Sub-Kelvin Coolers for Space Missions: ADR Development at NASA/GSFC

Dr. Peter Shirron
Cryogenics and Fluids Group, Code 552
Topics

• Science drivers for low temperature cooling
• ADR architectures and cooling capabilities
  – Single-stage ADR
  – Two-stage ADR
  – Astro-H 3-stage
  – Continuous ADR: 5-stage
The Microcalorimeter Arrays are X-ray microcalorimeters designed for thermal detection of individual x-ray photons. They offer:

- High Spectral Resolution
- High Intrinsic quantum efficiency
- Non-dispersive - spectral resolution non affected by source angular size

Arrays have been developed for sounding rocket payload and orbiting observatory:

- XQC
- Astro-E2/XRS
Instrument Trends

XRS2 on Astro-E2
  Launched July 2005
SXS on Astro-H
  Launch in 2013
Con-X ➔ IXO ➔ Athena, AXIO
  32-pixel array at 60 mK
  0.3 µW load
  32-pixel array at 50 mK
  0.3 µW load
  ~1000-pixel array at 50 mK
  2-5 µW load

Increasing need for more capable cooling systems
ADR Essentials

• Solid-state cooler
  – Paramagnetic material
    • “Salt pill”
  – Magnet
  – Heat switch
  – Suspension

• Based on the “magnetocaloric effect”
  – Increasing magnetic field generates heat
  – Decreasing magnetic field generates cooling
Basic (XRS) ADR

Salt pill, heat switch, Suspension, baseplate

Magnet (immersed In liquid helium)

Total mass: 15 kg
Practical Limits

• Single-stage ADR must cool from heat sink to low T

• Typical values
  – Net cooling power: ~0.5 µW
  – Heat sink: 1.3 K
  – Magnetic field: 2 T (2 amps)
  – Refrigerant mass: 1-2 moles
  – Operating T: 50-60 mK
  – Hold time: 24 hours
  – Recycle time: 1 hour

• Trends
  – Higher heat sink T: higher magnetic field
  – Lower operating T: higher magnetic field
  – Higher cooling power/longer hold time: higher magnetic field, more refrigerant, lower parasitics

• Magnet mass grows very rapidly with increased bore volume and increased magnetic field: >>2 T is unpractical

• Bottom line: improved performance ➔ multi-stage ADRs
Two-Stage ADR

- **Series configuration**
  - Upper stage pre-cools lower stage and reduces heat load
- **Upper stage can cool from much higher temperature and have much higher cooling power**

![Graph](chart.png)
• Redundant heat sink for ADR: 1.3 K helium, 4.5 K cryocooler
• 2-stage ADR operates by cascading heat from the detectors to the liquid helium
Astro-H Cryogenic System

- 3rd stage can pump heat from helium tank to JT cooler to extend helium lifetime

Critical Design Review, November 14-16, 2011
Astro-H Cryogenic System

- 1\textsuperscript{st} stage cools detectors from 1.3 K
- 2\textsuperscript{nd} stage maintains helium tank temperature at \textasciitilde1.3 K
- 3\textsuperscript{rd} stage transfers heat to JT cooler
ADR Interfaces - Thermal

Thermal link to JT cooler

Thermal and mechanical interface to helium tank

Thermal link to detectors
EM ADR
AGGHS Design

• Design goals
  – <0.25 mW activation power
  – >100 mW/K on-state conductance
  – Off-state conduction
    • 0.1 µW from 0.5 K to 50 mK
    • 1 µW from 1.3 to 0.5 K

• Key features
  – Getter is located in re-entrant tube assembly
  – Bellows/Vespel support has very low conductance from intermediate heat sink
  – Charcoal getter has direct view of HS interior
  – Mass which must be warmed is kept very low
Heat Switches

• Containment shell made from T300 composite (Composites Group) with 0.5 mil Ti15333 foil liner
  – End flanges epoxied with Scotchweld 2219

• Getter assembly uses indium, e-beam, and braze seals
Hold Time (Cryogen)

- Detector heat load is 0.27 \( \mu \text{W} \)
  - Total heat load is 0.86 \( \mu \text{W} \)
Temperature Stability

- Temperature stability requirement is 2.5 $\mu$K rms
  - Achieving $<0.4$ $\mu$K rms
 Cryogen-Free Operation

- 3rd stage is continually cycled to transfer heat from helium tank to JT cooler

- Cooling power is limited by low thermal conductance of thermal path between stage 2 and helium tank
Cryogen-Free Operation

- Stage 2 builds up cooling capacity
- Periodically recycles Stage 1
Magnetic Fields

- Optimization of Astro-H shield
  - Redistribute mass to minimize dipole moment
    - Reduced shield mass from 2.5 kg to 2.0 kg
- Fields at detector location $\sim 10^{-4}$ T
3-Stage ADR for Athena
3-Stage ADR for Athena

- Designed for 1 µW detector load at 50 mK
- Peak heat rejection rate of 20 mW at 4.5 K
- 15 kg total mass

- Recycle time of <2 hours
- Hold time of >30 hours
- Duty cycle of >94%
Continuous ADR

- Load is cooled by a “continuous” stage
- Other stages work to cascade heat up to the heat sink
  - Number of stages depends on temperature range and heat switch properties
- Cycle time can be short, 20-30 minutes
  - Much shorter heat storage time
  - Order of magnitude less refrigerant needed
- Can add stages to achieve lower $T_{\text{det}}$ or higher $T_{\text{sink}}$
4-Stage Cycling

Temperature (K)

Stage 1

Stage 2

Stage 3

Stage 4

Time (s)

0 1000 2000 3000 4000 5000 6000

20 min
4-Stage CADR

- Uses 4.2 K helium bath
- Total mass of 7.7 kg
- Magnets are fully shielded
- Fully automated operation

Complete in-house GSFC build
5-Stage CADR

- Provides 2 fixed temperatures: 50 mK and 1 K
  - Allows longer heat rejection to cryocooler at lower peak rate

- Improved performance at 50 mK over 4-stage
  - 1 K base temperature reduces radiated and conducted (suspension components, heat switch) loads on cold stages
Cooling Power at “1 K”

- Cycle time is approximately 15 minutes

3-stage load:

5 µW @ 50 mK

+ load from 4 K
1 µW @ 50 mK
5-stage CADR

- Funded by GSFC IRA

Thermal straps
not shown

2 stages cool
continuously
to ~1 K
(~15 minute cycle)
Cryocooled heat
sink at 4-5 K

3 stages cool
continuously
to 50 mK
(~15 min cycle)

1 K shield
not shown
5-stage CADR

- Highest fields away from detectors

- 2 T @ 1.5 A
- 1 T @ 2 A
- 0.1 T @ 0.5 A
- 0.5 T @ 1 A
- 4 T @ 3 A
5-Stage CADR

- Cooling requirements for future x-ray missions are typically:
  - Detector dissipation/wiring: 0.5-2 µW
  - “1 K” load
    - Wire conduction: <0.1 mW
    - Amplifiers: <0.1 mW
- Can reduce mass from current estimate of ~11 kg
- Low peak heat rejection rate (1-2 mW) also allows reduction in cryocooler requirements