# Sec 6.5

McLean seminar
2024.08.02

# Sec. 6.5 Cryogenics and vacuum methods

- Requirement of detector: cooling for optimum performance
- Several categories of cooling system in cameras and spectrographs for ground-based :

1. Thermoelectric coolers and liquid circulation coolers:
   - operate over the range -20 °C to -50 °C
   - suitable for photomultiplier tubes, CCDs which have low dark current, and telescope-guiding cameras
   - popular in CCD cameras used on small telescopes because it is much easier and simpler to use

2. Liquid and solid cryogens
   - Dry ice (solid $CO_2$):
     - cheap and readily available
     - Temperature around -78 °C can be achieved with dry ice
   - Liquid nitrogen ($LN_2$):
     - relatively cheap, cools detectors to -196 °C
     - used in almost all professional CCD cameras and near-infrared devices
   - Liquid helium (LHe):
     - expensive
     - cool detectors to -269 °C
     - used for low-bandgap semiconductor materials and bolometers used in infrared instruments
     - usually pre-cooled with $LN_2$ then blown out with LN2 gas and the LHe transfer begun immediately

# Sec. 6.5 Cryogenics and vacuum methods

- Cooling ability for liquid cryogens:
  - ρ: density
  - $L_V$: latent heat of vaporization

$$(\rho L_V)_{\mathrm{LHe}} = 0.74\ \mathrm{W\ h\ L^{-1}}$$

$$(\rho L_V)_{\mathrm{LN_2}} = 44.7\ \mathrm{W\ h\ L^{-1}}$$

  - Meaning:
    - a 10 W heat load boils away 1 liter (L) of LHe in 0.074 hours
    - a 10 W heat load boils away 1 liter (L) of $LN_2$ in 4.47 hours

- Liquid neon (LNe) and liquid hydrogen (LH):
  - Intermediate solution between LHe and $LN_2$
  - rarely used in astronomy

3. Electrical heat engines or closed-cycle refrigerators:

- many infrared instruments and sub-millimeter/radio receivers employ multi-stage closed-cycle refrigerators (CCRs)
- vibration damping is needed, especially for CCR-cooled instruments in sensitive AO system
- counter-balance weights may also required

# Sec. 6.5 Cryogenics and vacuum methods

4. $^3$He systems:
    - sub-millimeter and far-infrared bolometers
    - temperature below 0.3 K are obtained by reducing the vapor pressure on the top of the liquid helium-3
    - use internal sorption pump

# Sec. 6.5 Cryogenics and vacuum methods

- Detector temperature affect on dark current and noise
- Steps in the thermal analysis of an instrument:
  - Determine what is to be actively cooled (ex. Detector only, whole instrument)
  - Tabulate the required operating temperature (ex. Detector, optics)
  - Calculate the thermal energy removed from the mass to be cooled
  - Determine the heat loads due to conduction and radiation
  - Select the appropriate cooling system
  - Estimate the cool-down time
  - Estimate the 'hold' time (for liquid cryogens)

- Heat H (joules) removed from a mass *m* (kg) which is cooled from a temperature $T_h$ to $T_c$ is given by

$$H = mC(T_h - T_c)$$

  - C: specific heat of the material

- The rate of transfer of heat $Q_H$ (in watts) by conduction along a rod of uniform cross-sectional area (A) and temperature gradient dT/dx is given by

$$Q_H = -kA\frac{dT}{dx}$$

  - k: thermal conductivity

- Thermal resistance:

$$R = \frac{1}{k}\frac{1}{A/L}$$

  - L: length of the conductor

- Since k is a function of temperature, it is often convenient to integrate over the required temperature range and give $Q_H$ in the form:

$$Q_H = \frac{A}{L}[I_{T_h} - I_{T_c}]$$

  - L: length of conductor
  - I: tabulated property for many materials [watts/centimeter]

**Table 6.1.** Values of the thermal conductivity integrals in watts/centimeter for four materials.

| *Temperature* (K) | *OFHC Copper* (watts/cm) | *6061 Aluminum* (watts/cm) | *Stainless steel* (watts/cm) | *G-10 Fiberglass* (watts/cm) |
|---|---|---|---|---|
| 300 | 1,520 | 613 | 30.6 | 1.00 |
| 250 | 1,320 | 513 | 23.4 | 0.78 |
| 200 | 1,120 | 413 | 16.6 | 0.55 |
| 150 | 915 | 313 | 10.6 | 0.37 |
| 100 | 700 | 211 | 6.3 | 0.19 |
| 77 | 586 | 158 | 3.2 | 0.11 |
| 50 | 426 | 89.5 | 1.4 | 0.07 |
| 10 | 25 | 3.6 | 0.03 | 0.005 |

# Sec. 6.5 Cryogenics and vacuum methods

- Power radiated from a body of area A at an absolute temperature T is given by:

$$Q_H = \varepsilon \sigma A T^4$$

  - Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$
  - ε: emissivity of the surface

- The net rate of heat transfer by radiation from a body temperature Th onto a body temperature Tc is given by:

$$Q_H = \sigma A_c F_{hc}[T_h^4 - T_c^4]$$

  - $F_{hc}$: effective emissivity which depends on the geometry of the cryostat configuration

- The cooling time for a mass m from initial temperature $T_i$ to $T_{i+1}$ :

$$\Delta t_{T_i, T_{i+1}} = \frac{m C_p(T_i)[T_i - T_{i+1}]}{(A/L)k(T_i)[T_i - T_{\text{sink}}] - Q(T_i)}$$

  - $T_{sink}$: temperature of the cold source (such as $LN_2$)
  - Q(T): rate at which heat comes back into the mass at temperature $T_i$

# Sec. 6.5 Cryogenics and vacuum methods

- The larger the surface area of a cryostat, the greater the deformation due to the atmospheric pressure
  - The deflection at the center of a flat end plate clamped at its edge:

$$\delta = \frac{3(1-\mu^2)R^4}{16Ed^3}P$$

  - The maximum tensile stress, which occurs at the edge, is given by:

$$S_{\max} = \frac{3}{4}\left(\frac{R}{d}\right)^2 P$$

    - μ: Poisson's ratio (typically 0.3 for metals)
    - E: elasticity or Young's modulus
    - R: radius of the plate
    - d: thickness
    - P: external pressure

  - The deflection of a circular plate with unclamped edges, and maximum tensile stress at the center:

$$\delta = \frac{3(1-\mu)(5+\mu)R^4}{16Ed^3}P \qquad S_{\max} = \frac{3}{8}\left(\frac{R}{d}\right)^2 (3+\mu)P$$

# Sec. 6.5 Cryogenics and vacuum methods

- Design objective for a good cooling system should include the followings:
  1. Minimum detector movement
  2. Minimum effort to keep the system uniformly cold
  3. Good accessibility inside the cryostat
  4. Cost and manufacturing time

- A typical $LN_2$ cryostat used with a CCD is shown schematically in Figure 6.11

- Mean free path, average distance traveled between molecules collisions:

$$\lambda_{\mathrm{mfp}} = \frac{1}{\sqrt{2}n\pi d^2}$$

  - n: number density of molecules
  - d: diameter of the molecule

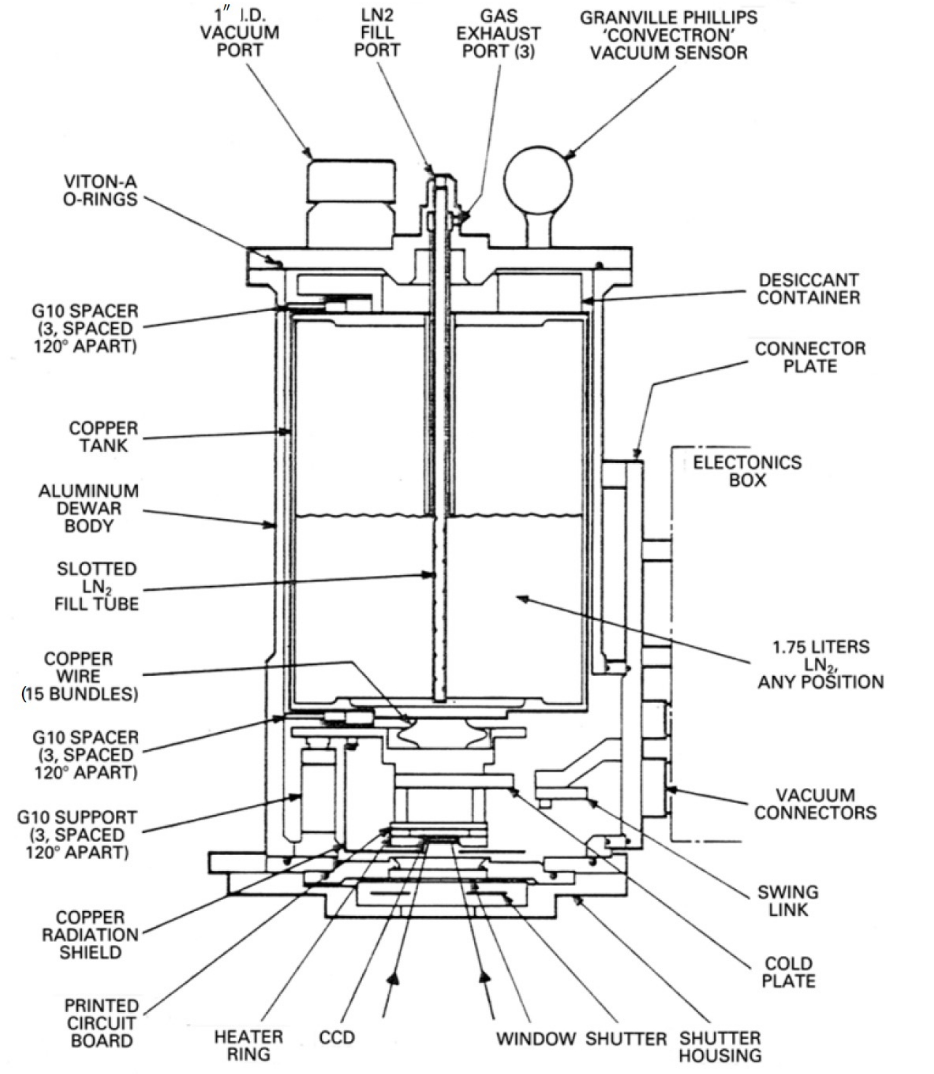


**Figure 6.11.** A cross-sectional view of a typical liquid-nitrogen ($LN_2$) cryostat illustrating all of the components needed in its construction. Credit: NOAO.

# Sec. 6.5 Cryogenics and vacuum methods

- Net pumping speed of a pump:

$$\frac{1}{S} = \frac{1}{S_{\text{pump}}} + \frac{1}{C_{\text{lines}}}$$

  - S: pumping speed
  - C: conductance which depends on gas pressure and viscosity
    - When mean free path is small:

$$C = 180\frac{D^4}{L}P_{\text{av}}$$

    - When mean free path is large:

$$C = 12\frac{D^3}{L}$$

      - D: diameter of circular tube
      - L: length [centimeters]
      - $P_{av}$: pressure

- Pump down time (in seconds):

$$t = 2.3\frac{V}{S}\ln\left(\frac{P_0}{P}\right)$$

  - Time required to collect refrigerant into the receiver or compressor and create a vacuum in the low-pressure side of the system
  - V: volume, S: net pumping speed, $P_0$: initial pressure, P: final pressure