# THE CASE FOR MODERATELY-COOLED, FAR-INFRARED THERMAL DETECTORS

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## ABSTRACT

There are moderately-cooled (around 77K) infrared detectors, for instance InSb (around 5 microns wavelength) and HgCdTe (around 15 to 20 microns wavelength). However for longer wavelengths there are either uncooled thermal-type detectors or highly cooled (about 4K and lower) quantum and thermal detectors, with the notable exception of high Tc superconductor detectors.

We will describe certain long-wavelength applications in space where only moderate cooling is feasible, and where better sensitivity is required than possible with uncooled detectors. These requirements could be met with high Tc bolometers, but it may also be prudent to develop other technologies. Additionally, over the past 16 years a marketplace has not developed for the commercial production of high Tc bolometers, indicating their production may be a natural endeavor for government laboratories.

## GENERAL OVERVIEW OF AVAILABLE DETECTOR TECHNOLOGY

Infrared (IR) detectors (direct detection only will be discussed here) are generally available in two modes, thermal and quantum, and for a range of operating temperatures. Colder detectors are generally faster, more sensitive, and usable to longer wavelengths. Uncooled (~300K) detectors are very broadly available, both in thermal mode (throughout the IR spectrum from a few microns to 1000 μm or so) and in quantum mode (generally in the near infrared, a few microns). Highly cooled (~4K and below) detectors are available throughout the IR spectrum, in both thermal and quantum modes. Moderately cooled detectors (~77K) are available as quantum detectors to 5 μm (InSb), about 15-20 μm (HgCdTe, varies with doping), but generally not as thermal detectors or for the far-infrared (FIR, from about 25 μm to 1000 μm). The major exception, of course, is the high Tc superconductor bolometer.

There is a huge difference between the performance of thermal-mode, room-temperature detectors (detectivity D* ~ $10^8$ to $10^9$ cmHz$^{1/2}$/W, where D* is an area-normalized measure of S/N, higher D* being better) and 4K detectors (D* ~ $10^{13}$). When the detector operating temperature is lowered, the phonon noise decreases; also, the minimum possible thermal conductance G (radiative) decreases. Furthermore, the heat capacity C declines as phonon modes freeze out (this happens sooner rather than later for high Debye temperatures). The theoretically possible D*, assuming the minimum thermal conductance and assuming all other noise sources are small compared with thermal fluctuation noise (phonon noise), scales as $T^{-5/2}$:

***Table 1:*** *Theoretical D*, limited by phonon noise*

| Temperature | limiting D* |
|---|---|
| 300K | $1.8 \times 10^{10}$ |
| 90K | $3.6 \times 10^{11}$ |
| 40K | $2.7 \times 10^{12}$ . |

This limit in general is not reached when looking at a target much hotter than the detector (due to photon noise) or for frequencies much higher than $\omega\tau = 1$ ($\tau$ is the time constant, C/G), since then the Johnson or electronics noise will begin to dominate the phonon noise. Low enough frequencies are also hobbled by 1/f

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noise. Thus at best the limiting D* can only be reached for a fairly small range of frequencies, falling away at lower and higher frequencies.

## RESOURCE LIMITATIONS FOR PLANETARY MISSIONS

Planetary missions, particularly those to the outer planets (the gas giants, Jupiter and beyond) are in general highly resources constrained. It is difficult to send heavy instruments to the outer planets, or to provide large amounts of electrical power. Thus cooling options are generally limited to passive coolers or single-stage mechanical coolers, with a lower limit around 60K. This poses a problem for FIR observations. In general (with one exception to be noted below) it does not appear feasible to launch 4K detectors to the outer planets. As has been noted above, this then restricts science instruments to the relatively insensitive, 300K thermal detectors. Moderately cooled FIR detectors with intermediate D* could greatly benefit outer planet missions.

The relative ease of moderate cooling can be appreciated by referring to the following table of planetary temperatures.

***Table 2:*** *Range of Planetary Temperatures*[1]

| **Planet** | $T_{surface}$ | $T_{sphere}$ |
|---|---|---|
| Mercury | 100-700K | 445K |
| Venus | 740 | 325 |
| Earth | 288-293 | 277 |
| Mars | 140-300 | 225 |
| Jupiter | 165 | 123 |
| Saturn | 134 | 90 |
| Uranus | 76 | 63 |
| Neptune | 72 | 50 |
| Pluto | 40 | 44 |

$T_{sphere}$ is the temperature of a black sphere in equilibrium with the Sun; a flat plate facing the Sun would have a temperature higher by $\sqrt{2}$. Except for the Earth and Venus, the temperature in space is not room temperature. Rather than call a 300K detector "uncooled", one might call a 90K detector at Saturn "unheated". In any case, the potential sensitivity benefit of moderate cooling combined with the ease of reaching the 77K neighborhood in the outer solar system makes a strong case for developing and using moderately cooled FIR detectors on outer planet missions. On the other hand, considering the relatively high target temperatures (for instance, Jupiter at 1 bar is 165K), there is in general no need for the coldest and most sensitive detectors (sub-Kelvin).

## MODERATELY-COOLED FIR DETECTOR PERFORMANCE AVAILABLE NOW AND IN THE NEAR TERM

COTS (commercial off the shelf) 300K pyroelectric detectors have D*'s around $10^8$ to 1-2 x $10^9$. The Cassini CIRS Fourier transform spectrometer (FTS) (launched in 1997; Jupiter flyby in 2000/2001/ Saturn arrival in 2004) has a FIR channel, focal plane 1 (FP1) with a BiTe thermoelectric detector operating at 170K. The FP1 D* is about 4 x $10^9$ near the low frequency end of a 0.4 to 30 Hz band pass (10 to about 670 $cm^{-1}$). As a self-biasing device, it is nearly free of 1/f noise. The CIRS instrument is shown in Figure 1, and an example of a FP1 spectrum of Jupiter is shown in Figure 2 (the regularly spaced sharp features above about 400 $cm^{-1}$ are due to electrical interference). Interestingly enough, such a spectrum has never been taken of the Earth, so that in this sense Jupiter is better characterized than Earth (the FIR spectrum). Beyond about 50 μm (lower than 200 $cm^{-1}$), the Earth has only been characterized by broad-band, radiometric observations.

*Figure 1. The Cassini CIRS FTS*

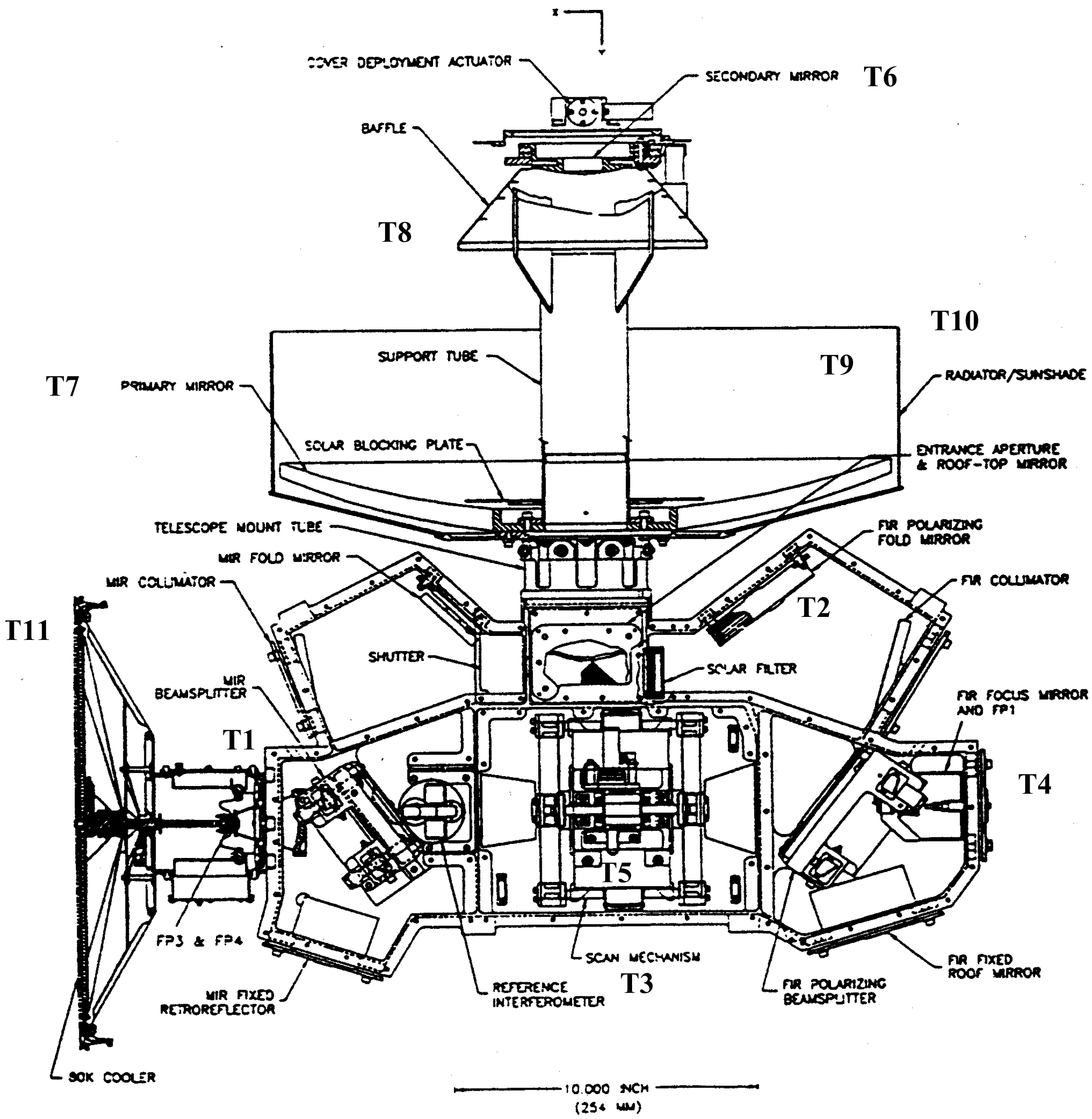
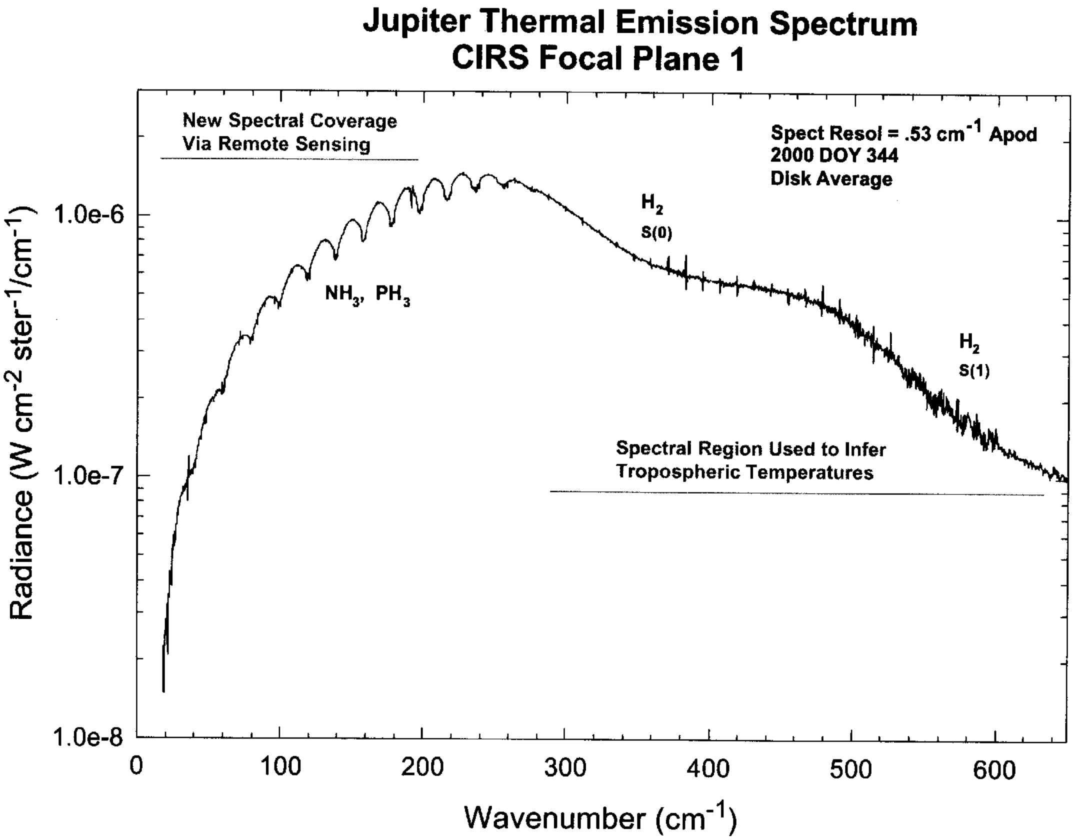


***Figure 2**. Cassini CIRS Jupiter Spectrum in the FIR*



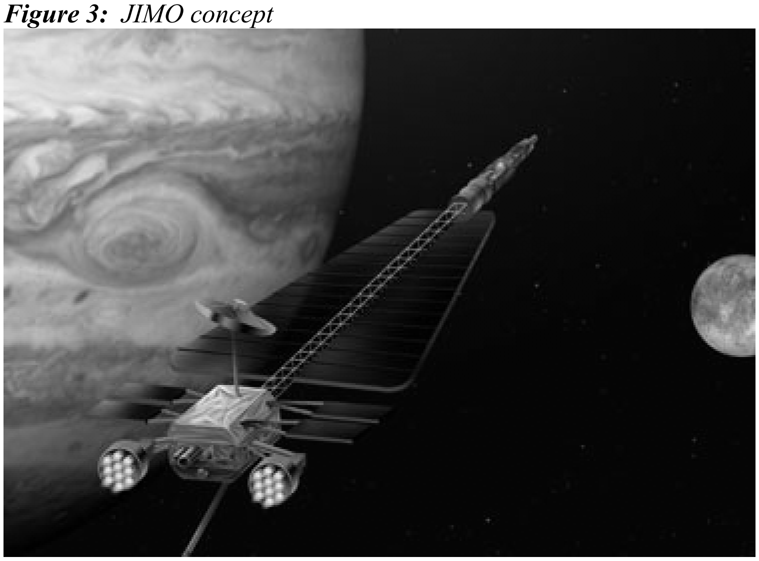

Due to the nature of the Planck function, the radiance is rapidly falling as one approaches 10 $cm^{-1}$. It is remarkable that such a fairly high resolution spectrum can be recorded of a fairly cold target with such an insensitive detector, not much more sensitive than the best COTS uncooled detectors. The drawback of course is the long integration time that may be required, easily hours for weak spectral features towards the longest wavelengths. The Cassini CIRS instrument, like the Voyager IRIS FTS before it, could very much benefit from improved sensitivity IR detectors consistent with the resources constraints of an outer planet mission. In fact, NASA Goddard has produced high Tc bolometers of increasing D*, culminating[2] in a D* of $1.2 \times 10^{10}$. This has been further improved to $2 \times 10^{10}$ @ 2Hz, using GdBaCuO instead of YBCO on a 5 µm thick sapphire substrate. This detector exceeds the performance of the Cassini CIRS detector over the entire FP1 frequency range, by about a factor of 5.

NASA Goddard has also funded numerous small companies through the SBIR program. The following companies were funded through both Phase I and Phase II: Advanced Technology Materials, Talandic, Excel Superconductor, Neocera, Conductus, and Energy Science Laboratories. There was a range of technical readiness at the completion of Phase II; in particular, Conductus came closest to having a device[3], producing array-compatible pixels for IR camera applications. However a commercial market never developed for high Tc IR detectors, and industry instead moved to provide products for wireless telecommunications such as passive RF filters for cell-phone base stations. Given the lack of a commercial market and yet the clear advantage of high Tc bolometers for outer planet missions, the production of high Tc bolometers may be a logical niche market for government laboratories. Meanwhile the academic and industrial sectors continue to play a key role in the discovery and development of high Tc materials, substrates, deposition techniques, and biasing techniques.

## ONE EXCEPTIONAL OPPORTUNITY FOR THE FUTURE

Till now, much has been made of the resource-starved nature of outer planet missions. There is an exception being contemplated, a once-per-decade opportunity for a quite large mission within the Prometheus program. The Prometheus program advocates sending nuclear reactors into space, producing 100 kW of electrical power and 600 kW of waste heat; by way of comparison, less than 1 kW of electrical power is available from the Cassini radioisotope thermoelectric generators. In the proposed first mission, JIMO (Jupiter Icy Moons Orbiter), the copious electrical power is used to power an ion drive for transit to Jupiter.

***Figure 3:*** *JIMO concept*



Prometheus encourages high power, high data rate instruments, with perhaps 500 kg for the total of the science instruments. Under these conditions a 200-300 W, ~45 kg multi-stage cooler can be flown, capable of reaching ~4K, instead of a 4 or 5 kg, single-stage mechanical cooler capable of reaching ~65K. This opens up the utilization of FIR detectors much more sensitive than the high Tc detectors. Still, for every such Prometheus mission there will be 10-20 regular missions with the usual constraint to moderate cooling.

## REFERENCES

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