WHEN IT ALL STARTED
October 1957

FROM RESEARCH TO INDUSTRY

The New York Times: 
SOVIET FIRES EARTH SATELLITE INTO SPACE; IT IS CIRCLING THE GLOBE AT 18,000 M. P. H. SPHERE TRACKED IN 4 CROSSINGS OVER U.S.

Explorer I
January 1958

Spoutnik

t0: 1957

WHY SPACE?

Earth Observation

50 - 200 K

Planetary Exploration

Scientific Missions

0.05 - 100 K

Cryogenics

• Detectors
• Optics
MAIN MOTIVATION: COOLING OF DETECTORS

<table>
<thead>
<tr>
<th>Photon detectors</th>
<th>Thermal detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming radiation</td>
<td>Interaction with electrons</td>
</tr>
</tbody>
</table>

- Photon detectors: wavelength dependent
  \[ E \rightarrow \Delta I, \Delta V, \Delta R \]
- Thermal detectors: wavelength independent
  \[ E \rightarrow \Delta T \]

- **Photon detectors**
  - CCD
  - Scintillators
  - Ge crystals
- **Thermal detectors**
  - Photo-conductors
  - HEMT
  - Bolometers & Microcalorimeters
  - Ternary alloy
  - Binary alloy
  - Si:X
  - Ge:X

Infrared instruments: largest application of space cryogenics

\[ \text{Incident light produces charge carriers} \]
\[ \text{Thermal fluctuations generates noise} \]

\[ h \nu > \Delta E \]

\[ \Delta E \]

\[ E \rightarrow \Delta T \]
EARTH OBSERVATION: WEATHER SATELLITE

Meteosat 2G
EARTH OBSERVATION: WEATHER SATELLITE MTG

2 instruments
IRS: Infrared Michelson Interferometer
FCI: High spatial and spectral resolution imagery

55 K and 60 K needed
(photoconductors HgCdTe)
MARS SCIENCE LABORATORY (MSL)

Launched Nov. 2011
Trip: 8 months (570 \(10^6\) km)
Landed Aug. 2012
Lifetime: 22 months

Curiosity
Mass \(\approx 900\) kg

Has life ever existed out there?
Chemistry and Mineralology (CheMin): CheMin is a mineralogy instrument, onboard MSL, that identifies and quantifies the minerals present in rocks and soil delivered to it by the Sample Acquisition, Sample Processing and Handling (SA/SPaH) system. The Ricor K508 rotary cooler provides cooling to CCD at ~210K with a lifetime requirement of 1600hrs for surface operations.
SCIENTIFIC MISSIONS

M31 Andromeda
M31 Andromeda
Access to extended spectrum
How to measure those very faint signals?

Thermal detector: Bolometer

\[ \Delta T = \frac{E}{mC} \]

\[ \tau = R_{th}C = \frac{C}{K} \]

Measurable \( \Delta T \) ?  
Minimize \( C \)  
Low Temperature
How to measure those very faint signals?

Thermal detector: Bolometer

Transition Edge Sensor (TES)

Measurable $\Delta T$ ? Minimize

$K = \frac{\Delta T}{C} \tau = R_{th}$

small change in $T$
big change in $R$
SPACE ENVIRONMENT: CONSTRAINTS

1. Survive launch

2. Mass, power to be minimized

3. Operation in free fall

4. Reliability: 1500 000 km

5. Lifetime: (> 5 ans)

No moving parts or absence of any friction
IS IT COLD OUT THERE?

Ozone absorbs UV and T stabilizes and then increases.

Ozone concentration decreases and so does T.

Recombination of molecular O2.

Expansion of warm air from the ground.

Everest

Cumulonimbus

Cirrus

Ozone

Balloon

Stratosphere

Mesosphere

Thermosphere

Ionosphere

Geostationary satellite

36000 km

0 - 5 - 10 - 20 - 40 - 50 - 85 - 36000 km

-90 -50 0 T (°C)
IS IT COLD OUT THERE?

- Geostationary satellite
- IONOSPHERE (3600 km)
- THERMOSPHERE
- MESOSPHERE
- STRATOSPHERE
- TROPOSHERE
- Everest
- Balloon
- Ozone
- Cirrus
- Auroral borealis

Temperature:
- ≈ 6000 K (Sun)
- ≈ 293 K (Earth)
- ≈ 20 K (Stratosphere)
- ≈ 30-40 K (Troposphere)
- ≈ 2.7 K (Geostationary satellite)
SPACE: NATURAL RESOURCES

Radiative heat transfert (deep space @ 2.7 K)

Solar photons

≈ High Vacuum
SPACE COOLING CHAINS

Reliability

No moving parts or absence of friction

"Ultra" low T coolers
(3 technologies: sorption, magnetic, dilution)

Active "mechanical" coolers

Stored cryogen (Cryostat)

Passive Radiators
SPACE CRYOGENICS - CURRENT GENERAL TENDENCY

Extended mission
Cryogens Coolers

Higher and farther
Engines & μGravity
Zero boil off

Colder
50 mK

Mass
Thermal links
Stability & T control
I CANNOT BE EXHAUSTIVE - SORRY
SPACE COOLING CHAINS

0.01 K  0.1 K  1 K  10 K  100 K  300 K

- Passive Radiators
- Stored cryogen (Cryostat)
- Active "mechanical" coolers
- "Ultra" low T coolers
  (3 technologies: sorption, magnetic, dilution)

* Efficient
* Simple
* Reliable
* Vibration free

* Limited performance @ low T
* Orbit / orientation dependent
RADIATIVE COOLING

Direct coupling to deep space via thermal self emission

\[ Q_{\text{Space}} = Q_{\text{Dissip}} + Q_{\text{Losses}} \]

\[ Q_{\text{Space}} = \varepsilon \cdot \text{A.F.} \cdot \sigma \cdot (T^4 - T_{s}^4) \approx \varepsilon \cdot \text{A.F.} \cdot \sigma \cdot T^4 \]

- \( \sigma = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4} \)
- \( F \approx 1 \) (form factor)
- \( \varepsilon \approx 0.9 \) to 1 (black paint, open honeycomb)
Direct coupling to deep space via thermal self emission

\[ Q_{\text{Space}} = Q_{\text{Dissip}} + Q_{\text{Losses}} \]

\[ Q_{\text{Space}} = \varepsilon A F \sigma (T^4 - T_s^4) \approx \varepsilon A F \sigma T^4 \]

\( \sigma = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4} \)

\( F \approx 1 \) (form factor)

\( \varepsilon \approx 0.9 \) to 1 (black paint, open honey comb)
EXAMPLE METEOSAT 2 GENERATION

Two stages
85 K - 95 K
≈ 120 K
MLI / V-GROOVES - HERSCHEL / PLANCK

“Classical”
MLI: radiation trapped between layers

Radiator
n layers

Equivalent emissivity: \( \varepsilon/n \)

Warm 300 K

≈ 70 K

≈ 70 K

88 K

293 K

MLI / V-GROOVES - HERSCHEL / PLANCK

“V-Grooves”

Radiator

Radiation rejected to space

Equivalent emissivity: \( \varepsilon^n \)

Warm 300 K

50 K

100 K

140 K

300 K Service Module

Telescope 50 K

50 K
SPACE COOLING CHAINS

- Passive Radiators
- Stored cryogen (Cryostat)
- Active "mechanical" coolers
  - "Ultra" low T coolers
    (3 technologies: sorption, magnetic, dilution)

- Efficient
- Simple
- Reliable
- Cold vapor

- Limited mission duration
- only selected T available
- Volume & Mass
- On ground management
LOW TEMPERATURE MISSIONS WITH STORED CRYOGENS (4K OR LESS)

- IRAS (1983)
- COBE (1989)
- ISO (1995)
- ASTRO-E (2000)
- Gravity Probe B (2005)
- SPITZER (2009)
- SUZAKU (2009)
- HERSCHEL (2009)
Telescope passively cooled to ≈ 80 K
He cold vapor loop

$L_0 \approx 1.7 \text{ K}$

$L_1 \approx 4 \text{ K}$

$L_2 \approx 10 \text{ K}$

Helium tank

($\approx 2400 \text{ l}$)

Instruments

HERSCHEL CRYOGENIC CHAIN - 2
He cold vapor loop

Helium tank ($\approx 2400$ l)

$L_0 \approx 1.7$ K

$L_1 \approx 4$ K

$L_2 \approx 10$ K

Parasitics $40$ mW

Superfluid helium tank

$L_0 \approx 1.6$ K

PACS

$300$ mK

$25$ mW

SPIRE

$300$ mK

HIFI

$15$ mW

$L_3 \approx 15$ K

To space $\approx 2.3$ mg/s

Optical Bench Plate

L0

$L_0 \approx 10$ mW

$50$ mW

$15$ mW

$12$ K

$15$ K

$12$ K
SPACE COOLING CHAINS

0.01 K  0.1 K  1 K  10 K  100 K  300 K

- Passive Radiators
- Stored cryogen (Cryostat)
- Active "mechanical" coolers
- "Ultra" low T coolers
  (3 technologies: sorption, magnetic, dilution)

- Lifetime
- Warm launch
- Ground tests

- Peak power
- Thermal interfaces
- Vibration
SPACE CRYOGENICS: CURRENT TENDENCY

- Thermal interface
- Peak Power
- Distribution (vapor)
- Vibration free
- Passive (once in space)

- Limited lifetime
- Volume
- Mass
- On ground management
  - Vacuum shell needed

He cold vapor loop

Superfluid helium tank

Instruments
SPACE CRYOGENICS: CURRENT TENDENCY

He cold vapor loop

Superfluid helium tank

Instruments
SPACE CRYOGENICS: CURRENT TENDENCY

- Lifetime
- Volume
- Ground tests
- Warm launch

- Heat distribution
- Interface
- Vibration
- Thermal peak power
ONLY THE BEST: MYTHICAL CARNOT CYCLE

Example
300 K - 60 K cooler

Carnot cycle pressure ratio $\frac{3}{4} \approx 120$ !!
ONLY THE BEST: MYTHICAL CARNOT CYCLE

Example
300 K - 60 K cooler

Carnot cycle
pressure ratio \( \frac{\theta}{\delta} \approx 120 \)

In theory, COP \( \approx \) Carnot

Isentropic evolution

Isochoric (Stirling)

Isobaric (Ericsson, GM)

heat transfer at variable \( T \)

Regenerator (thermal sponge) or counter flow heat exchanger

heat extracted at \( T_{\text{cold}} \)
(MOST) MECHANICAL CRYOCOOLERS

Expansion of maximum amount of gas at the right place and right time

Mass flow rate & pressure oscillation in phase
**STIRLING VERSUS PULSE TUBE**

- **High efficiency**
- **Low induced vibration**
- **Robust / Ease of integration**

**Phase shift mechanically controlled**

**Displacer**

**Pressure oscillator**

**Regenerator**

**Cold spot**

**Buffer volume**

**Inertance**

**Tube**

**Phase shift pneumatically controlled**
STIRLING VERSUS PULSE TUBE

**Stirling**

**Pulse Tube**

**Buffer volume**

**Source:** ICEC 25 / ICMC 2014 - Lionel Duband, Univ. Grenoble Alpes, CEA-INAC-SBT, F-38000 Grenoble - July 2014
High Frequency (≈ > 30 Hz)

Motion without friction (≈)

No Maintenance

Key Concept

The precursor
80K Single Stage Stirling

So called "Oxford type"
Overall:

- Mature technology
- High Technical Readiness Level (TRL)
- Several thousands of hours in operation in orbit

Original BAe 50-80 K cooler: currently 23 in orbit, 177 years accumulated in orbit,
AIRS PT: over 12 years of operation

On going: Multi stage, low T system, Miniature cooler, high frequency
SENTINEL 3: OCEAN & GLOBAL LAND MONITORING

Main satellite characteristics
• 1250 kg maximal mass
• 3.89 m x 2.202 m x 2.207 m
• Average power consumption of 1100 W
• 7.5 years lifetime (fuel for 5 add. years)

Scheduled to launch mid 2015

1.5 W @ 80 K with 80 W input
50 K Single Stage

2.3 W @ 50 K
160 W input
5.1 Kg

Also used in CSO program

5 W @ 80 K
2 W @ 50 K

S/N003
S/N004
S/N005

Cooling power (W)
Cold tip Temperature (K)

160 W AC input
10°C warm end

“High costs”: Full space qualification, Maximum performance.

- In line with ESA standards, adherence to ESA/NASA guidelines

“Low costs”: Reliability is important, High price level not affordable.

- Products based on normal definition and production standards
- Special but limited screening of parts / products
- Extra burn-in to avoid infant mortality

Cost effective solution: Reliability is key, No extreme performance.

- Design based on existing / proven definitions
- Extra but limited effort on parts and processes (based on risk assessment)
- Extensive screening of subassemblies / final products
LOW TEMPERATURE MULTISTAGE PULSE TUBE

300 mW @ 15 K

ATHENA Mission

4 K Pulse Tube

20 K Pre-cooling stage

4 K PT

3.86 K reached June 2014!

15 mW @ 4.5 K
CAN'T BE EXHAUSTIVE - MANY SUPPLIERS!

685W Compressor Input Power
5.5 W cooling at 68 K

4th Stage Cooling Power (mW)
4th Stage Temperature (K)

16 mW @ 1.69K
PULSE TUBE MICROCRYOCOOLER

Low SWaP (Size, Weight and Power)

690 mW @ 150 K
10 W input
100 Hz
compressor Ø32 x 90 mm
Cold finger Ø42 x 110 mm
Mass: 328 gr (comp. 210, CF 118)

Could be used in the NASA MatISSE program
(Maturation of Instruments for Solar System Exploration)
LOWER TEMPERATURE OR VIBRATION LESS: JOULE THOMSON SYSTEM

Direct benefit from heritage (flexure spring)
JOULE THOMSON LOOP

ISENTHALPIC EXPANSION

Helium: $T \approx 40 \text{ K}$

Maximum inversion temperature

Pressure

Temperature

Cooling effect

Heating effect !!

Compressor (Pressure oscillator)

Heat Exchanger

Counter flow heat Exchanger

Throttle valve

Heat Exchanger

LP

HP

ISENTHALPIC EXPANSION
4K JT SYSTEM - PLANCK

- JT Orifice
- 4K Stage
- 18K Stage
- 50K stage
- 4K cooling (~19mW)
- Rejection to Sorption Cooler (~45mW)
- Rejection to Radiators (~80mW)

4K Cooler total electrical input power (~110W)

Cooler Drive Electronics & Pre-charge Regulator

JT Compressors
Ancillary Panel
SVM Pipework (warm)
PLM Heat Exchangers (cold)
4K JT SYSTEM - PLANCK

RAL - Astrium 4K JT Loop onboard PLANCK (HFI Instrument)
ADVANCED 2 K COOLER PROGRAM

Objective of 20 mW @ 2 K

Cooler layout 4 stage Compressor

Heat Exchangers

ATHENA Mission

Possible application
JT SYSTEM - JAXA (ASTRO-F, SPICA, ...)

JT compressors
(4 stages: 8 kPa to 0.7 MPa)
(ratio 87)

Prototype cooler

EM unit (with 4 compressors) under fabrication
(SPICA/SAFARI mission)

16 mW @ 1.7 K with 160 W input
VIBRATIONLESS ? ALTERNATIVE COMPRESSOR

1 order of magnitude in T
8 orders of magnitude in P

No mechanical equivalent (in 1 stage)
JOULE THOMSON WITH SORPTION COMPRESSOR

Amount of gas adsorbed vs. Pressure and Temperature diagram.

High Pressure

Low P.

Temperature

Pressure

HELIUM & HYDROGEN JT COOLER - VIBRATION FREE

Heat sink
sorption cell

check valves

high pressure buffer

low pressure buffer

p_H
Q
p_L

cold stage

4.5 K helium cooler (ICC14, 2006)

14.5 K hydrogen cooler (ICC17, 2012)
Typical results (Lab prototype)

4.5 mW @ 4.5 K

T stability ≈ 1 mK

cold tip temperature stabilized by PID controller and heater
9 grams of carbon

flat-to-flat seal
3 bar to 0.1 bar

flap: Au layer 10 µm

knife-edge seal
50 bar to 3 bar

SMALL IS BEAUTIFUL
SPACE COOLING CHAINS

0.01 K  0.1 K  1 K  10 K  100 K  300 K

"Ultra" low T coolers

Active "mechanical" coolers

Stored cryogen (Cryostat)

Passive Radiators
PAST (LAST DECADE) & FUTURE SUBKELVIN MISSIONS

- **ASTRO E2 (SUZAKU)**: 0.3 µW @ 60 mK
- **PLANCK**: 0.2 µW @ 100 mK
- **HERSCHEL**: 10 µW @ 290 mK
- **ATHENA**: TBC: 1.2 µW @ 50 mK
- **SPICA**: TBC: 1.2 µW @ 50 mK
- **HERSCHELPLANCK**: 0.3 µW @ 60 mK
- **ASTRO H**: TBC: 1.2 µW @ 50 mK

Missions:
- **ASTRO E2 (SUZAKU)**: 2009-2013
- **HERSCHEL**: 2009-2013
- **ATHENA**: TBC: 2028
- **SPICA**: TBC: 2032

Temperature ranges:
- 10 mK
- 100 mK
- 1 K

Energy levels:
- 0.5 µW @ 50 mK
- 14 µW @ 300 mK

Only 3 (4) options

- Evaporative (+ sorption)
- Dilution
- Adiabatic demagnetization (ADR)
- Evaporative + ADR

Typical combination: 80 K and 15-20 K
Evaporative cooling

![Graph showing saturated vapour pressure versus temperature for Helium 3 and Helium 4, with a temperature difference of 400 mK.](image)

- **Temperature (K):** 300, 100, 10, 1, 0.2
- **Saturated vapour pressure (Torr):** 10^3, 10^2, 10^1, 10^0, 10^-1, 10^-2, 10^-3, 10^-4

- **Helium 3**
- **Helium 4**

- **Temperature markers:**
  - 300 K
  - 100 K
  - 10 K
  - 1 K
  - 0.2 K

- **Temperature ranges:**
  - 15-20 K
  - 80 K

**3HE EVAPORATIVE COOLING**
HELIUM EVAPORATIVE COOLING

Helium 4

Helium 3

\[ T_{\text{critical}} \]

\[ \Delta T = 400 \text{ mK} \]

Saturated vapour pressure (Torr)

Temperature (K)

P

T

Condensation

Cooldown (evaporation)

Low T phase (evaporation)

Heatsink \( T \leq T_c \)

Main sorption pump

Helium Sorption stage

Evaporator

HS2

HS1

300 mK

Pumping line

HS: Heat Switch

HERSCHEL

SPIRE Sorption unit

Two units (SPIRE and PACS Instruments)
3.8 years in orbit at L2
3He SORPTION COOLER: ULTIMATE T ?

In practice
Multistage system
(\(^4\)He, \(^3\)He, \(^3\)He)
Ground based
Dilution Cooler

- 50 mK
- 100 mK
- 1 K
- 10 K
- 100 K
- 300 K
- 80 K
- 15-20 K

Dilution stages:
- 4 K stage
- 1.6 K
- 300 mK

Components:
- Mixing chamber
- Joule-Thomson throttle valve
Gravity dependent
DILUTION

Gravity dependent

- Can be operated from a 4 K heat sink
- Cooling P @ T ultimate
  + available cooling continuously from 4K down to T ultim.
PLANCK DILUTION COOLER

200 nW @ 100 mK

continuous cooling
from 1.6 K ($\approx 8 \mu W$)

Open cycle:
Lifetime limited
$\approx 2$ years mission

---

Isotope Supply Unit

- Pre-cooling circuitry
- Filling & venting panel
- Gas Storage Unit (295 b)
- DCP
- SVM
- PPLM

> Control electronics, valve & Pressure reduction, and P measurement panel

Dilution Cooler Electronics
Latest result:
1 µW @ 51 mK (liquid T !)

CONTINUOUS DILUTION COOLER

Circulate the $^3$He

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Compressor (JAXA + SHI)</th>
<th>Sorption Compressor (COOL + U.Twente)</th>
<th>Holweck Compressor (CNRS + AL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio</td>
<td>5.4mb/140mb (@17µmol/s)</td>
<td>5mb/200mb (@20µmol/s)</td>
<td>5mb/200mb (@20µmol/s)</td>
</tr>
<tr>
<td>Input Power (no margin)</td>
<td>&lt;80W</td>
<td>~10W@300K (estimated)</td>
<td>~100W@300K (estimated)</td>
</tr>
<tr>
<td>Mass (without electronics &amp; margin)</td>
<td>~20kg</td>
<td>~2.2kg</td>
<td>~2kg</td>
</tr>
<tr>
<td>Heat lift below 300K</td>
<td>None</td>
<td>~80mW@15K</td>
<td>None</td>
</tr>
<tr>
<td>Heritage</td>
<td>Based on 1K-Class JT Cooler EM compressors</td>
<td>Based on the 4K JT Sorption Cooler EM for Darwin</td>
<td>No space heritage except for gas bearings (MELFI)</td>
</tr>
<tr>
<td>Dev. Status</td>
<td>BBM under assembly</td>
<td>Check valves demonstrated</td>
<td>Compression ratio demonstrated</td>
</tr>
<tr>
<td>Next development steps</td>
<td>BBM evaluation</td>
<td>15K demonstrator</td>
<td>Demonstrate gas bearings</td>
</tr>
</tbody>
</table>
ADIABATIC DEMAGNETIZATION

Magnetic cooling

Temperature range:
- 50 mK
- 100 mK
- 1 K
- 10 K
- 100 K
- 300 K

Cooling stages:
- 80 K
- 15-20 K
ADIABATIC DEMAGNETIZATION

Detectors

Paramagnetic salt

Coil

Heat switch

Heat sink

H=0 T

Detectors

Paramagnetic salt

Coil

Heat switch

Heat sink

H=0 T

ADIABATIC DEMAGNETIZATION

FROM RESEARCH TO INDUSTRY

GRENOBLE

RAPID RECYCLING TANDEM ADR (CONTINUOUS)

- Tandem magnetic refrigerators
- Utilizes two magnetic cooling chains
- Provides continuous cooling
- Magnets are shielded
- Single thermal interface (4 K or lower)

Preliminary results on single stage

200 mK - 4 K:
Recycling time ≈ 2.5 minutes
(4K to 170 mK in 30 sec.)

Next step

Estimated base operating T:
80 mK from 4 K
50 mK when operated from 2 K

H 355 x  W 120 x D 56 mm
8.3 kg

Predicted cooling powers
based on hold time of 10 minutes
and operated from 4 K:
1 µW at 80 mK
5 µW at 100 mK
41 µW at 300 mK
ASTRO E2 (SUZAKU) ADR & CADR

60 mK reached on orbit!
Lowest T of (known) universe

Continuous ADR

Load is directly cooled by one stage
Upper stages cascade heat to the heat sink

First stage
-0.05 K
Superconducting (Tin) HS

Second stage
-0.045-0.3 K
Active Gas-Gap HS

Third stage
-0.25-1.3 K
Passive Gas-Gap HS

Fourth stage
-1.2-6+ K
Ferromagnetic Shields

6-10 K mechanical cooler

Continuous operation
High cooling power
Capable of rejecting heat at 6+ K
Requires development of Nb3Sn magnets

Continuous operation
High cooling power
Capable of rejecting heat at 6+ K
Requires development of Nb3Sn magnets
ASTRO-H: 3 STAGES ADR

First stage
47 mK (0.8 K)  

Second stage
0.5 K (1.5 K)  

Third stage
1.2 K (4.7 K)  

Dewar (1.3 K)

HS1  

HS2  

HS3  

HS4

Active Gas-Gap Heat Switch

4.5 K JT Cryocooler

Dewar

Detectors

NbTi magnet

Refrigerant "salt pill"

Hybrid cooler: combination of a 300 mK sorption and miniature ADR stages
TWO EM MODEL DEVELOPED

ESA TRP (IXO/ATHENA)
To specifications

123 x 185 x 300 mm

10 µW @ 300 mK
(37 hours)

5846 gr

1 µW @ 50 mK
(34 hours)

Infrared astronomy mission ≈ 5 - 210 µm
New framework and schedule
Launch date ≈ 2026

Mission being re-optimized
(M4 selection)
TWO EM MODEL DEVELOPED

ESA TRP (IXO/ATHENA)
To specifications

123 x 185 x 300 mm
5846 gr

10 µW @ 300 mK (37 hours)
1 µW @ 50 mK (34 hours)

X-IFU Instrument
Focal Plane Assembly

50 mK TES sensor array

ATHENA
THE ASTROPHYSICS OF THE HOT AND ENERGETIC UNIVERSE
Europe’s next generation X-RAY OBSERVATORY

Distance to detectors could be meters
Temperature stability
Induced vibrations
Absorption of peak powers
Temperature gradient
On ground management (time constant)
Space Dynamics Laboratory (SDL) has the facilities and experience to meet the most stringent link requirements. SDL thermal links have been selected for NASA’s JWST program. Full support services include thermal and dynamic testing and certification at cryogenic temperatures.

**SDL’s Flexible Thermal Links**
- **Eliminate**: Jointing materials including solder
- **Internal contact resistance**
- **Wicking into braid/foil**
- **Outgassing**
- **Maximize**: Thermal conductance
- **Dynamic/mechanical flexibility**
- **Provide**: High Performance
- **Affordable Solutions**

---

**SPECIFICATIONS**

- **CONDUCTANCE**: 0.01 - 10W/K
- **STIFFNESS**: Typically < 1 N/mm all axes
  - (flexibility)
- **MASS**: 5g - 10kg
- **MATERIAL**: Copper, Aluminum, etc.
- **TYPE**: Foil or Braid
- **TRANSFER LENGTHS**: 2mm - 2m

---

**≈ Simple but not easy to make**

**On-going activities in the frame of CSO and MTG**

**CSO**: 2 sets of FMs delivered
**MTG**: 6 sets delivered

**99.999% AL**
- High flexibility in all direction (< 5N/mm)
- High K: >1W/K @ 80K
- Mass < 100g for complete thermal link

**99.99% OFHC**
- High flexibility in all direction (< 0.5N/mm)
- High K: >0.5W/K @ 300K
- Mass < 350g for complete thermal link
**HEAT PIPE & PHP**

**Heat pipe**

80 mW/K ! @ 3.4 K

3.8 W/K @ T ≈ 80 K
60 cm long

≈ 25 kg of copper (RRR 100)

**Condenser (cooler side)**

**Evaporator (detector side)**

**Loop heat pipe**

600 mW/K ! @ 1.7 K

120 g, 1.2 m Heat pipe (SHe)

Also tested @ 0.7 K

**Pulsated heat pipe (PHP)**

400 mW/K ! @ 4.2 K

Sustained oscillations of liquid plugs and bubbles

**PHP**

Liquid
Gas

Heat Transfer
Fluid circulation

Evaporator
Condenser

**Superfluid heat pipe**

600 mW/K ! @ 1.7 K

120 g, 1.2 m Heat pipe (SHe)

Also tested @ 0.7 K
ANCILLARY EQUIPMENT: HEAT SWITCH

Most commonly used: Gas Gap Heat Switch

**PLANCK Helium gas gap heat switch**

- **Flight and Spare Models (HS1 & HS4)**
- **Thermal performance - ON and OFF position**
- **First, second and third set of test**
- **Switch interface : 4.2K**

**Switch hot end (K)**

- **Applied load (mW)**
- **Flights and Spare Models (HS1 & HS4)**
- **Hydrogen \( \approx 20 \text{ K} - 60 \text{ K} \)**
- **100 mW/K @ 20K**

**Other geometry (NASA Goddard)**
Magnetoresistive heat switch made from tungsten
Works by the slowing down of electrons in a metal due to a tangential magnetic field

- Instantaneous switching – limited by speed of generating the magnetic field, currently 30 seconds to go from 0 to 2 Tesla
- High thermal conductivity 200 W/cm/K
- High switching ratio $\sim 10^4$ (related to the magnetic field)
Several applications

- Attenuate temperature oscillations
- Absorbs peak power (then energy dumped over longer period)
- cooler turned OFF: provides stable operation for a limited time

Example of Thermal Buffers:

- Liquid-Gas Hydrogen
  400 J between 15 and 16 K
  V ≈ 20 cm³

- Liquid-Gas Neon
  1000 J at 40 K ±/− 50 mK
  2000 J between 38 and 40 K
  35 cm³
These systems will deliver what the community needs: better access to cold in space. But you know what will happen. Scientists will develop better detectors, and demand lower temperature, longer mission lifetimes, lower cost, mass, size, etc. We should hope for no less. That’s what will keep space cryogenics as exciting and relevant into the next 50 years as it has been over the last.