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Upcoming Planetary Missions and the Applicability of High Temperature Superconductor Bolometers

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Abstract

A brief overview is given of planetary exploration to date, with a focus on outer planet missions, in particular the proposed 1996 Cassini mission to Saturn and Titan. A proposed infrared spectrometer, CIRS, for remote sensing of the atmospheres of Saturn and Titan from the Cassini orbiter is presented. The science return of CIRS would be significantly enhanced if a near phonon-noise limited 65-90K infrared detector could be developed. A description of the ongoing Goddard/NIST-Boulder effort to build a high sensitivity, high T_c bolometer is also presented.

Past and Present Planetary Exploration, and the 1996 Cassini Mission

A long line of Fourier Transform Spectrometers (FTS's) has made significant contributions to our understanding of planets and satellites, from the earth-observing FTS's of Nimbus 3 (1969) and Nimbus 4 (1970), through the Mars observing FTS of Mariner 9 (1971/1972) to the Voyager IRIS observations of Jupiter (1979), Saturn and Titan (1981), Uranus (1986), and Neptune (1989). These interferometers have returned substantial scientific benefits (see Figure 1), in spite of using relatively insensitive near-room-temperature thermal-type infrared detectors (detectivity $D^* \leq 10^9$ cm$Hz^{1/2}$/W) as compared with the much more sensitive detectors ($D^* \geq 10^{14}$) available at liquid helium temperature. D* is related to noise equivalent power (NEP) by the relationship NEP = $A_d^{1/2}/D^*$, where A_d is the detector area. A severely limited mass budget, and long lifetime in the case of outer planet missions, rule out the use of liquid helium. Radiative and mechanical coolers remain, for which the practical lower limit for the focal plane is 65-90K. There are no thermal detectors specifically optimized for these temperatures, and in fact no moderately-cooled thermal detector (T $\geq$ 65K) offers substantial improvement in performance beyond the thermopile used on Voyager/IRIS ($D^* = 0.9 \times 10^9$).[1] To enhance the return from infrared remote sounding of the planets, planetary missions have a compelling need for sensitive 65-90K thermal-type detectors, a need that has not been met by detector development programs.

Preliminary investigations of the outer planets were performed by the Pioneer and Voyager spacecraft. Subsequent missions planned for in-depth exploration of Jupiter and Saturn from orbital spacecraft are Galileo and Cassini. Galileo, launched in 1989, is to acquire data while in Jupiter orbit. A probe will also be sent into Jupiter's atmosphere. A series of planetary missions utilizing a newly-designed generic spacecraft, the Mariner Mark II, is now under development. The first two missions under the Mariner Mark II series will be the CRAF cometary encounter, and the Cassini mission to Saturn and Titan. The CRAF and Cassini missions are intended to provide information on the origin and evolution of the solar system.

The Cassini mission is a joint NASA/ESA enterprise. It will be launched in 1996 aboard a Titan/IV Centaur, with a Jupiter flyby in 2000, and Saturn arrival in 2002. At Saturn the ESA-supplied probe will enter the atmosphere of Titan. Subsequently, the NASA-supplied orbiter will orbit Saturn about 60 times, making 35 close Titan flybys during 2002-2006. Figure 2 shows the outline of the Cassini orbiter and probe. (To get a sense of scale, the high-gain antenna (HGA) has a diameter of 3.66 m). The orbiter has an allocation of 197 kg and about 200 watts for scientific instruments, and can return to earth about 1 to 2 million bits per overpass of the deep-space network on earth.

CIRS is one of the baseline infrared experiments on the Cassini orbiter model science payload. CIRS will retrieve information on the atmospheres of Titan and Saturn with good vertical resolution, from deep in their tropospheres to high in their stratospheres, and into the upper few centimeters of the regoliths of icy objects. The science addressed by CIRS includes: 1) determination of the global thermal structure to test theories of atmospheric dynamics and general circulation, 2) mapping and tracking the motion of thermal patterns to determine their role in dynamics, 3) determination of global gas composition (including isotope ratios), 4) mapping and tracking composition variations to determine effects of chemistry, photochemistry and dynamics, 5) studying the synthesis of organic compounds, 6) determination of global information on clouds and hazes, 7) determination of information on non-equilibrium processes in the upper stratosphere, and 8) determination of information on atmospheric transport and other processes obtained from simultaneous measurements of composition, temperature, and winds. The science addressed for satellites and rings includes the mapping of composition and thermal characteristics, to test theories of their origin and evolution.

CIRS will use a dual interferometer configuration with a common linear motor (figure 3). The far-infrared FTS (table 1) will cover 10-300 cm^{-1} with a single thermopile detector. The mid-infrared FTS will cover 200-1400 cm^{-1}, with a single thermopile detector from 200-650 cm^{-1}, a 1x20 photoconductive HgCdTe array from 600-1100 cm^{-1}, and a 1x20 photovoltaic HgCdTe array from 1100-1400 cm^{-1}. The choice of detectors is limited by the minimum achievable focal plane temperature, around 75K for the radiative cooler design in CIRS. The long-wavelength infrared detectors proposed for CIRS in focal planes 1 and 2 (table 1) are Schwarz-type thermopile detectors to be supplied by Karlsruhe University in Germany. The dc detectivity is 3 to 4×10^{9}, with a time constant of 25 ms (Shimadzu of Japan makes a similar detector). By comparison, the thermodynamic limit (phonon-noise limit) at 80K is a D* of 5×10^{11}. The area-solid angle product for CIRS dictates a minimum detector diameter of 1.1 mm for perfectly concentrating f/0.5 optics in vacuum.

A rich array of molecular species on Saturn and Titan may be studied with the thermopile detectors currently baselined for CIRS. Nevertheless, a greater array of trace molecules over a wider range of altitudes could be observed, were more sensitive detectors to become available. Beyond Cassini, an improved thermal detector would benefit proposed missions to study the elemental composition, cloud structure, and meteorology of the planetary atmospheres of Uranus and Neptune.[2] Planetary observations from earth-orbiting telescopes (Plato) and on the Space Station would also benefit.

Possible Improvement with Long-Wavelength Detectors

Higher sensitivity with high temperature superconductor (HTS) detectors would greatly improve the determination of the presently detected hydrocarbons and nitriles in Titan's atmosphere, and will permit the detection of new nitriles. Knowledge of the altitude and spatial distribution of CO is central to the understanding of the chemistry of the oxygen-bearing molecules in Titan's atmosphere. A synthetic far-infrared limb spectrum has been calculated for Titan, a portion of which is shown in Figure 4. The emission lines are due to HCN and CO-- a strong CO line is evident at 42.2 cm^{-1}. Also shown are the error bars for the projected sensitivity of the CIRS thermopile detector, and for an HTS detector with an assumed D* of $3x10^{10}$. It is evident from the comparison that the increased sensitivity of the HTS detector is required for CIRS to map the altitude and spatial distribution of this key oxygen-bearing species.

The sharp change in magnetic and transport properties of high T_c superconductors at the transition opens the possibility of near-phonon-noise limited performance at or near 80K. Bolometric responses in granular and epitaxial HTS films have been demonstrated by a number of groups,[3,4,5] including a collaboration between Goddard and NIST/Boulder.[6] Another possibility for a sensitive detector is the kinetic inductance bolometer,[7] which has been demonstrated in low Tc materials but not yet in high Tc.

The initial Goddard/NIST effort was a transition-edge resistance bolometer in the composite geometry,[8] with independently fabricated radiation absorber, superconductor thermometer, and thermal isolator (figure 5). The superconductor thermometer is in the form of a meander line which is also suited to implementation as a kinetic inductance bolometer. A prototype device was fabricated in early 1989. The prototype suffered from a long time-constant, 30 seconds, due to the heat capacity of the underlying $SrTiO_3$ substrate, 500 microns thick.

Efforts since then have centered on reducing the heat capacity of the substrate. Attempts are underway at Goddard to etch $SrTiO_3$ to a thickness of 25 microns or so. Also under consideration is using a substrate with a lower specific heat. Work is being pursued under Goddard sponsorship at a number of locations to attempt HTS deposition on diamond, which has a volume specific heat 5 to 15 times lower that alternate substrates at 80K. The ATM corporation (Conn.) is being funded within the Small Business Innovation Research program, first under Phase I and now under Phase II, to grow HTS thin films (YBaCuO and

BiSCCO) via the MOCVD technique on artificially grown diamond films. Initial attempts without a buffer layer have failed; buffer layer development has begun and will be continued under Phase II. A small purchase order was awarded to CVC (New York) to attempt sputter deposition of YBaCuO on natural type IIa diamond. Deposition without a buffer layer resulted in poor adhesion. The initial attempt with a polycrystalline MgO buffer layer resulted in good adhesion. At Catholic University an attempt was made to deposit a thick film of YBaCuO on natural diamond -- this also resulted in poor adhesion. NIST/Boulder has implemented a laser ablation system and will attempt laser ablation deposition on diamond. NIST and Goddard will also be looking into a silicon based bolometer. Silicon as a substrate is a compromise choice -- while not having as low a specific heat as diamond, there is much more experience in working/thinning it, and various groups have already deposited HTS thin films on silicon.

In addition to the time constant, the low-frequency excess noise in HTS films needs to be controlled. It has been noted that minimization of the excess noise in YBaCuO films on $SrTiO_3$ requires c-axis alignment.[8,9,10] It is not known to what degree this is possible on diamond: Undoubtedly the choice of buffer layers will play a key role. As it has been noted that thallium films can have high critical currents even in unoriented form,[11] thallium films appear to have better intergranular contact and may be a candidate for low-noise, non-epitaxial films on diamond. Alternatively, a bolometer could be made with a silicon substrate and a $SrTiO_3$ buffer layer[12] or a $BaTiO_3/MgAl_2O_4$ buffer layer,[13] upon which epitaxial c-axis oriented YBaCuO has been grown.

Prospects for HTS Bolometers on Planetary Missions

Exciting data on the outer planets and their satellites have already been obtained with fairly insensitive, thermal-type infrared detectors. Future studies would benefit greatly from an improved sensitivity detector: In principle, HTS bolometers could provide this improved sensitivity. What needs to be demonstrated is superiority to Schwarz-type thermopiles, which are capable of a D* of 3 to 4×10^9 and a time constant of about 25 ms; for the CIRS detector diameter of 1.1 mm the NEP is about 3×10^{-11} $W/Hz^{1/2}$ over wavelength ranges of 16 to 50 microns and 30 to 1000 microns. To displace the thermopile detectors, the HTS bolometer would need either to improve the time constant to at least 10 ms, or improve the D* to at least 7×10^9. If improved sensitivity is demonstrated, certain environmental capabilities also need to be demonstrated. Below is a brief list of nominal requirements for the Cassini mission.

Lifetime/passivation (high vacuum):	12 years
Thermal cycling, 300K to 80K:	numerous times
Radiation hardness:	15 krads, total dose
Launch vibration:	~15 g's, ~ 3 minutes.

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TABLE 1 CIRS INSTRUMENT PARAMETERS

TELESCOPE DIAMETER (CM):	50	
INTERFEROMETERS:	FAR-IR	MID-IR
TYPE:	Polarizing	Michelson
SPECTRAL RANGE (cm^{-1}):	10 - 300	200 - 1400
SPECTRAL RESOLUTION (cm^{-1}):	0.5 - 20	.05 - 20
INTEGRATION TIME (sec):	50	50

FOCAL PLANES:	FP1	FP2	FP3	FP4
SPECTRAL RANGE (cm^{-1}):	10-300	200-650	600-1100	1100-1400
DETECTORS:	Thermopile (1)	Thermopile (1)	HgCdTe (1x20)	HgCdTe (1x20)
PIXEL F-O-V (mrad):	4.3	4.3	.2	.2
PIXEL AΩ ($cm^2 sr$):	3×10^{-2}	3×10^{-2}	8×10^{-5}	8×10^{-5}
D* (cm $Hz^{1/2}$ W^{-1})	3×10^{9}	2×10^{9}	3×10^{10}	5×10^{11}
NEP ($WHz^{-1/2}$):	3×10^{-11}	5×10^{-11}	8×10^{-13}	5×10^{-14}
NESR (W cm^{-2} sr^{-1}/cm^{-1}):	4×10^{-9} (0.5 cm^{-1})	6×10^{-9} (0.5 cm^{-1})	4×10^{-10} (5 cm^{-1})	2×10^{-10} (5 cm^{-1})
DATABAND (Hz):	.4 - 12	8 - 26	24 - 44	44 - 56
TEMPERATURE (K):	170	170	80	80
INSTRUMENT TEMPERATURE (K):		170		
DATA BIT RATE:		2000 Bits/sec		
POWER:		21 W (Avg):	26 W (Peak)	

WEIGHT:	INSTRUMENT	19 Kg
	ELECTRONICS/POWER SUPPLY	8 Kg
	TOTAL	27 Kg

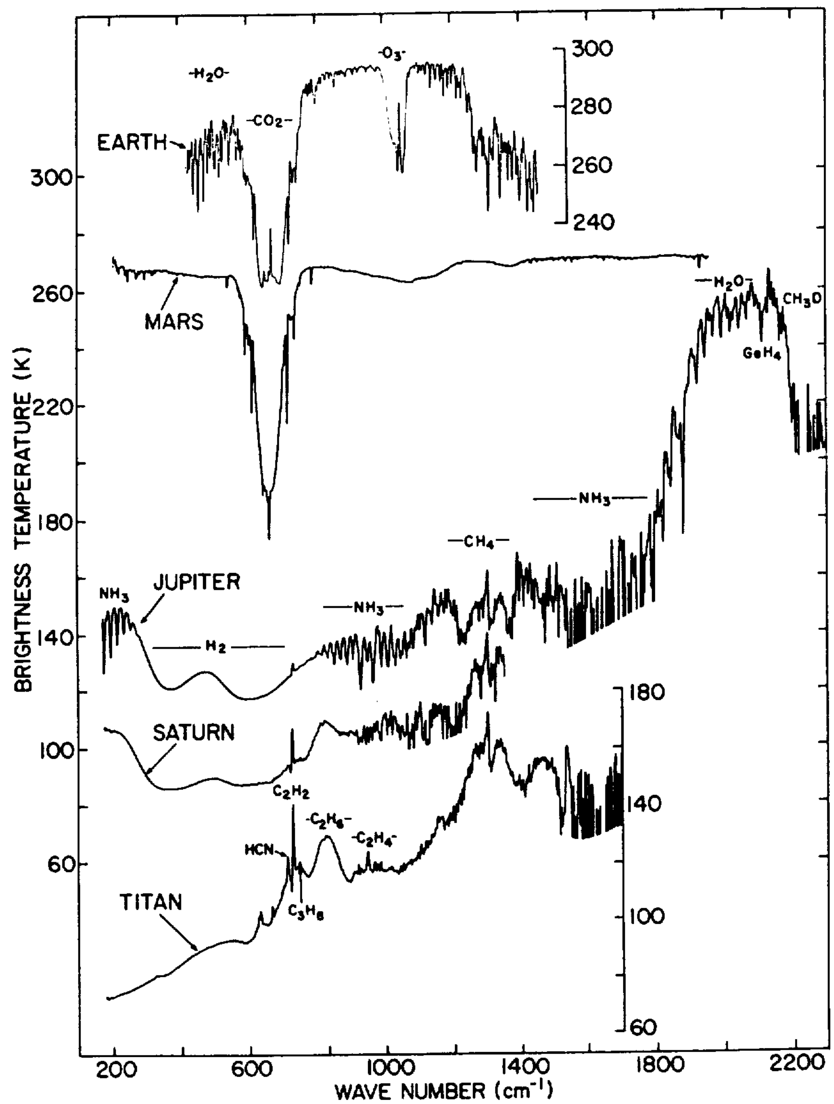

Fig. 1 The brightness temperatures of typical nadir emission spectra obtained by various spacecraft. The broad spectral coverage permitted unanticipated discoveries as well as the simultaneous retrieval of many atmospheric parameters including temperatures, gas abundances, and aerosol properties. CIRS will use limb sensing of Saturn's and Titan's stratospheres to obtain an altitude resolution < one scale height for temperature and composition studies.

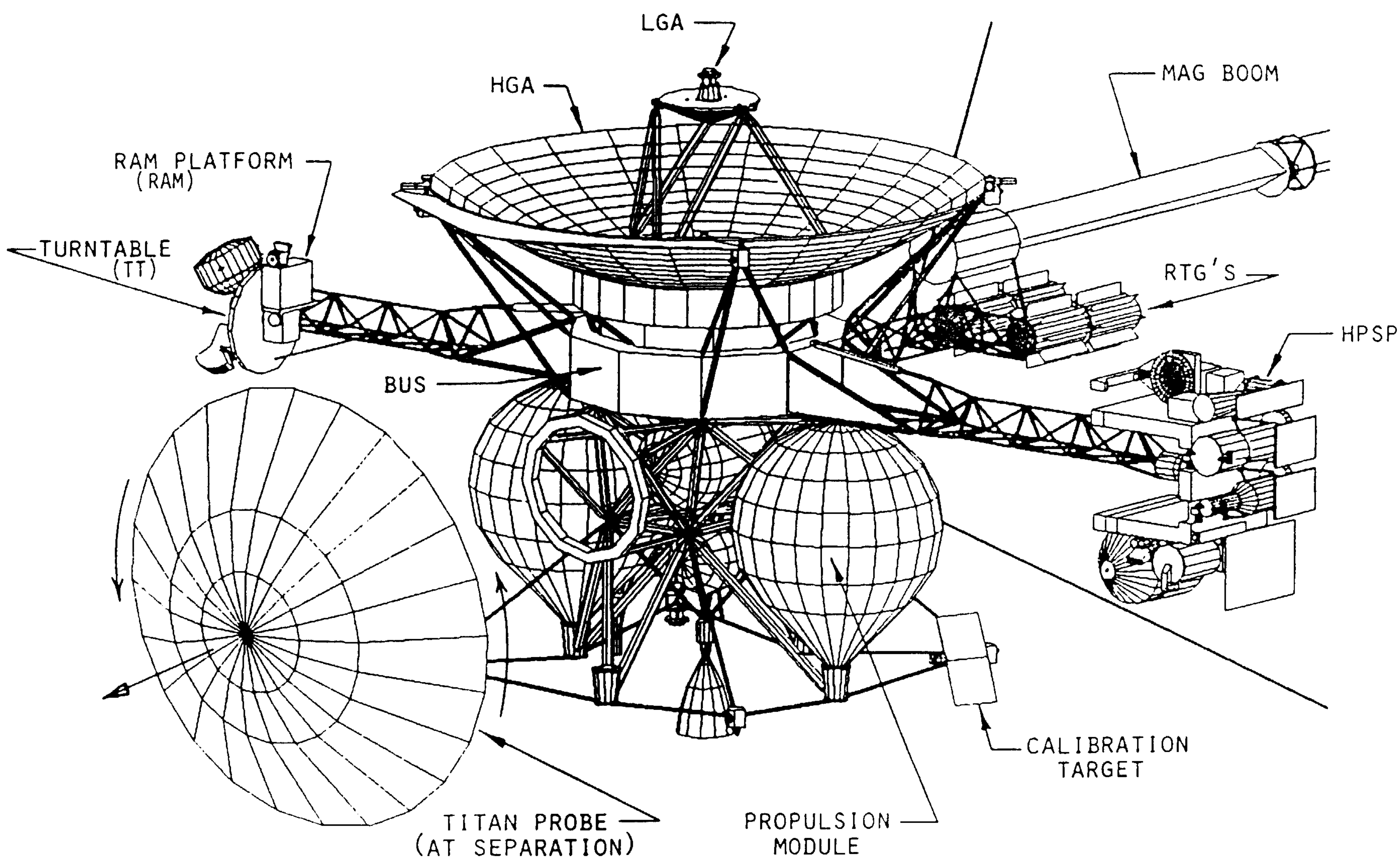

Fig. 2 CASSINI SPACECRAFT CRUISE CONFIGURATION - FRONT ISOMETRIC VIEW

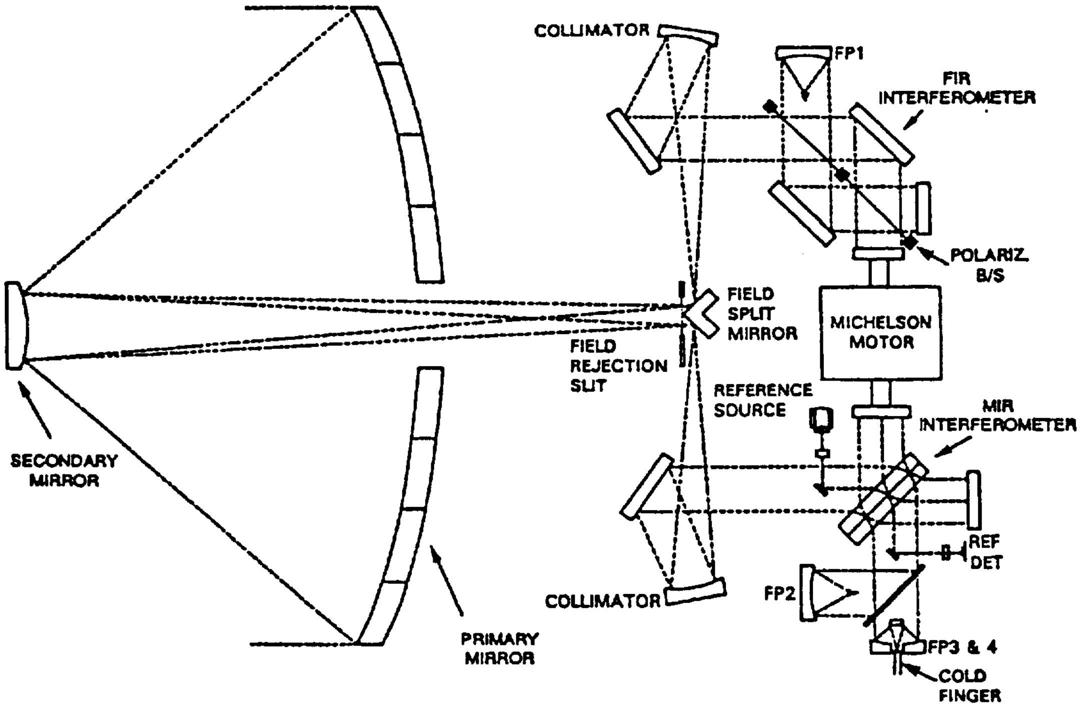

Fig. 3a Optical schematic of CIRS.

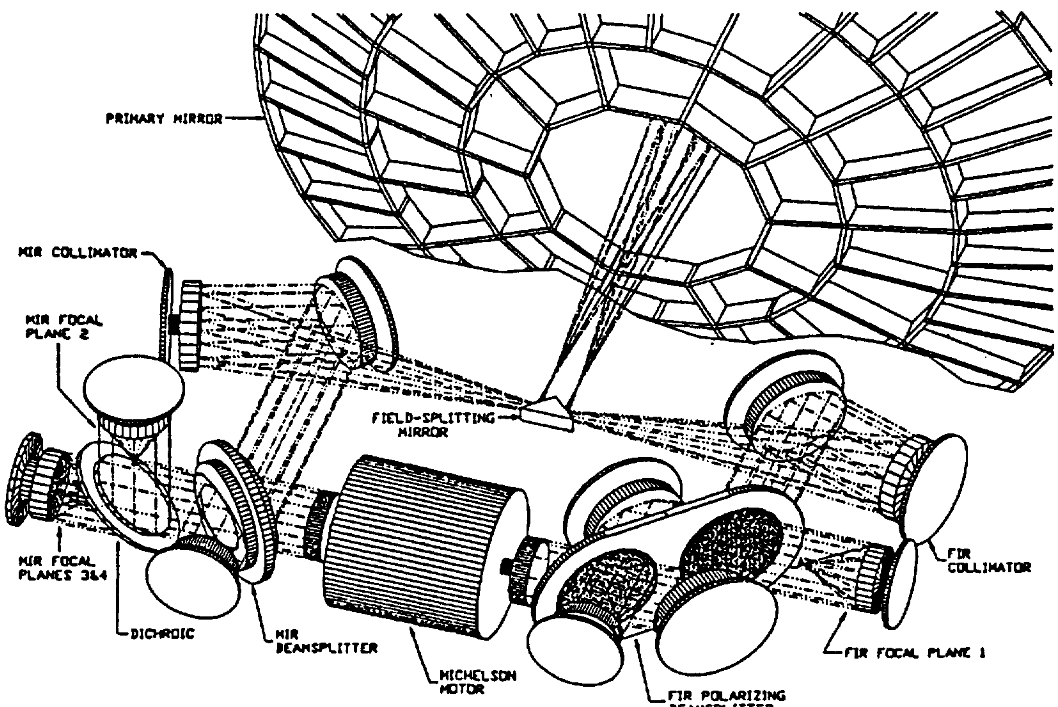

Fig. 3b Exploded view schematic of CIRS.

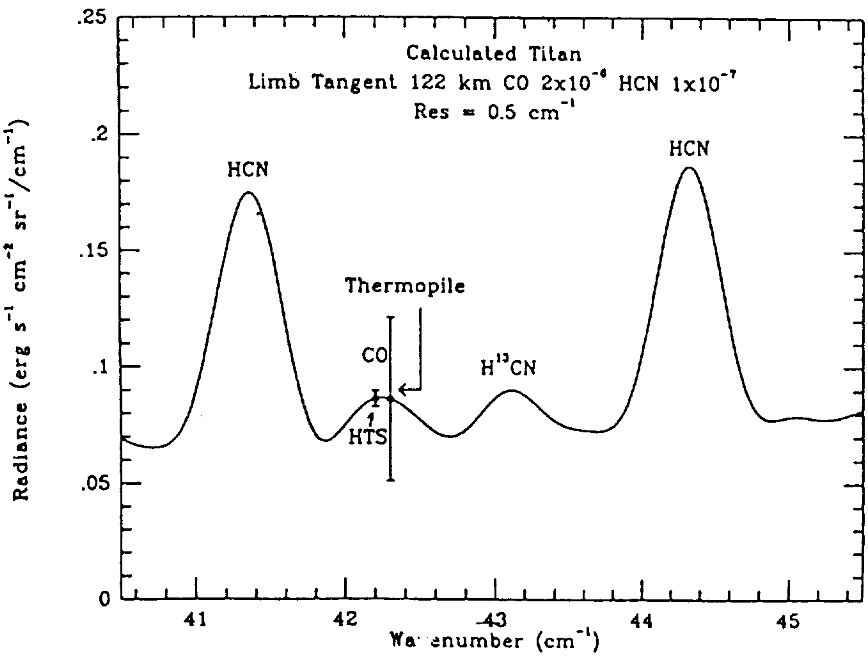

Fig. 4. Synthetic Titan limb tangent spectrum. The smaller 1σ error bars of the HTS detector will allow CO to be measured in the FIRS spectrum.

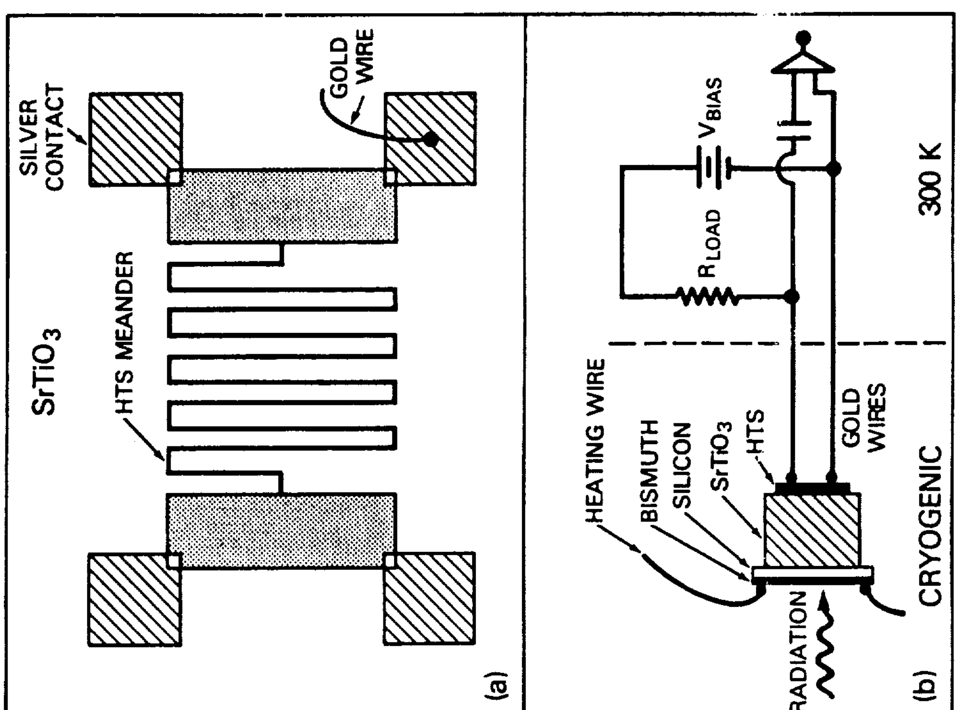

FIG. 5 a) 0.2-μm-thick $Y_1Ba_2Cu_3O_x$ film is patterned into a meander line with 20 μm width, filling an area of 1.5×1.5 mm with a total length of 76 mm; the 1.8×2.7 mm $SrTiO_3$ substrate is 500 μm thick. (b) 2.5×4.0 mm Si wafer, 25 μm thick, is coated on one side with 0.1 μm of bismuth and is bonded on the other side to the $SrTiO_3$ with epoxy.