR) has demonstrated 6 μW of cooling at 50 mK with no life-limiting parts.[13] This technology is currently being advanced toward TRL 6 by 2020 through Strategic Astrophysics Technology (SAT) funding[14] (Fig. 5). Demonstration of a 10 K upper stage for this machine, as is planned, would enable coupling to a higher temperature cryocooler, such as the one produced by Creare, that has a near-zero vibration technology.[8] The CADR is modular and allows additional continuous cooling at other temperatures. It can be configured as the base four-stage design, producing 6 μW of cooling at 0.05 K, with one or two additional stages to provide additional cooling at higher temperatures. The design includes a surrounding magnetic shield, resulting in <1 μT external field. The large gray pill-shaped structure in Fig. 5 is the notional magnetic shield and will easily meet the requirement.

The CADR design is aided by software that accurately simulates its operation. This allows users to vary salt pill sizes, materials, operating temperatures, magnetic field strengths, and heat switch conductance to approach an optimum design. The CADR for the Origins/FIP instrument, shown schematically in Fig. 6, will include five stages made of elements nearly identical to those used in the new 2019 CADR. The CADR for the Origins/OSS instrument will have an additional two stages, similar to stages 4 and 5 (not shown), to provide 1 mW (factor of 2 higher than requirement) of cooling at 1.3 K. The first and third stages will remain continuously at 0.05 K and 0.6 K, respectively. The fourth stage cools to absorb heat from the second and third stages on

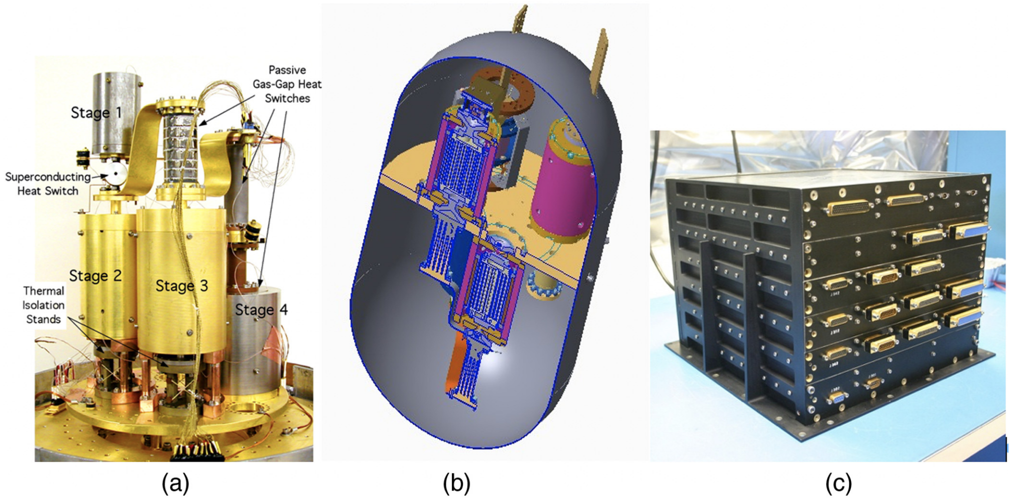

Fig. 5 (a) CADR provides 6 μW of cooling at 50 mK; (b) CADR under development at NASA will provide 6 μW of cooling at 50 mK and also has a precooling stage that can be operated from 0.3 K to 1.5 K. The drawing shows a notional enclosing magnetic shield for <1 μT fringing field. Overall dimensions are 445 mm tall by 225-mm diameter. (c) ADR controller flown on Hitomi. The box is roughly cubic with 300-mm sides. The Origins CADR will use duplicates of the controller cards and temperature readout cards from this flight unit.

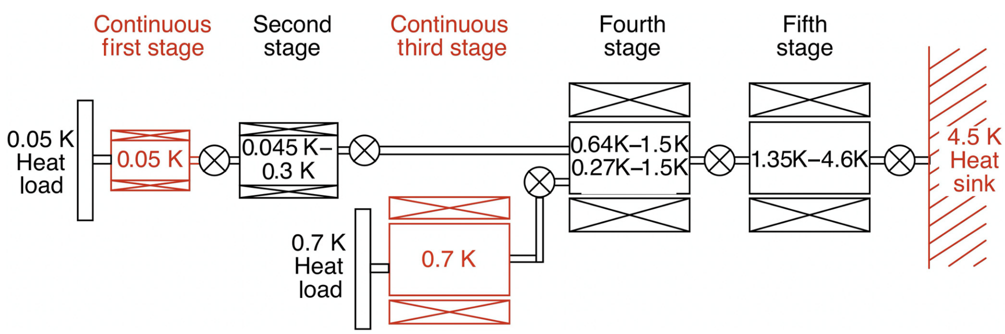

Fig. 6 A schematic representation of the FIP and OSS CADRs. The ADR stages are synchronized to move heat from the 50-mK and 0.6 K stages to the 4.5 K stage, where it is lifted by the 4.5 K cryocooler(s). Salt pill operating temperature range is indicated. The average cooling power for each continuous stage and heat rejection to the sink are indicated in red as they are called out in instrument requirements.

alternate cycles. Each stage cycles between maximum and minimum magnetic fields in ∼20 to 30 min.

The five Origins ADR stages use two different magnetocaloric materials: gadolinium-lithium-fluoride (GLF) and chrome-potassium-alum (CPA). GLF can provide useful cooling over the range of 0.5 K to <10 K. CPA can provide useful cooling from 30 mK to <2 K. Performance of these materials in an actual ADR are well understood and accurately modeled. Based on the design study, the two cooling power values are 100% higher than the corresponding heat load predictions.

The flight control electronics for this ADR is based on the flight-proven Hitomi ADR controller, and has achieved TRL 6 by employing the same cards used in the Hitomi flight unit (Fig. 5).

The CADR components are modular, so the CBE design (Fig. 5) may be easily rearranged to better conform with volume constraints. Heat straps shown exiting the magnetic shield are notional and a penetration that prevents fringing magnetic field from reaching the outside of the shield is underway. This notional CADR design has an estimated mass of 21 kg, including 9 kg for the outer magnetic shield.

The electronics box (Fig. 5) includes eight thermometry channels per card, with adjustable excitation and resolution that provides complete temperature readout for the host instrument, as well as CADR control.

4 Summary

The Origins Space Telescope requires two types of cryocoolers: one to bring the telescope and instrument heat sink to 4.5 K, and another to cool parts of two instruments. This paper showed that promising technologies exist to achieve the temperature and cooling load requirements with modest increases in TRL.

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Biographies of the other authors are not available.