Dilution Refrigerator Status

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Core and Beyond – 2012-06-26
Outline

- why closed cycle dilution refrigerator?
- CORE cryogenic requirements?
- overview closed cycle dilution refrigerator
- optimization $\Rightarrow$ still $\Rightarrow$ pump requirements
- option for pumps
- still and vapor liquid phase separation
- conclusion: status summary
### Scaling the Planck dilution refrigerator

<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Temperature</th>
<th>Cooling Power</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009: Planck</td>
<td>(CMB)</td>
<td>100 mK</td>
<td>200 nW</td>
<td>2 years</td>
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<td>2019: SPICA</td>
<td>and/or Athena</td>
<td>50 mK</td>
<td>1 µW</td>
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#### Helium Flowrates
- **2009: Planck (CMB)**
  - $3 \text{ He } 6 \text{ µmols}^{-1}$
  - $4 \text{ He } 18 \text{ µmols}^{-1}$
- **2019: SPICA and/or Athena**
  - $3 \text{ He } 12 \text{ m}^3 \text{stp}$
  - $4 \text{ He } 36 \text{ m}^3 \text{stp}$

#### Storage on Satellite
- **2009: Planck (CMB)**
  - $3 \text{ He } 90 \text{ m}^3 \text{stp}$
  - $4 \text{ He } 180 \text{ m}^3 \text{stp}$
- **2019: SPICA and/or Athena**
  - $3 \text{ He } 90 \text{ m}^3 \text{stp}$
  - $4 \text{ He } 180 \text{ m}^3 \text{stp}$

Too costly, too heavy, and too big $\Rightarrow$ closed cycle is required!
Scaling the Planck dilution refrigerator

2009: Planck (CMB)
- temperature: 100 mK
- cooling power: 200 nW
- lifetime: 2 years
- helium flowrates:
  - $^3\text{He}$ 6 µmol s$^{-1}$
  - $^4\text{He}$ 18 µmol s$^{-1}$

2019: SPICA and/or Athena
- temperature: 50 mK
- cooling power: 1 µW
- lifetime: 5 years
- helium flowrates:
  - $^3\text{He}$ 18 µmol s$^{-1}$
  - $^4\text{He}$ 360 µmol s$^{-1}$

Vermeulen, Volpe, Camus, Benoit, Triqueneaux, Tirolien, d'Escrivà

Dilution Refrigerator Status
Scaling the Planck dilution refrigerator

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too costly, too heavy, and too big $\Rightarrow$ closed cycle is required!
CORE requirements?

- fit into Planck cooling chain
- $T = 0.1 \text{ K}$
- $\dot{Q}_{\text{lift}}$?
CORE requirements

- fit into Planck cooling chain
- $T = 0.1\,K$
- $\dot{Q}_{\text{lift}}$?

$\dot{Q}_{\text{lift}}$

- design of our system: $\dot{Q}_{\text{lift}} \geq 5\,\mu W$ at $T = 0.1\,K$
- smaller $\dot{Q}_{\text{lift}}$ has a favorable system impact
  - lighter cooling chain
  - smaller pumps
Overview closed-cycle dilution refrigerator

Planck: open cycle dilution refrigerator

- \( \dot{n}_3 = 6 \, \mu\text{mol s}^{-1} \)
- \( \dot{n}_4 = 18 \, \mu\text{mol s}^{-1} \)
- mixture exit JT cooler \( \Rightarrow 1.5 \, \text{K} \)
- precooler: 10 mW at 4.5 K
Overview closed-cycle dilution refrigerator

Heat exchanger (HX)

3-tube HX ↔ 2-tube HX || superleak (SL)

Vermeulen, Volpe, Camus, Benoit, Triqueneaux, Tirolien, d'Escriv
Overview closed-cycle dilution refrigerator

Heat exchanger (HX)
3-tube HX ⇔ 2-tube HX || superleak (SL)

Still with vapor-liquid phase separator
making progress, but not yet working

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Overview closed-cycle dilution refrigerator

Heat exchanger (HX)
3-tube HX ⇔ 2-tube HX || superleak (SL)

$^4$He circulation: fountain pump (FP)

$n_4 \approx 400 \mu \text{mol/s for } Q_{fp} = 3.5 \text{ mW and } T = 2.1 \text{ K}$
Overview closed-cycle dilution refrigerator

Heat exchanger (HX)
3-tube HX ⇔ 2-tube HX || superleak (SL)

He circulation: fountain pump (FP)
\[ \dot{n}_4 \approx 400 \mu\text{mol/s for } \dot{Q}_{fp} = 3.5 \text{ mW and } T = 2.1 \text{ K} \]

He circulation: pumps under development
\[ \dot{n}_3 \text{ from } 20 \mu\text{mol s}^{-1} \text{ to } 60 \mu\text{mol s}^{-1} \text{ for } p_{\text{still}} \text{ from } 0.3 \text{ mbar to } 15 \text{ mbar} \]

Precooling heat load \( \approx 6 \text{ mW at } T = 1.7 \text{ K} \)

Vermeulen, Volpe, Camus, Benoit, Triqueneaux, Tirolien, d'Escriv
Overview closed-cycle dilution refrigerator

Heat exchanger (HX)
3-tube HX $\Leftrightarrow$ 2-tube HX $\parallel$ superleak (SL)

$^4$He circulation: fountain pump (FP)
\[ \dot{n}_4 \approx 400 \, \mu\text{mol/s} \text{ for } \dot{Q}_{fp} = 3.5 \, \text{mW} \text{ and } T = 2.1 \, \text{K} \]

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Precooling
heat load $\approx 6 \, \text{mW} \text{ at } T = 1.7 \, \text{K}$
Overview closed-cycle dilution refrigerator

$T < 50 \text{ mK}$

$T = 1.0 \text{ K}$

$T = 1.5 \text{ K}$

$T = 100 \text{ mK}$
OCDR (Planck) versus CCDR (CORE?)

**OCDR (Planck)**
- **fridge:** $\dot{Q} = 200 \text{ nW at } T = 100 \text{ mK during 2 years}$

**CCDR (CORE?)**
- **fridge:** $\dot{Q} > 5 \mu\text{W at } T = 100 \text{ mK for 5 years}$
OCDR (Planck) versus CCDR (CORE?)

**OCDR (Planck)**
- fridge: $\dot{Q} = 200 \text{ nW}$ at $T = 100 \text{ mK}$ during 2 years
- precooler: $\dot{Q} = 10 \text{ mW}$ at $T = 4.5 \text{ K}$

**CCDR (CORE?)**
- fridge: $\dot{Q} > 5 \text{ µW}$ at $T = 100 \text{ mK}$ for 5 years
- precooler: $\dot{Q} = 6 \text{ mW}$ at $T = 1.7 \text{ K}$ (OK on SPICA?)

Vermeulen, Volpe, Camus, Benoit, Triqueneaux, Tirolien, d'Escriv
OCDR (Planck) versus CCDR (CORE?)

**OCDR (Planck)**
- fridge: \( \dot{Q} = 200 \text{nW at } T = 100 \text{ mK during 2 years} \)
- precooler: \( \dot{Q} = 10 \text{ mW at } T = 4.5 \text{ K} \)
- He circulation:
  - space

**CCDR (CORE?)**
- fridge: \( \dot{Q} > 5 \mu \text{W at } T = 100 \text{ mK for 5 years} \)
- precooler: \( \dot{Q} = 6 \text{ mW at } T = 1.7 \text{ K (OK on SPICA?)} \)
- He circulation:
  - \(^3\text{He pump at } T = 15 \text{ K or } T = 300 \text{ K} \)
  - \(^4\text{He pump at } T = 2.1 \text{ K} \)
Thermal model for low temperature part

Thermal model is design guide

- Enthalpy $\propto T^2$
  - old $\dot{Q}/\dot{n}_4 T^2 = 5.7 \text{ J/mol/K}^2$
  - new $\dot{Q}/\dot{n}_4 T^2 \approx 3.0 \text{ J/mol/K}^2$

$\dot{Q}_{mco} = \dot{Q}_{detector}$
Thermal model for low temperature part

Thermal model is design guide

- Enthalpy \( \propto T^2 \)
  - old \( \frac{\dot{Q}}{\dot{n}_4} T^2 = 5.7 \text{ J/mol/K}^2 \)
  - new \( \frac{\dot{Q}}{\dot{n}_4} T^2 \approx 3.0 \text{ J/mol/K}^2 \)

- Viscous dissipation \( \propto \frac{1}{T^2} \)
  - \( \dot{q}_{3,\text{visc}}^0 \) of pure liquid \(^3\text{He}\)
  - \( \dot{q}_{m,\text{visc}} \) averaged over coexisting pure and dilute phases
Thermal model for low temperature part

Thermal model is design guide

- Enthalpy \( \propto T^2 \)
  
  \[
  \frac{\dot{Q}}{\dot{n}_4 T^2} = 5.7 \text{ J/mol/K} \\
  \text{new} \quad \frac{\dot{Q}}{\dot{n}_4 T^2} \approx 3.0 \text{ J/mol/K} 
  \]

- Viscous dissipation \( \propto 1/T^2 \)
  
  \[
  \dot{q}_{3,\text{visc}}^0 \text{ of pure liquid } ^3\text{He} \\
  \dot{q}_{m,\text{visc}} \text{ averaged over coexisting pure and dilute phases} 
  \]

- Kapitza resistance
  
  \[
  \dot{q}_{\text{ex}} = \frac{P_3 P_m}{P_3 + P_m} \alpha (T_3^4 - T_m^4) 
  \]
Better understanding of Planck OCDR

**Planck qualification model tests**

![Graph showing a linear relationship between applied power (nW) and T^2 (K^2). The equation P = 2.44 n4 T^2 - 308 is highlighted.

**Revisit Planck**

- \( \dot{Q}_{\text{exp}}/\dot{n}_{4} T^2 = 2.44 \text{ J/mol/K}^2 \)
- closer to \( \dot{Q}_{\text{new}}/\dot{n}_{4} T^2 \approx 3.0 \text{ J/mol/K}^2 \)
- than \( \dot{Q}_{\text{old}}/\dot{n}_{4} T^2 \approx 5.7 \text{ J/mol/K}^2 \)
- estimated \( \dot{Q}_{\text{visc}} = 257 \text{ nW} \) in detector HX (\( L = 5 \text{ m} \), \( \varnothing = 0.3 \text{ mm} \)) is 80% of experimental 308 nW

Triqueneaux et al, Cryogenics 46 (2006) 288
Detector heat lift test setup

\[ \dot{Q}_{mco} \approx \dot{Q}_{detector} \]

\[ T_{qo} = T_{detector} \]

\[ T_{load} = T_{liquid} \]

Experiment

Thermometers and heater mounted on copper cylinders and soldered to a spiral of CuNi or Ag tubing:

- viscous heating
- thermal contact
Viscous heating: $\varnothing = 0.6\,\text{mm} \text{ vs } \varnothing = 1.0\,\text{mm}$

Lower temperatures with $\varnothing = 1.0\,\text{mm}$ are due to less viscous heating. Different colors indicate different $p_{\text{still}}$. 
More exchange area decreases $T_{\text{detector}}$. For Ag tube red, green, blue, and cyan indicate $p_{\text{still}} = 0.3, 5, 10, \text{ and } 15 \text{ mbar.}$
Performance and still conditions

Effect of $p_{\text{still}}$ on performance

<table>
<thead>
<tr>
<th>$p_{\text{still}}$ (mbar)</th>
<th>$\dot{n}_3$ (µmol s$^{-1}$)</th>
<th>$\dot{n}_4$ (µmol s$^{-1}$)</th>
<th>$T_{\text{liquid}}$ (mK)</th>
<th>$T_{\text{detector}}$ (mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>16.7</td>
<td>398</td>
<td>44.0</td>
<td>51.4</td>
</tr>
<tr>
<td>5.0</td>
<td>18.5</td>
<td>349</td>
<td>45.0</td>
<td>51.7</td>
</tr>
<tr>
<td>10.0</td>
<td>28.8</td>
<td>346</td>
<td>46.7</td>
<td>52.6</td>
</tr>
<tr>
<td>15.0</td>
<td>57.0</td>
<td>301</td>
<td>51.8</td>
<td>56.5</td>
</tr>
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</table>

best = lowest $\dot{n}_3$ and highest $\dot{n}_4$ working; data shown is best

Optimum pump conditions

$^4$He pump  low $\dot{n}_4$, low $T_{\text{still}}$, and low $x_{\text{still}}$

$^3$He pump  low $\dot{n}_3$, high $p_{\text{still}}$, high $x_{\text{still}}$

Conclusion

best is $p_{\text{still}} = 5 \text{ mbar}$, $x_{\text{still}} = 10 \%$, and $T_{\text{still}} = 1 \text{ K}$
Development of $^3$He pumps

**JAXA** SPICA Joule-Thompson cooler $^3$He pump: 1.7 K stage!
- improve passive check valves from 40 mbar to 5 mbar
- pushing for collaboration

**Twente** adsorption pump at 15 K: 1.7 K stage!
- active check valves are being developed
- ESA funds prototype using Darwin pump cells

**CNRS-AL** Holweck (viscous or molecular drag) pump
- verification of CNRS model of Adixen pump
- prototype is built using ball bearings and off-the-shelf motor

**CREARE** Miniature turbo/drag pump? Costs 2 M€
- 2011 Mars Science Laboratory (NASA)
- 2018 ExoMars (ESA)
Vapor liquid phase separator (VLPS) in the still

Objectives, test whether

- only capillary forces can confine liquid mixture
- confinement is robust to upstream bulk liquid
- fountain pump can be connected upstream
- it works for $p_{\text{still}} > 5 \text{ mbar}$
- it works for $x_{\text{liquid}} = 10\%$

 Veronica, Volpe, Camus, Benoit, Triqueneaux, Tirolien, d'Escriv
Vapor liquid phase separator (VLPS) in the still

Functionality

- $h$ by capacitive level gauge in hole to amplify sensitivity
- $h$ check by $T_{\text{below}}$ after evaporation by $\dot{Q}_{\text{below}}$
- measure $\dot{n}$ and $T$ versus $\dot{Q}$ for several $^3\text{He}$ and $^4\text{He}$ amounts $\Rightarrow x_{\text{in}}$
- get $x_{\text{liquid}}$ from known $\rho_{\text{vapor}}(x_{\text{liquid}}, T)$ for $0.6 \, \text{K} < T < 1.7 \, \text{K}$ and $x_{\text{liquid}} < 28 \%$
- only $^3\text{He}$ circulates instead of $^3\text{He}$ and $^4\text{He}$ as in the CCDR
Vapor liquid phase separator (VLPS) in the still

\[ x_{in} = 26.3\% , \ p = 4 \text{ mbar}, \ V_{in} = 2.63 \text{ cm}^3, \ T_{bath} = 14.9 \text{ k}\Omega \]

Best VLPS results so far:
- \( x_{\text{liquid}} = 1.78\% \) at \( \dot{n} = 15.7 \mu\text{mol/s} \)
- \( x_{\text{liquid}} = 16.5\% \) at \( \dot{n} = 1.5 \mu\text{mol/s} \)

Next months:
- measure \( x_{\text{vapor}} \)
- other porous materials
Still is a vapor liquid phase separator

Still is a single capillary

- negative gravity test
- maximum \( \varnothing \) for stable interface? \( \varnothing \leq 2 \text{ mm} \)
- remove \(^4\text{He}\) in case of overflow
Conclusion: status summary

- thermal model is design guide for optimizing heat exchanger and mixer part ⇒ real progress with respect to Planck
- heat lift mixing chamber is 1 µW at $T_{\text{heater}} = 51.4 \text{ mK}$ and $T_{\text{liquid}} = 44.0 \text{ mK}$ ⇒ interface with a real detector?
- heat load precooler is 6 mW at 1.7 K due to helium circulation
  - must be possible to decrease it to 3 mW
- $^3\text{He}$ pump specifications: fridge works well at $p_{\text{still}} = 5 \text{ mbar}$ and $\dot{n}_3 = 20 \mu \text{mol/s}$, but $p_{\text{still}} = 10 \text{ mbar}$ and $\dot{n}_3 = 30 \mu \text{mol/s}$ is possible
- work in progress on three different $^3\text{He}$ pumps
- work in progress on the vapor-liquid phase separator in the still
- support structure (done for BLISS and at the Néel Institute)

- like to integrate any astrophysical instrument (also on earth)
Thank you!