



Low-Temperature Cryocooler Status Review

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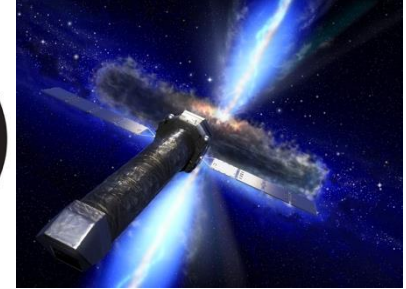
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Low-Temperature Cryocooling Need

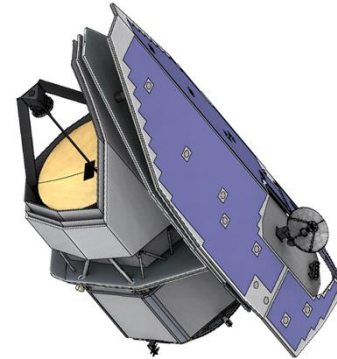
- **Science Applications:** < 4.5 K cooling are critical for X-ray, Far-IR/sub-mm, and CMB observations using high-sensitivity detectors:
 - **Detector Types:** TES, MKID, SNSPD, and silicon-thermistors
- **Mission Context:**
 - **Flight Heritage/Planned:** XRISM (2023), *PRIMA*, *NewAthena*, and *LiteBIRD* (In Development)
 - **Key Requirement:** All necessitate high-performance 4.5 K mechanical precoolers
- **Key Requirements for Mechanical Coolers:**
 - High cooling power: > 50 mW @ 4.5K
 - Ultra-low exported vibrations (specifically below 500 Hz for HWO)



XRISM



NewAthena



PRIMA



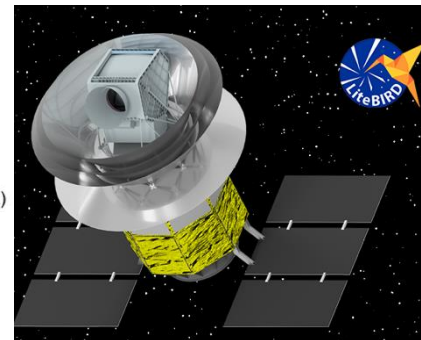
HWO



List of Potential < 10 K Cryocoolers

Vendors	TYPE	Cooling Power	Mass	Input Power	TRL	References
SHI XRISM (2023 –)	JT/Stirling	40 mW @ 4.5 K (EOL for XRISM)	~15 kg for JT Stage	< 90 W _{AC}	9	Sato et. al., 2021
		200 mW @ 20 K for JT precooling only	2 x 9.5 kg for JT cooler (one for redundancy)	< 90 W _{AC}	9	
RAL	JT with Sorption Precooler	19.2 mW @ 4.5 K with precooling at 17.5-19 K	27.7 kg TMU 8.6 kg CCE	120 W _{DC}	9	Ade et al., 2011
NG MIRI (2022 –)	JT/Pulse Tube	> 230 mW at 18 K	48 kg TMU	400 W _{DC}	9	Petach, M. B. and Michaelian 2014 Chen and Moore 2025
		> 60 mW @ 6.2 K (MIRI)	9.5 kg CCE			
		> 49 mW @ 4.5K (PRIMA)	(w/o redundancy)			
SHI LiteBIRD	JT/Stirling	XRISM + 10 mW @ 1.7K	~38 kg for 1.7 JT stage and its precooler	170 W _{AC} for 1.7-5 K stage	5	Shinozaki et al. 2025
Ball Aero. ACTDP	JT/Stirling	75 mW @ 6.2 K and 77 mW at 18 K with compressor input power of 240 W _{AC} (~320 W _{DC})	Data not publicly available		5	Glaister et al., 2014
LM ACTDP	4-stage Pulse Tube	20 mW @ 6K and 150 mW at 18K with compressor input power of 208 W	24.5 kg	208 W _{AC}	5	Olson et al., 2006
Creare	3-stage Reverse Brayton	40 mW @ 4.5 K	33 kg	344 W _{DC}	3	Private Communication
		878 mW @ 25 K; 6.4 W @ 75 K				

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- The diagram illustrates the cryogenic system architecture for the JAXA/SHI experiments. It shows the flow from the ADR driver through various stages (2K-JT, 4K-JT, 2ST) to the coolers, compressors, and drivers. The diagram includes labels for components like JTCH, JTCM, JTCL1, JTCL2, PC, PCD, JTD-2K, JTD-4K, and PCD. It also shows the temperature ranges for each stage: 0.1K, 1.75K, 15K, 20K, and 132K. The diagram is divided into three sections: Multi-stage ADR (CNES/CEA), 2K-JT (JAXA/SHI), and 4K-JT (JAXA/SHI).
- Multi-stage ADR (CNES/CEA)**
- 2K-JT (JAXA/SHI)**
- 4K-JT (JAXA/SHI)**
- 2STs (JAXA/SHI)**



Shinozaki et al. 2025



Development of Other Low-T Flight Cryocoolers

NewAthena Cryocooler

- Cooling Requirement: 50 mW @ 4.5K and 200 mW @ 20 K
 - Remote cooling: 1-m separation distance between cold head's warm interface and the 50 K payload compartment
- Currently in technology maturation phase to demonstrate cooling performance at 4.5 K, largely with vendors participating in NASA's previous ACTDP program

Habitable World Observatory

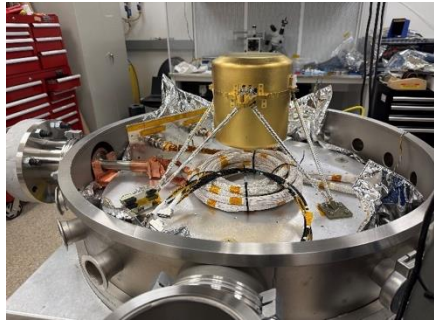
- Assessing whether vibrations exported by an active mechanical cryocooler can be mitigated with advanced technologies to levels acceptable for the instruments
- Key challenge is measuring extremely small exported forces on the order of micro-Newtons, or induced vibrations with amplitudes below 1 nanometer
 - Required an environment with very low seismic background noise

PRIMA Hybrid Cryocooling System

- **Passive Stage:** Radiators and shields for cooling down to 45 K
- **Active Mechanical Stage:** Modified MIRI flight spare using ^3He
 - Capacity: 256 mW @ 16 K | 49 mW @ 4.5 K
- **Sub-Kelvin Stage (GSFC CADR):** 700 μW @ 1.0 K for two instruments and 13 μW @ 0.12 K for cooling six FPAs
- **^3He JT Loop:** Delivers distributed cooling along an ~10-meter loop
- **Payload Mass:** 805 kg (@45K) | 608 kg (@4.5K) | 144.5 kg (@1K)



Test Setup for ^3He JT Stage Cooling Power Demonstration at 4.5 K



PRIMA Observatory with 4.5K Primary Mirror and 0.12 K MKID Detectors





Active Cryocooling Technology Development

Mechanical Coolers

- **Pulse Tube & Stirling:** Optimizing component-level performance and stage-coupling strategies
 - Lightweight coolers providing >50 mW @ 20 K (Input Power < 50 W) for superconducting MgB_2 detectors
 - Efficient 4.5K PT/Stirling coolers, especially with remote cooling capability
- **JT Coolers:** Advancing compressor dynamic center control, high volumetric flow rate, and high-capacity cooling cycles (> 100 mW at 4.5K)
- **Reverse Brayton:** Developing advanced miniature turboexpanders to improve efficiency (< 200 mW @ 4.5 K)

Sub-Kelvin-Cooling

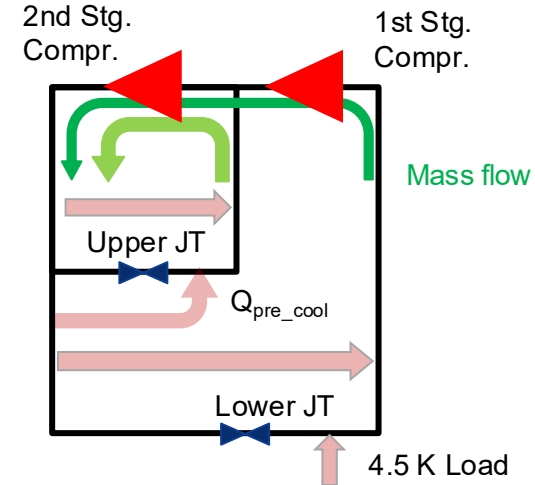
- **ADR:** The current standard for future missions
- **Continuous Dilution:** Early-stage development, leveraging COTS technologies
 - **Balloon-borne (Chase Research):** Utilizing hydrostatic pressure for ^3He recirculation
 - **Spaceborne Roadmap:** Transitioning from open-cycle (Planck) to closed-cycle systems

Control Electronics

- Low-cost 600W-class units for Stirling/Pulse Tube (e.g., Sunpower DS30 by IRIS)

JT Cycle with Shared Compression Stage (SCS)

- **Support Future Missions:** The SCS cycle enables the use of existing flight JT compressors to meet large 4.5 K cooling
- **High Cooling Capacity:** Predicted capacity of 125 mW at 4.5 K with two MIRI JT compressors
- **New Compressor and Precooler Development Required:**
 - Precooling power requirements compatible with existing flight PT cooler
- **Improved Thermal Efficiency:**
 - Reduces compressor power by 33% compared to conventional 2-stage JT cycles
 - Outperforms He-3 JT cycles with a 50% reduction in precooling power (at 17 K) and a 60% reduction in compressor power



JT Cycle with Shared Compression Stage (ICC 24, Chen) 8

Comparison of SCS 2- Stage JT Cooler with Conventional JT Cycles. All with Same Set of MIRI Compressors			
	2-stage SCS JT	Conv. He-4 JT with 2 Compr Stg.	He-3 JT with 2 Parallel Compr.
Lower stage cooling power 4.5 K (mW)	124.92	45.59	100.1
Precooling power at 17 K / Cooling power (W/W)	1.249	1.221	2.46
Total ideal compr. work/cooling power (W/W)	199.8	310.5	490.3

Challenges and Paths Forward

- **The New Bottlenecks:** While performance is now mature, the primary constraints are now cost, delivery schedules, and a dwindling expert workforce
 - **The Knowledge Gap:** Loss of critical skills due to retirements is limiting new low-temperature cooler development
- **The Path Forward: COTS Integration**
 - Leverage existing low-cost COTS components to bypass conventional provider constraints
 - **Proven:** JPL's >8-year success with COTS coolers on ISS payloads
- **Objective:** Build community capability to assemble low-cost 18K coolers and JT compressors using COTS subsystems