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FLYING INFRARED TELESCOPE

FINAL REPORT

NASA Grant NSR 44-006-065

1 April 1967 to 31 May 1971

PRINCIPAL INVESTIGATOR F. J. LOW

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ABSTRACT

A telescope has been developed which makes possible routine flux measurements of astronomical objects whose spectral energy peak occurs at wavelengths longer than 25 microns. The 12 inch (30 cm) gyrostabilized instrument, known as the Flying Infrared Telescope, is operated by an observer flying on a jet aircraft in the lower stratosphere. This report discusses the historical development, engineering aspects and the observational record of the Flying Infrared Telescope.

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CONTENTS

I. INTRODUCTION:

The Flying Infrared Telescope has opened a new era in observational astronomy by making possible routine flux measurements of objects whose spectral energy peak occurs at wavelengths longer than 25 microns. This spectral region, extending out to approximately 1000 microns, is essentially unavailable for ground based astronomical observations due to water vapor absorption of the atmosphere.

This report discusses the historical background of the Flying Infrared Telescope. The telescope and its supporting apparatus is illustrated and explained. More than one hundred missions have now been flown with the system installed in NASA operated Lear jets (figure 1). These flights, summarized in table 1, show a broadly based attack on the special problems encountered in this the last spectral region to be explored by astronomers.

It is fitting that a report covering the development, checkout and operation of a unique and powerful new instrument should discuss the new scientific results. Section IV covers the far infrared radiometric observations of the planets Venus, Jupiter, Saturn and Mars. A substantial effort here to understand the planetary spectral information has been necessary because our Flying Infrared Telescope observations yield broadband integrated flux measurements which are calibrated in flight relative to one or more bright planets.

Reported herein are the first observations of several sources associated with galactic H_{II} regions. They are found to have large far infrared (45 - 750μ) fluxes. The galactic nucleus and the discrete sources near the galactic nucleus have been observed on several flights with these results being discussed in some detail. The observations of extra-galactic sources in the far-infrared were made as part of this program.

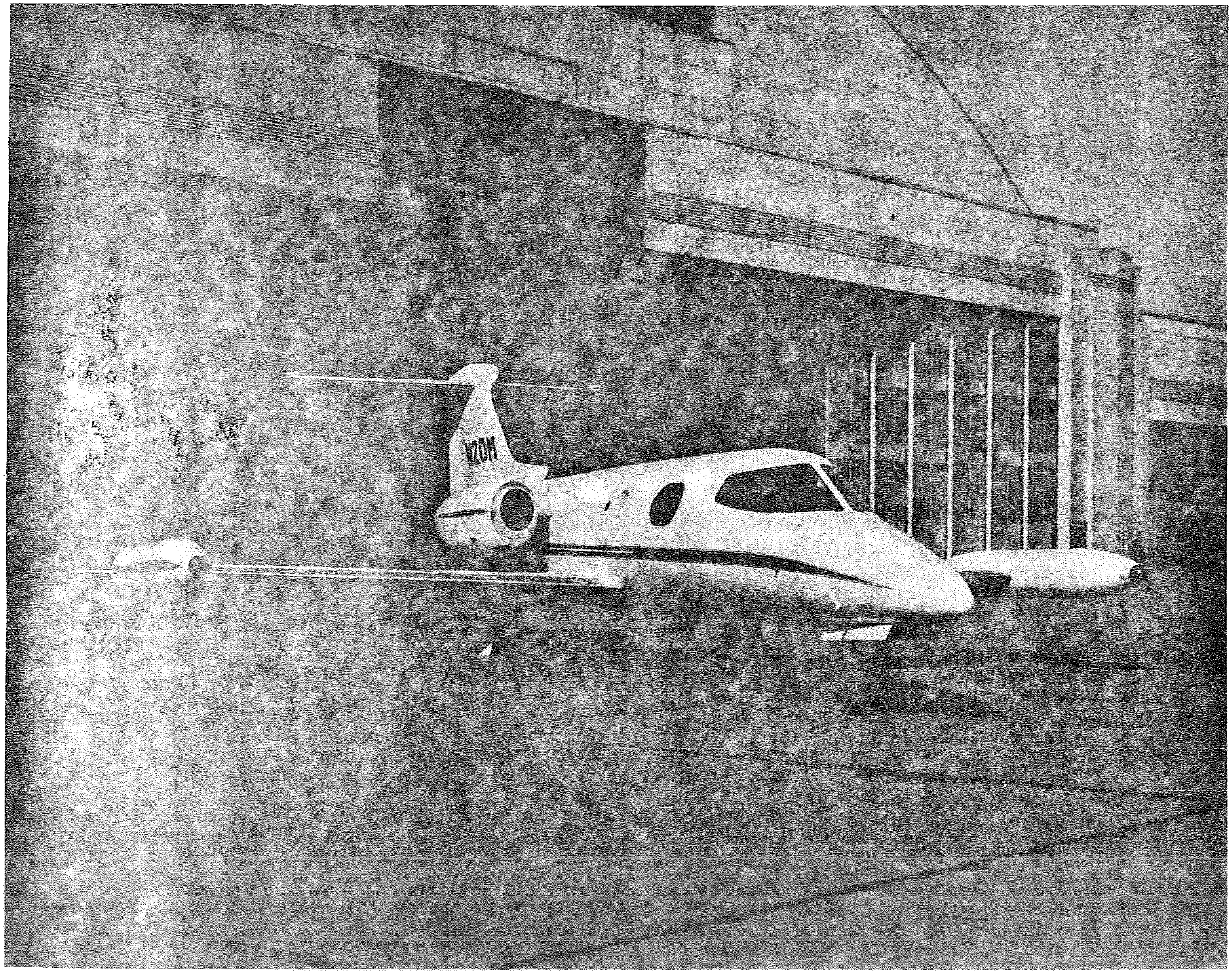

Figure 1

II. HISTORICAL BACKGROUND

Astronomers have long been challenged by the possibility of operating an astronomical telescope at infrared wavelengths on a stable platform high above most of the filtering effects of atmospheric water vapor. Spacecraft, balloons and high altitude aircraft have each been considered in the search for an optimum stable platform for telescope service.

Cost-benefit-time comparison studies were undertaken in 1965 to determine the most economical approach offering a reasonable chance of success in obtaining new data leading toward understanding the nature of astronomical sources whose spectral energy peak is beyond 25 microns. Aircraft seemed to offer the most telescope observing time per unit cost for the period 1965-1970. However, it was necessary to make some flight tests to check the validity of our estimates. A high performance jet aircraft (Douglas A3-B) was made available to us on an occasional basis by the Naval Ordinance Test Station, China Lake, California through the assistance of Dr. Pierre St. Amand of that station.

During the winter 1965-1966 a radiometer and the associated electronics package was designed and fabricated for installation in the Douglas Jet. The brightness temperature of the sun was measured at the wavelength of 1 mm with the aircraft operating at 44,000 feet. It was found that the plane was stable enough to permit the sun's image to be hand guided onto the radiometer for periods ranging from several seconds to several minutes. The experience thus gained confirmed the following facts:

(1) A high performance jet aircraft could be used as an observing platform for an astronomical telescope.

(2) Liquid helium cooled detector technology already in use for ground based infrared astronomy could be extended to aircraft applications.

(3) Sky background vs altitude measurements showed that by penetrating the topopause and climbing a few thousand feet into the lower stratosphere we were in fact operating above most of the obscuring water vapor.

It was with this background and experience that we proposed to NASA the building of a Flying Infrared Telescope.

The proposal to Headquarters (dated December, 1966) was funded in 1967 and called for the design and construction of a 6-inch diameter refracting telescope. The concept involved testing and operating the telescope on the NASA Lear-jet flying out of Ames Research Center. Co-ordination was through Dr. Michel Bader, Chief of the Airborne Science Office at Ames.

Once the design work was under way, it became apparent that a telescope mount accommodating an instrument as large as 12 inches diameter could be fitted into the Lear-jet escape hatch opening. At the same time it was felt that a more useful telescope could be developed by using Cassegrain reflecting optics. Happily, it was determined that these significant improvements could be made without additional cost.

The 12-inch diameter telescope and telescope mount were fabricated and the initial test flight of the basic telescope without a helium cooled detector or a secondary mirror, was flown in December 1967. (figure 2 shows the configuration on this flight) This flight demonstrated that a large open-port instrument could be successfully operated in high performance jet aircraft. Nevertheless, some basic problems came to light


EMERGENCY EXIT
LIFT RED KNOB & PUSH STRAIGHT IN
Guide telescope view port.
Air bearing surface permitting ±3° telescope movement.

FIGURE 2

requiring several months of engineering time and experimentation. Basically the problems were grouped into the following areas: (1) Cabin Pressurization, (2) Organ Piping of the Open-Port Telescope and (3) The star-light chopper or modulating mechanism.

The Lear-jet cabin could not be maintained at the normal 8 PSI differential without the cabin air pressure deforming the telescope gimbal ring in a manner which prevented free movement throughout the ±3 degree (roll and yaw) design range. A two fold solution involved increasing the load bearing capability of the gimbal ring and lowering the cabin differential pressure to 4.5 PSI above the outside (cabin altitude about 18,000 feet with the Lear-jet at 50,000 feet). The lower cabin pressure presented no new problems as it had already been decided that the crew would wear oxygen masks as a safety precaution. The result was that the telescope could now move throughout its design range.

When the open port main telescope tube was first test flown without the secondary mirror installed (figure 2) there was a moderate vibration and a loud audio note due to the slipstream flowing past the large orifice. A two-fold solution was found: (1) The sound was greatly reduced when the secondary mirror and its supporting spider was installed- apparently breaking up the turbulence at the mouth of the tube and (2) by restricting the aircraft speed in the denser air at low altitudes (not more than 250 kt. IAS below 20,000 feet). With the secondary installed there is no audible sound above 20,000 feet at any airspeed. Later a boundary layer deflector was developed by Ames and installed on the forward edge of the special telescope mounting window. This effectively eliminates the noise at low altitude (during climb-out and let-down) without causing any noticeable effect on performance of the far-infrared system at high operational altitudes.

The third major problem encountered was with the chopper. In any infrared telescope it is necessary to modulate the incoming signal before it reaches the detector. This modulation is usually done in such a way as to separate the wanted signal from the large background on which it is superimposed. Various schemes are possible and many have been tried. In working with the Flying Infrared Telescope we arrived at a new chopping technique built around a mechanism which moves the small secondary mirror back and forth through an arc just large enough to shift the star image on and off of the detector. There are several advantages to a system of this type. First, the geometrical equivalence of the two paths through the telescope is easily accomplished. By adjusting the time spent in each of the two fixed positions of the secondary, it is possible to minimize the unwanted DC offset resulting from the background. Second, the adjustments are relatively simple and do not require the cryogenic dewar containing the detector to be installed at the time of chopper adjustments.

Incidentally, it has been shown that this same method of chopping can be used to greatly increase the sensitivity of ground-based infrared telescopes due to the almost complete cancellation of sky noise. An interesting sidelight is that this technique, so beneficial to ground based astronomy, emerged as a result of development work on the airborne telescope, which is supposed to operate in an environment essentially free of sky noise.

Simultaneously with the chopper development work, we assembled and flew a direct power radiometer open in the wavelength region from 1.6 microns to 50 microns. Sky brightness measurements were made with this instrument at altitudes up to 50,000 feet, both with and without the telescope optics in the path (i.e. the secondary and its supporting spider were removed for one flight). These measurements demonstrated that: (1) above the tropopause the sky brightness remains essentially constant at about 120°K, and (2) the thermal emission from the two mirrors in the telescope dominates the sky emission. It is this background radiation which sets the ultimate limit to the sensitivity of our detector and, in fact, it is necessary to know the magnitude of this background in order to optimize the design of a particular detector.

This series of measurements, which were obtained on 2 and 3 May, 1968, led us to two important conclusions: (1) The transmission and thermal emission of the Earth's atmosphere above the tropopause is such that astronomical observations throughout the far infrared are entirely feasible from jet aircraft; (2) It will be a difficult problem to design an infrared telescope for aircraft use which has thermal emission as low as the inherent sky emission. Unwanted instrumental background radiation can be reduced by cooling the telescope optics and tube baffle system by means of a liquid and/or solid cryogen(s).

A cooled airborne telescope is currently being built by this group with an NSF grant. The instrument is small and not tailored for regular astronomical observing (it is part of a cosmological background experiment) but the solution of problems encountered will undoubtedly point the way toward a major Cooled Infrared Flying Telescope. A moderate sized instrument of this type designed for astronomical observations could be operating within a year if construction funds were available.

Additional information on the operation of the telescope program is available in the technical literature(1).

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(1) Closing Astronomy's Last Frontier - FAR INFRARED; Low, Aumann, and Gillespie, Astronautics and Aeronautics, July 1970.

III. THE FLYING INFRARED TELESCOPE SYSTEM

A. THE AIRCRAFT:

The first airplane used for our infrared experiments was a twin jet Douglas A3-B*, operating at an altitude of 44,000 feet. Other planes (RB-57F, U-2, and SR-71) capable of working above 60,000 feet were carefully considered but would have required unmanned automatic operation of the telescope. It was felt that in a first generation system the increased complexity and sophistication would be too high a price to pay for the additional 20 or 30 thousand feet of operational altitude which might be gained.

In retrospect starting with a manned telescope has proven to be the correct approach. Manned operation using an observer and a console operator or assistant observer has enabled our group to get a first hand understanding of problems as they were encountered and on occasion to make corrections in flight. Not only are the above mentioned extremely high altitude airplanes very expensive to fly but development and laboratory testing costs of a semi-automatic system would have been 2 to 5 times higher than has actually been spent on the <u>Flying Infrared Telescope</u>.

Aviation physiologists have advised that 50,000 feet is a practical altitude limit for routine manned operation (in the time frame 1966-1971) without having the crew in pressure suits. That is, even with a pressurized cabin, the dangers to human life make operation above 50,000 ft unacceptable due to the possibility of explosive decompression, compressor-failure etc.

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*This Navy airplane and its crew were tragically lost in 1967 while on a routine administrative flight not connected with our research.

This can be understood when it is considered that in the unlikely event of such a failure the total useful consciousness of the crew is in the range of 12 to 15 seconds. Undoubtedly, if a substantial need were demonstrated, special research vehicles for operation in the 50,000 to 80,000 foot region could be developed which would provide a shirt sleeve environment with manned spaceship reliability. We accepted 50,000 feet as a working ceiling and started looking for an aircraft which would serve as a stable telescope platform.

Preliminary discussions with George Cooper, Chief of Aircraft operations, at NASA- Ames Research Center led us to think that the NASA owned Lear Jet model 23 (shown with the telescope installed in the escape hatch in figure 3) might be an ideal aircraft for these high altitude missions. An agreement was reached between the Flight Operations and the Airborne Science Office at NASA-Ames for three feasibility test flights.

A high pressure oxygen system for the crew was temporarily installed along with the hand guided radiometer previously used aboard the A3-B. Ames pilots, Glen Stinette and Gordon Hardy and Rice University observer Carl Gillespie Jr. flew the three 50,000 feet test missions. Two flights were very smooth with some moderate turbulence encountered 10,000 feet above a massive cumulonimbus cloud formation on the third and last flight.

Three conclusions were reached: (1) A model 23 Lear jet could reach 50,000 feet with about 1 hour working time on track at that altitude. (2) Significantly more working time (up to 2 hours total) on track would be available if the airplane could be operated at 47,000 to 48,000 feet depending on outside air temperature and possibly other atmospheric parameters. (3) The roll axis stability is excellent if the aircraft control rigging

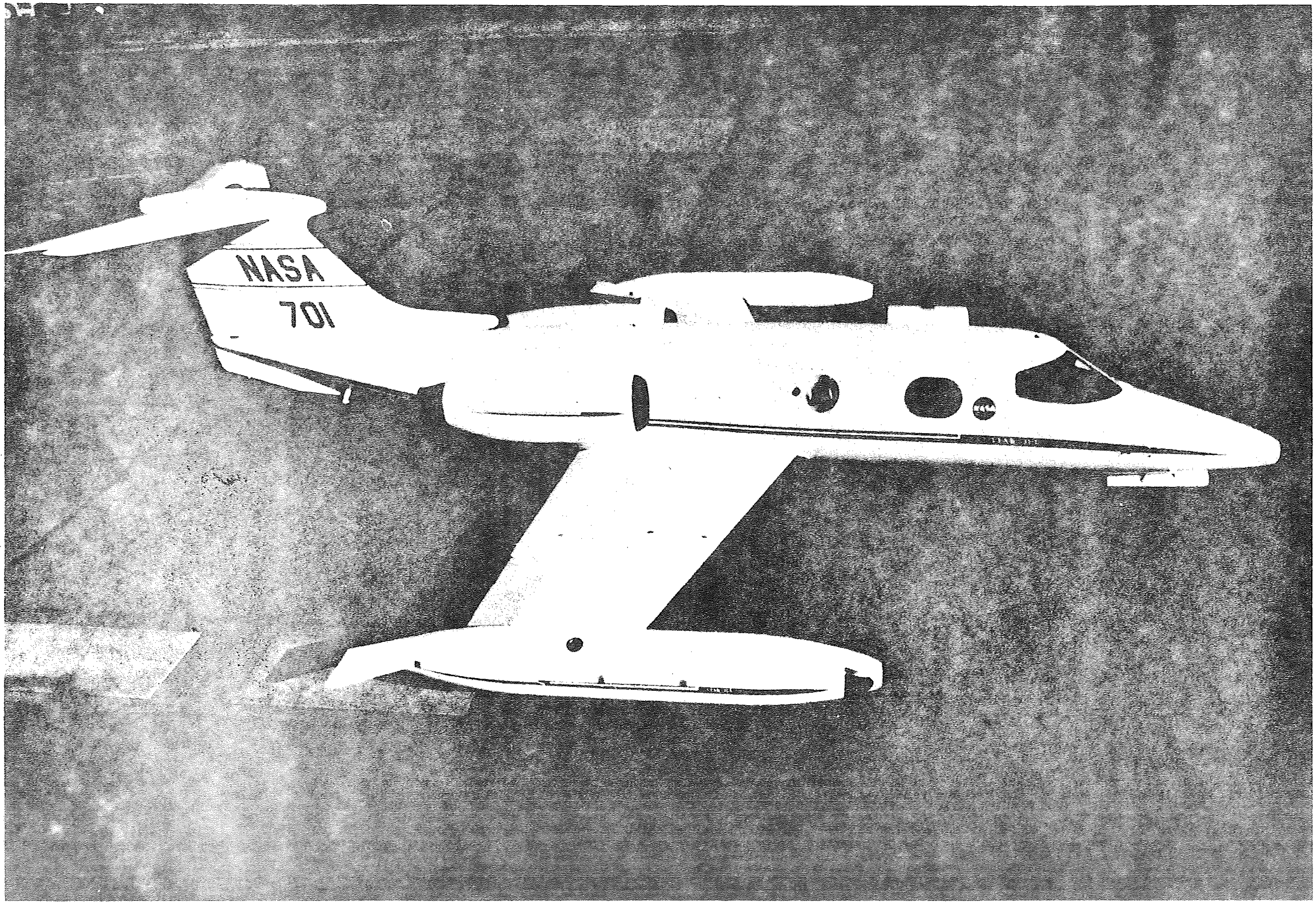

Figure 3

is in good repair and the auto-pilot is properly adjusted. As a result of these tests we estimated that a telescope could achieve 1 arc minute guiding under stable conditions at altitude. This guiding accuracy was, in fact, more difficult to obtain than first believed but was finally achieved in routine operation during calendar year 1970.

It was recognized early that not all flights would need to be operated at the maximum altitude and that an operational floor might be established a few thousand feet above the observed tropopause (most ascending tropopause penetrations are accompanied by a clearly measurable warming of the outside air temperature). The British pioneered with water vapor measurements in the lower stratosphere (vicinity of 50,000 feet) in 1954 and 1955. This work, summarized by Craig(2), points to the existence of a frost point tropopause located three to six thousand feet above the temperature tropopause. Additional information on the upper troposphere and lower stratosphere at mid-latitudes in the western United States was obtained from meteorological records(3) compiled at U. S. Naval Ordinance Test Station, China Lake, California.

In practice, on our flights, the mid-latitude tropopause has been found at altitudes as low as 34,000 feet in the winter and up to 49,500 feet in the summer. Thus, in more than 90% of the flights, we have been able to work at what would appear to be the best altitude, from the point of view of precipitable water vapor above the aircraft, without making a quantum jump to a very much more expensive aircraft and telescope apparatus. The stratospheric water vapor problem should be better understood before any additional altitude (beyond 50,000 feet) can be justified.

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(2) The Upper Atmosphere, Richard A. Craig, Academic Press 1965, Chapter 2.

(3) Tropopauses and Related Atmospheric Phenomena at the Naval Ordinance Test Station, P. H. Miller and D. L. Farnham, NAVORD Report 6533, 1959.

One of the great virtues of the Lear jet is that it is physically small enough so that maintenance and flight scheduling can be kept very flexible. Once astronomers have been freed from the constraints of atmospheric obscurations (clouds-both visible and invisible) there are not many observations that cannot be shifted a few days if necessary to permit unscheduled aircraft or telescope maintenance or to accommodate another aircraft user. One exception to this is moonlight which can cause a failure if the mission calls for offset guiding on very faint stars. Such missions now are planned for dark of the moon periods.

Other aircraft in the light to intermediate business jet category have been considered but without special engines and/or other modifications it has not been shown that routine stratospheric operation could be achieved above the high mid-latitude summertime tropopause.

B. THE TELESCOPE:

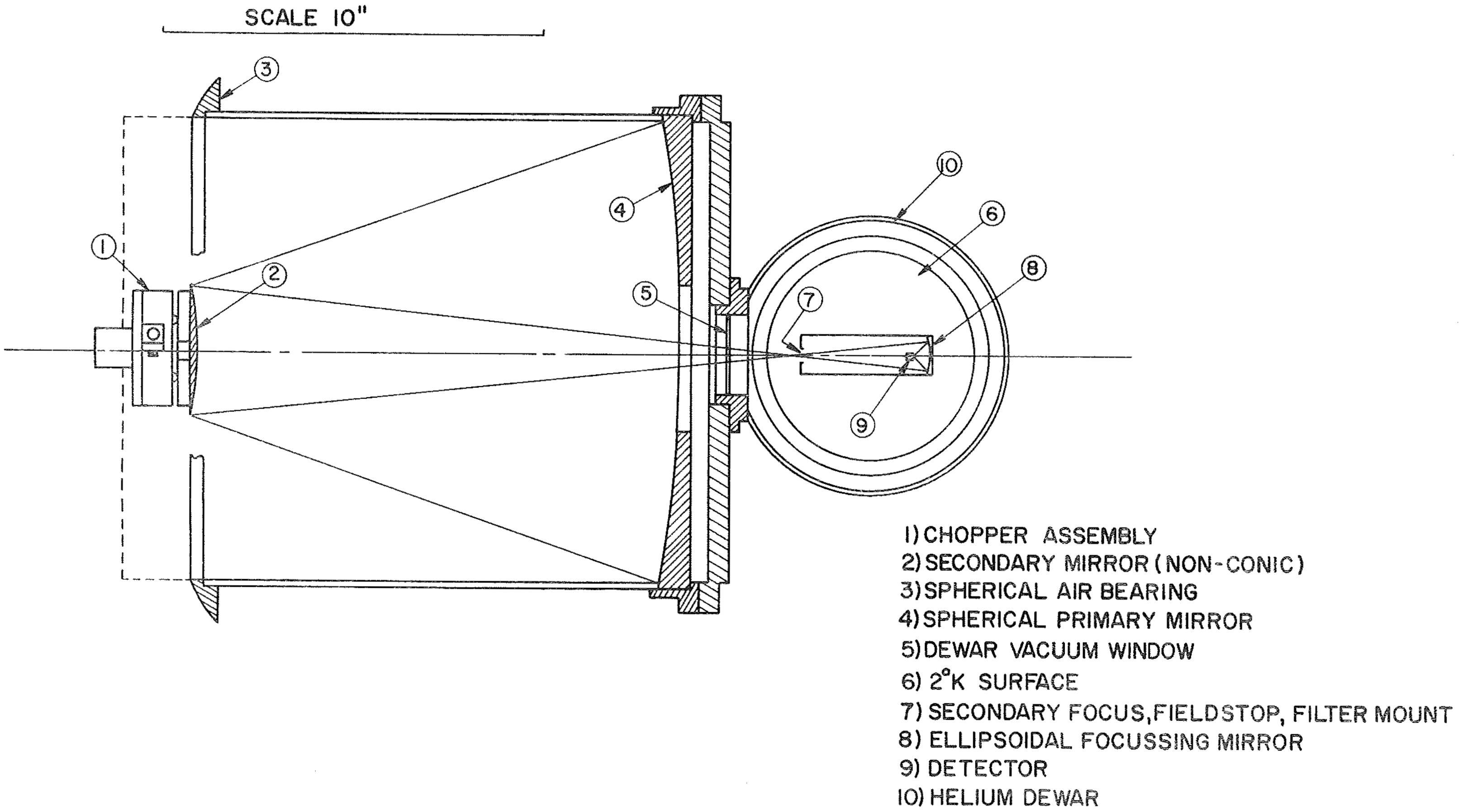
Some characteristics of the Flying Infrared Telescope have been mentioned in section II which traces the historical development of the instrument.

The telescope is a Cassegrain system with a 12" diameter f/1.5 spherical primary mirror and a 3.4" diameter non-conic secondary mirror. The effective f-number of the system, depending on the location of the focal point, is near f/5, with a telescope scale of about 2 arcmin/mm.

A simplified schematic view, figure 4 , shows the primary mirror (4) and the secondary mirror (2) attached to the optical chopper assembly (1). The telescope focuses on a fieldstop (7) mounted to the $2^{\circ}K$ surface (6) in the helium dewar (10). The vacuum window (5) of the helium dewar may be transparent throughout the infrared or define, together with the cooled filters (7), the wavelength passband of the system.

Beam size requirements determine the location and the size of the fieldstop and whether further baffles and lenses or mirrors are needed to focus the energy in the telescope beam onto the detector (9). The detector output is amplified and recorded electronically.

The details of the configuration inside the dewar are changed for almost every sequence of flights in order to optimize signal-to-noise ratios to achieve specific mission objectives. The vacuum jacketed helium dewar attaches with two mounting bolts to the back mounting plate of the telescope. This quick disconnect feature has permitted us to develop a family of dewars each with slightly different properties but all interchangeable on the telescope. In addition to the dewar layout shown in figure 4 , we have been successfully using a silicon field lens system to



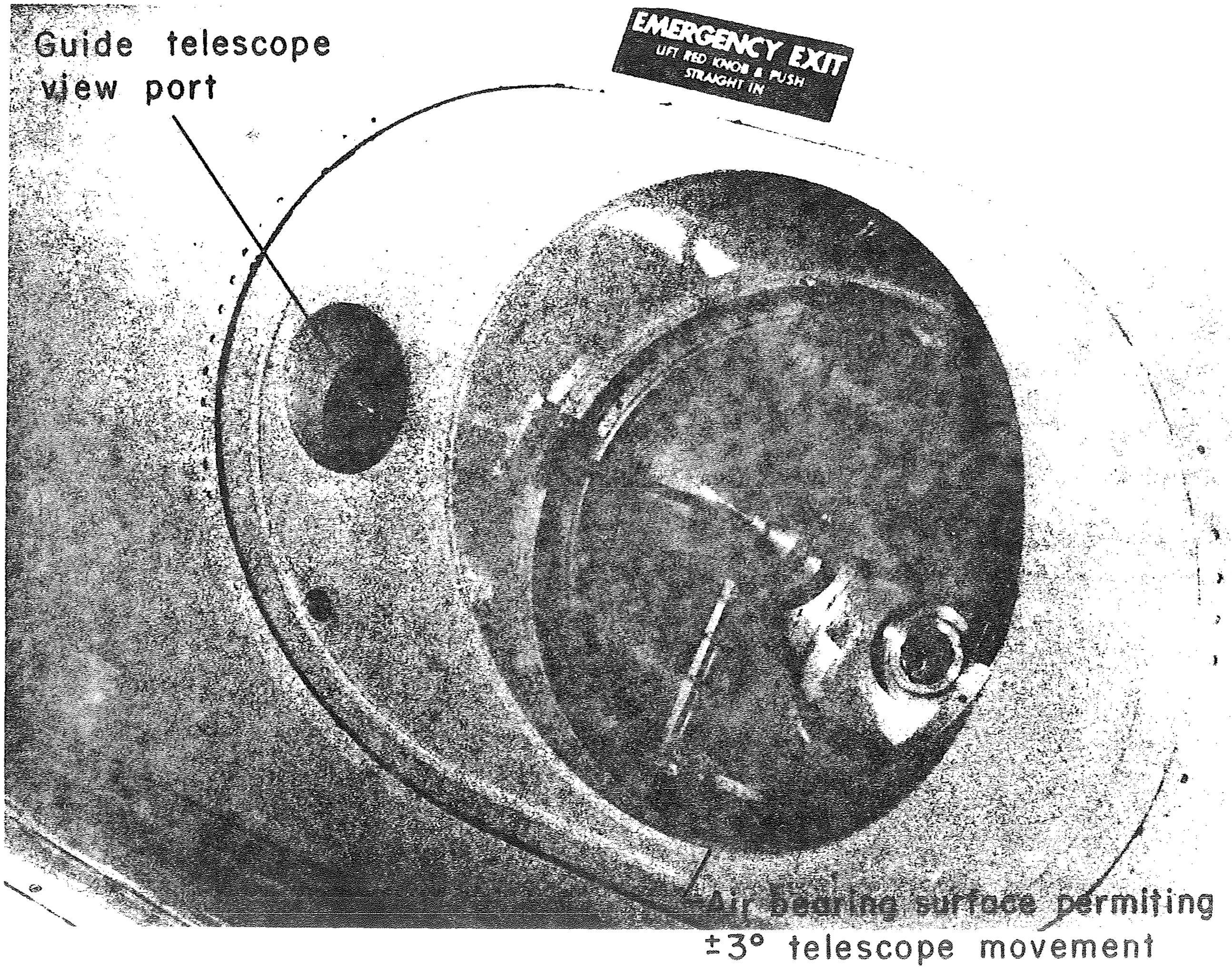
Flying Infrared Telescope simplified schematic view
Figure 4

focus the energy on the detector. In like manner, still another dewar has been configured with a 6 position cold ($\approx 2^{\circ}K$) far infrared filter wheel. This dewar has been particularly useful in the moderate resolution radiometric observations of the planets reported in section IV.

The telescope is mounted in the emergency exit (aft window on the right side of the airplane) by means of a special window mount (figure 5). Two such window mounts have been fabricated, one centers the telescope viewing angle at 22°, the other at 45° above the horizon.

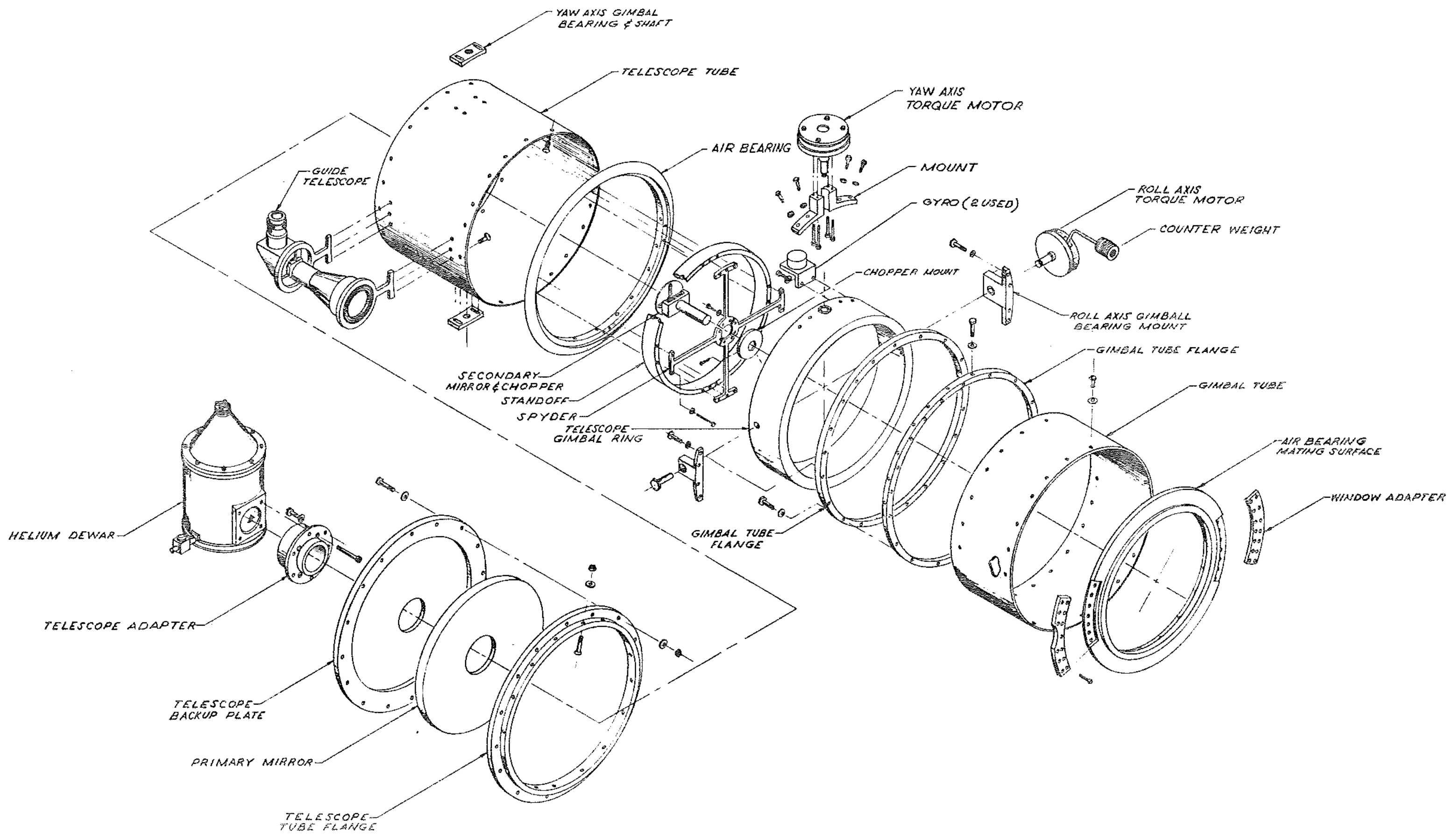
An exploded view of the telescope is shown in figure 6. The telescope tube is mounted via a gimbal ring and a gimbal tube to the window mount. The gimbal ring and two mating air-bearing surfaces permit ±3° movement of the telescope in azimuth (yaw) and elevation (roll) relative to the airplane. The spacing between the pseudo air-bearing surfaces is carefully adjusted such that free movement is possible with up to 4.5 psi differential pressure across the telescope-backup-plate which also serves as the pressure bulkhead. Most of the force tending to drive the telescope through the wall of the cabin (from 500 to 1500 pounds depending on cabin pressure) is carried by the low-friction bearings in the gimble rather than by the air bearing; however, deformation of the gimble under maximum pressure simply forces the tube into a frozen position in the spherical bearing, and is completely safe.

The optical system consists of (1) a 12-inch diameter spherical primary mirror and (2) a 3.4-inch diameter figured secondary mirror made of silicon. Both mirrors are optically polished and metallic coated by vacuum deposition to achieve high infrared reflectivity and low emissivity.



TELESCOPE WINDOW MOUNT

Figure 5



Exploded view of the Telescope

Figure 6

A unique feature of this telescope, now copied to great advantage on many larger groundbased telescopes, is the chopper. In all infrared telescopes it is necessary to modulate or chop the incoming signal from a given source. If the source is very small in angular size it can be modulated by switching the beam of the telescope on and off the source. Here, this is accomplished by moving the secondary mirror through a small angle between two fixed positions. This divides the light from a star into two equally bright images separated by the size of the focal plane diaphram, through which only one image can pass. In both positions of the secondary mirror, the background radiation emitted by the telescope and by the atmosphere is almost identical and is not modulated. This allows signals much weaker than the background to be measured.

The wobbling secondary mirror mechanism is rigidly attached to the front of the movable telescope tube by means of a four-leg spider. The primary mirror is supported at the back of the open telescope tube by means of a backup plate. The other side of this plate also serves as the mounting surface for the helium dewar.

A 10-power, 2" diameter telescope with a 6° field of view is fastened to the side of the main IR telescope tube. This guide scope is aligned with the optical axis of the main telescope and permits positive starfield identification and guiding. The observer controls the orientation of the telescope relative to the airplane with a joy stick which activates yaw-axis and roll-axis torque motors. Both axes are gyrostabilized. The weight of the telescope unit, approximately 120 lbs., is kept low through the use of light-weight aluminum construction. Both mirrors are light weight and have high enough thermal conductivity to reach thermal equilibrium with the ambient atmosphere as the plane climbs into the stratosphere.

C. THE RADIOMETER:

The discussion of the Flying Infrared Telescope radiometer can be divided into 3 basic elements: detector, Dewar and filters.

The heart of any infrared telescope is the detector, since its performance determines the ultimate sensitivity of the entire system. The detector we are using is the germanium bolometer (4), cooled to $2^{o}K$ by liquid helium. It has an almost uniform spectral response from the near infrared to millimeter wavelengths and more than adequate sensitivity for our present requirements.

A vacuum jacketed liquid helium container or Dewar provides the cryogenic environment required for operation of the detector. The bandwidth of this type of radiometer is determined by transmission filters placed in the radiation beam just in front of the detector. The materials making the filter may be fixed in place in the case of a single band instrument or on a filter slide or filter wheel in the case of multiband radiometers. Each of these 3 elements is discussed in this section.

A. Detector

The detectors used throughout this work have been Ge:Ga bolometers. The detector, consisting of a single gallium doped germanium crystal operates at a temperature of approximately $1.8^{o}K$, achieved by pumping on liquid helium. It has an essentially flat response from 1.5μ wavelength to 1000μ.

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(4) "Low Temperature Germanium Bolometer" F. J. Low, J. Opti. Soc. Am., Vol. 51, pp. 1300-1304, Nov. 1961.

The sensitivity of cryogenic bolometers has been discussed in detail by Low and Hoffman(5). It is commonly characterized by the amount of incident power necessary to achieve unit signal-to-noise ratio, the noise equivalent power (N.E.P.).

In general, the N.E.P. of a bolometer decreases, i.e., improves, with decreasing background radiation. The N.E.P. of a nearly "perfect" bolometer is determined by phonon noise and photon noise. The former is due to temperature fluctuations caused by the random flow of heat, the incident background radiation, between the sensing element and the heat sink. The random arrival of photons incident on the detector from the background gives rise to photon noise.

With present technology, N.E.P. values very close to theoretically limiting values are possible. In application with low background levels ($\leqslant 10^{-7}$ watt) where a relatively slow response time can be tolerated ($\geqslant 2 \times 10^{-2}$ sec) values of $10^{-14} \frac{\text{watt}}{\text{Hz}^{\frac{1}{2}}}$ have been achieved.

b) Detector Size and Beam Size

For operation of this telescope, beam sizes well above the diffraction limits, ranging from 3 arcmin to 15 arcmin, were dictated by limited pointing capabilities and the necessity to offset guide (on faint objects such as the galactic center).

If the detector is placed at the focal point of the telescope, the detector size defines the beam size. Since the response speed of the Ge:Ga bolometer decreases with increasing detector area, optimum detector design considerations make a detector larger than 1.5 mm diameter impractical. Thus, with the telescope scale of approximately 2 arcmin/mm, the maximum field of view is 3 arcmin. Larger fields of view, while still using detector no larger than 1.5 mm in diameter, can be

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(5) The Detectivity of Cryogenic Bolometers, F. J. Low and A. R. Hoffman, Applied Optics, 2, 649, 1963.

achieved through the use of additional field lenses or mirrors which focus the energy in the beam onto the detector.

Several methods have been employed to couple the incoming infrared radiation onto the detector. Two are described in some detail here.

1) A Fabry lens is mounted at the focal point of the telescope such that it images the primary mirror onto the detector. Plano-convex spherical lenses made of intrinsic silicon and high density polyethylene have been used. The beam diameter of the telescope equals the aperture d_F of the Fabry lens. Since aberations make the use of spherical lenses with focal length $f_F < 2\ d_F$ unadvisable, the maximum detector magnification achievable is half the f-number of the telescope, 2.5 in our case. With a 1.5 mm diameter, detector beams with 7.5 arcmin diameter are obtainable.

2) A mirror images a fieldstop, defining the beam diameter and placed at the focal point of the telescope, onto the detector. For detector magnification of less than 4 the mirror can be spherical. A detector magnification of 7 has been achieved with an ellipsoidal mirror. Using a 1.5 mm diameter detector this magnification would permit a 21 arcmin beam.

The design, fabrication, assembly and testing of the radiometer system is a time consuming and expensive process but the results have been gratifying. We have built and flown instruments of great sensitivity and moderate spectral resolution in a wavelength region where little or no previous work has been done.

B. Cryogenic Dewars

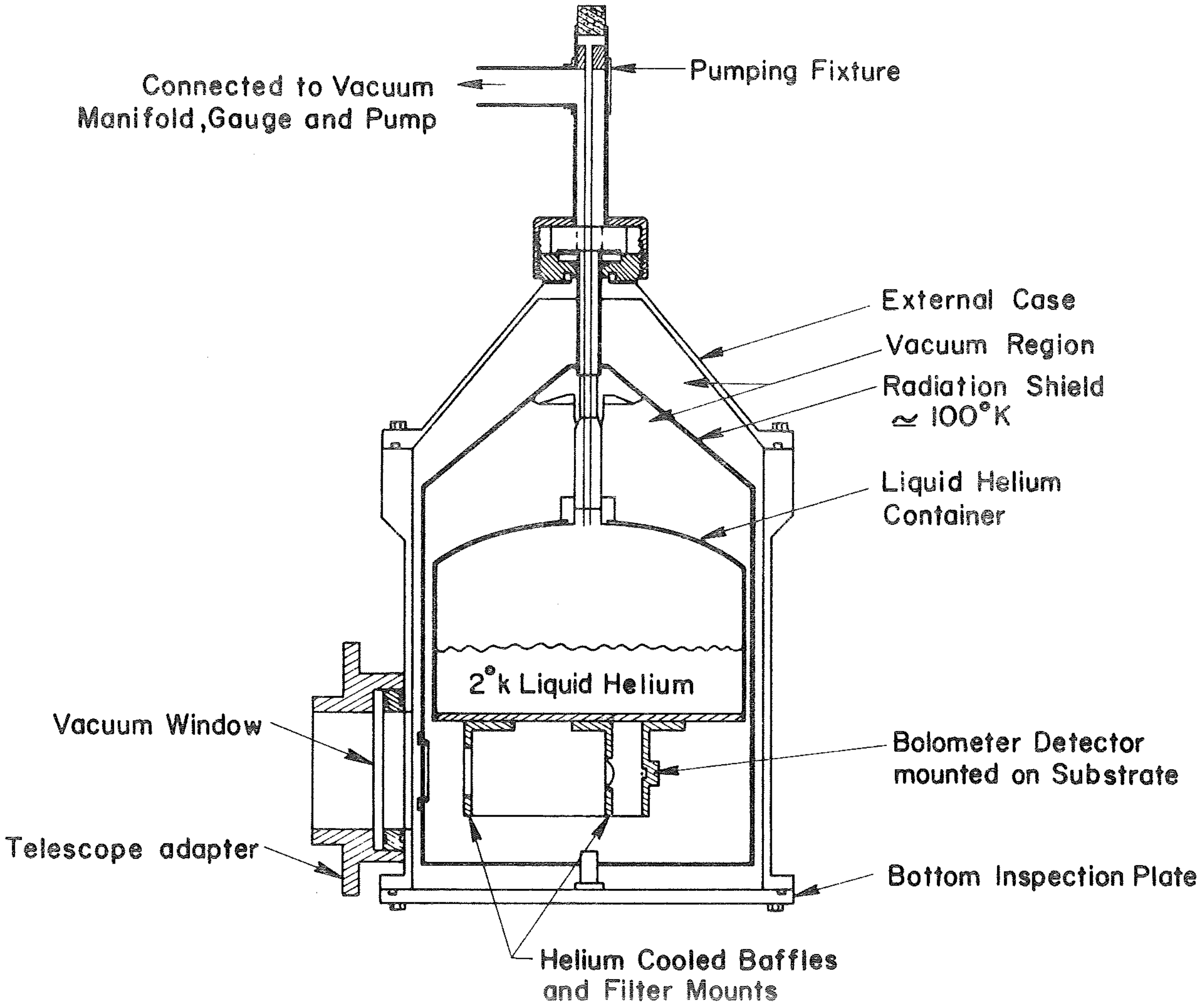
The dewar contains the liquid helium necessary to cool the detector to $\approx 2^{\circ}K$. This dewar differs from helium cryostats in common laboratory usage in that it is of all-metal construction and that it does not need liquid nitrogen to cool the radiation shield. Both features are the keys to the successful use of helium-cooled detectors on a telescope operated aboard a high performance jet aircraft.

The dewar is shown in Figure 7 . A stainless steel can with a copper bottom contains the helium. The pieces to be cooled -- detectors, lenses, mirrors, filters, light baffles -- are attached to the copper bottom and are cooled by conduction. The stainless steel necktube, with .008" thick walls, supports both the dewar and the radiation shield. Lateral motions are minimized through the use of nylon spacing screws. The radiation shield is attached to the neck tube by means of a copper heat exchanger; the shield is then cooled to about 100°K by the helium vapors passing through the tube. The entire volume between the dewar and the case is evacuated to provide insulation. The dewar attaches to the telescope by means of an adapter which also serves as a mount for the dewar vacuum window which can in some cases perform a part of the filtering function.

A family of radiometers have been assembled during the course of this program each differing in some respect in the way that the chopped infrared radiation is manipulated onto the detector or in the type of bandpass filtering used.

C. Far Infrared Filters:

One result of the Flying Infrared Telescope program has been the construction of high throughput, moderate to wide passband filters to be used for photometry of far infrared sources. The filters were designed to operate in the spectral range between 30 and 300 μ, wavelengths which are strongly absorbed by tropospheric water vapor. Special attention has been given to the 30 - 100 μ interval since most of the observed sources radiate their peak fluxes in that region.



FLYING INFRARED TELESCOPE DEWAR

Figure 7

Conventional thin film technology begins to fail between 20μm and 30μm because of the dearth of suitable dielectric materials and the difficulty of depositing increasingly thick films in durable multilayers. On the other hand, techniques which are applicable at submillimeter wavelengths (e.g., multilayer low pass filters constructed from capacitive meshes deposited on thin plastic films) become extremely difficult as the characteristic dimensions of the systems drop below 100 μm. Extension of either the thin film or submillimeter technology to the 30 - 100μ region would require a complex and expensive development program and would probably result in extremely fragile filters unsuitable for the demanding experimental environment of the <u>Flying Infrared Telescope</u> system. Therefore we have concentrated on utilizing the natural absorption characteristics of plastics and crystalline materials and on those submillimeter techniques which can be readily scaled down to the 30 - 100 μm wavelength region without sacrificing simplicity and durability (i.e., interference filters constructed from commercially available electroformed metal mesh).

Emphasis has been placed on integration of the various filter techniques into the infrared radiometer in such a manner that the overall signal-to-noise ratio of the system is maximized. The required filter characteristics are determined by the following considerations:

(1) Since it is necessary to use the planets as calibration objects, the stopband blocking below 30 μm must be quite effective, particularly for systems with narrow bandwidths or low pass cut-ons beyond 100 μm. The problem is especially acute for the warmer objects such as Venus and Mars and for Jupiter which has an anomalous peak in its spectrum at ~ 4-5μm.

4-6μm radiation is particularly difficult to attenuate due to a scarcity of materials which absorb in the desired interval yet transmit efficiently beyond 30μm. For instance, 0.1 mm thick black polyethylene transmits 4% of the radiation of 5μm but only 50% at 40μm. Crystalline materials which are transparent beyond 30μm are, as a rule, also transparent at 5μm (e.g., quartz, sapphire, silicon, and germanium).

(2) A major source of noise in the Flying Infrared Telescope system has been thought to be vibrational modulation of the instrumental thermal background radiation. Thus the lowest intrinsic system noise is achieved with helium cooled filters with narrow bandwidth or long wavelength cut-ons. Ambient temperature filters attenuate the signal while resulting in noise at a level greater than or equal to its broadband value.

(3) Since many of the far infrared sources are relatively faint and observing time is limited, the filters should have high passband transmission and sharp cut-ons.

We have found that satisfactory solutions to the problems stated above can be achieved by the following means:

(1) We have developed efficient low pass filters for blocking 4-5μm wavelengths. These filters consist of a layer of high refractive index particles (diamond dust) deposited on a polyethylene substrate and bonded with plastic spray paint. The diamond scatters wavelengths smaller than the particle size with high efficiency. The layer rapidly becomes transparent at longer wavelengths, however. For an equivalent amount of attenuation at 5μm, the diamond dust filter is much more efficient than black polyethylene between 30 and 80μm. (see Figure 8). Since the properties of the filters are dependent on the refractive index and size of the particles rather than absorption, they can be tailored to meet a wide range of specifications.

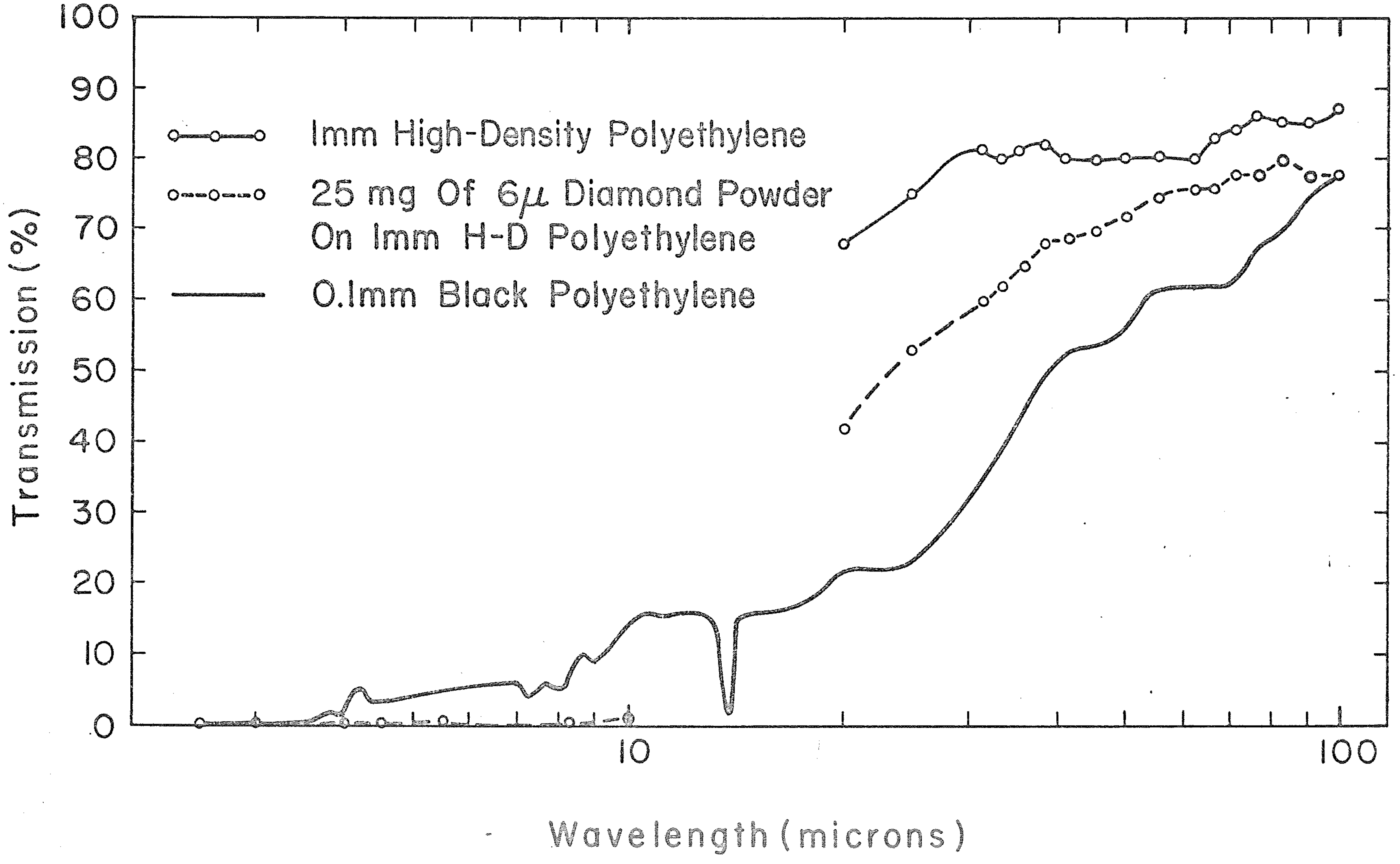

100
90
80
70
60
50
40
30
20
10
0
Transmission (%)
Imm High-Density Polyethylene
25 mg Of 6μ Diamond Powder
On Imm H-D Polyethylene
0.Imm Black Polyethylene
10
100
Wavelength (microns)

Figure 8

An additional advantage of the process is that the required blocking may be achieved by treating the surface of the polyethylene vacuum window of the radiometer dewar, eliminating an extra element from the optical path. Such a window has operated in the Flying Infrared Telescope system for approximately 20 flights with no sign of deterioration.

(2) A helium cooled filter turret has been designed and installed in one of the flight radiometer systems. The device allows us to restrict noise and bandwidth simultaneously. It also permits the use of crystal filter materials which display sharp cut-ons when cooled to cryogenic temperatures. (For a summary of low temperature transmission data in the current literature, see Hadni 1967.)(6) The use of these materials in low pass and bandpass filters is illustrated in Figures 9 and 10. Their principal advantages as low pass filters are a rapid cut-on and good stopband blocking. For example (Figure 9) calcium fluoride displays a significantly sharper cut-on in the form of a helium-cooled single crystal than when incorporated in a powder-type filter such as those described by Yamada et. al. (1962).(7) On the other hand, the calcium fluoride stopband extends below 27μ while teflon, which has a relatively rapid cut-on at 50μ, is partially transparent between 20 and 50μ. The stopband blocking of the teflon can be enhanced by increasing the thickness of the sample, but only at the expense of reducing the slope of the cut-on. The shape of the calcium fluoride cut-on is relatively insensitive to sample thickness, depending primarily on the rate of change of index of refraction with wavelength. The 35μ and 60μ bandpass filters shown in Figure10

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(6) Essentials of Modern Physics Applied to the Study of the Infrared, Armand Hadni, Pergamon 1967.

(7) Yamada Y., Mitshuishi A. and Yoshinaga H., J. Opti. Soc. Am. 52, 17 (1962)

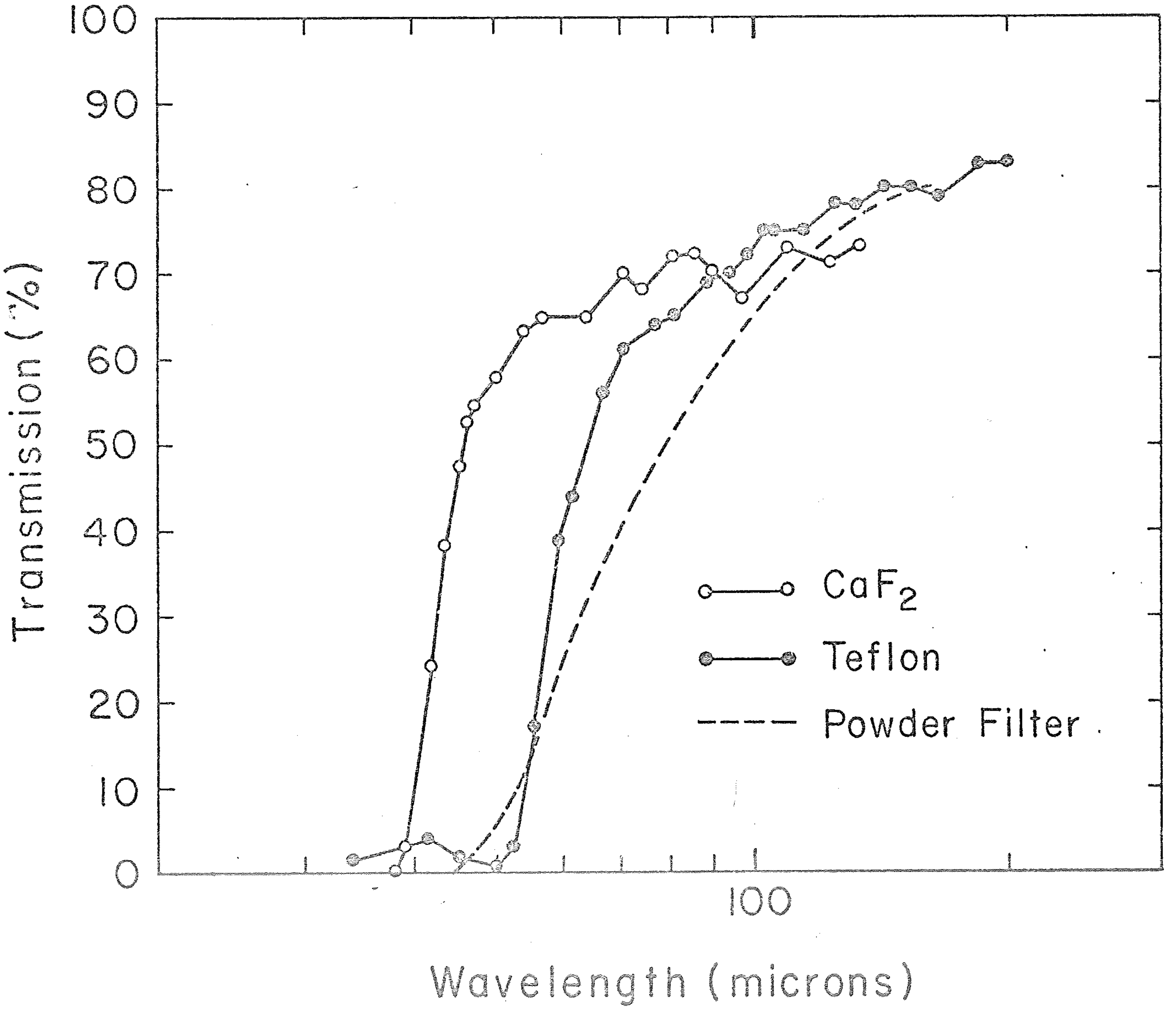
Transmission (%)
100
90
80
70
60
50
40
30
20
10
0
100
Wavelength (microns)
CaF_2
Teflon
Powder Filter

Figure 9

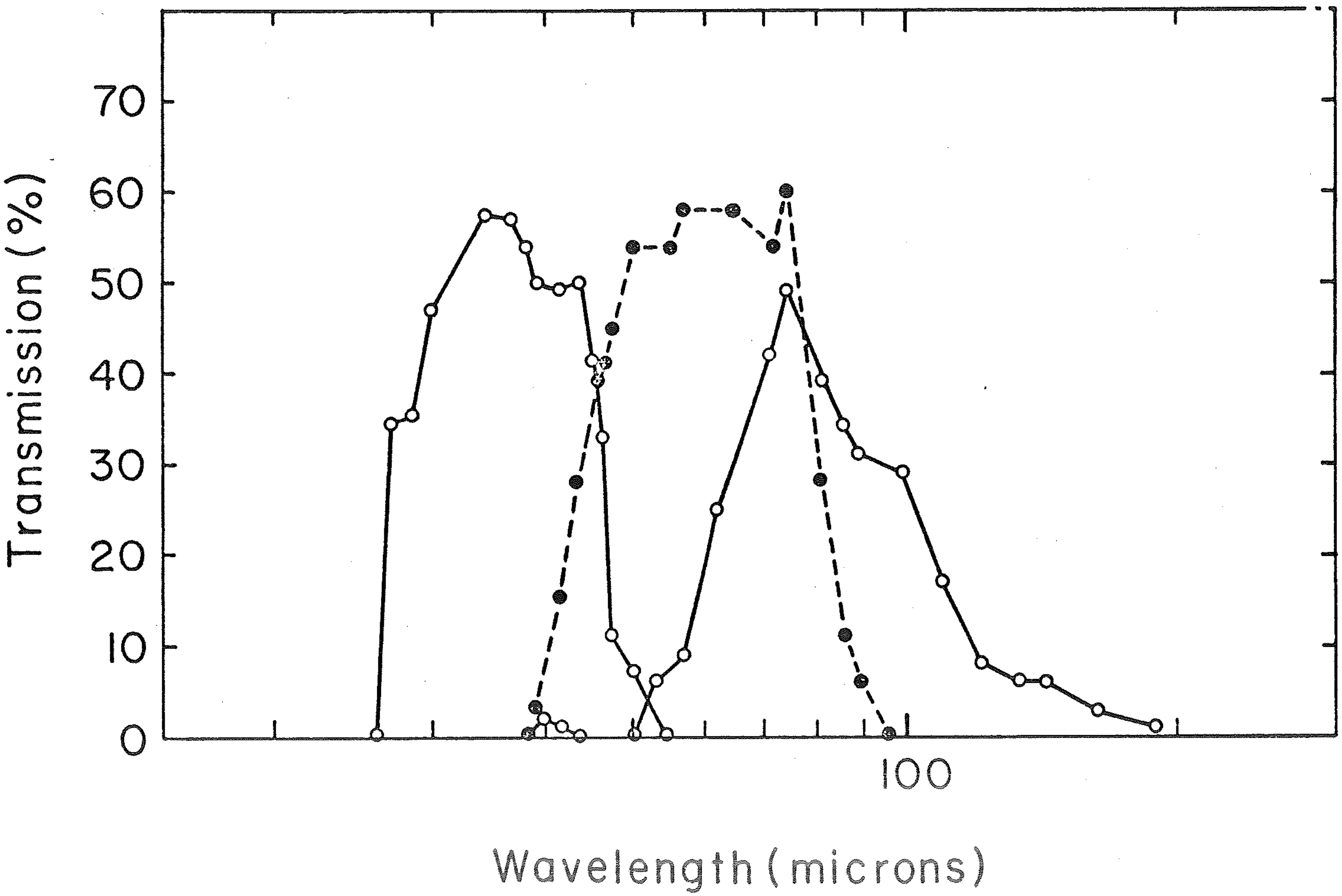

Figure 10

are the result of combining sapphire with thallium chloride (open circles) and sapphire with calcium fluoride and KRS-5 (closed circles). We know of no crystalline materials which possess high pass cut-ons at wavelengths longer than 100μ. However, it is possible to construct metal mesh interference filters with relatively sharp high pass cut-ons and bandwidths of approximately one octave (Ulrich 1968).(8) Such a filter has been combined with sapphire, calcium fluoride, and 0.5 mm of teflon to produce the 80μ bandpass filter in Figure 10. This particular filter was prepared rather hurriedly. Both low and high pass cut-ons could be improved by a more judicious selection of components.

(3) In single band radiometers the overall transmission can be maximized by mounting the crystalline materials (used to block thermal background radiation and delineate the system bandwidth) in optical contact with the silicon field lens used to focus the radiation from the telescope onto the bolometer. By this means Fresnel reflection losses associated with the separate filter elements can be eliminated.

The techniques outlined above have been applied successfully in observations described in Section IV of this report. These observations have demonstrated the feasibility of performing high efficiency, moderate bandwidth photometry with the Flying Infrared Telescope. In particular, it is significant that the addition of the helium cooled filter turret mechanism resulted in no observable increase in the basic noise level of the radiometer. The observed transparency of the crystal filter materials indicates that thermal contact with the helium bath was quite good, and the mechanical coupling introduced a negligible heat load.

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(8) Ulrich R., Applied Optics Vol. 7. No. 10 1968.

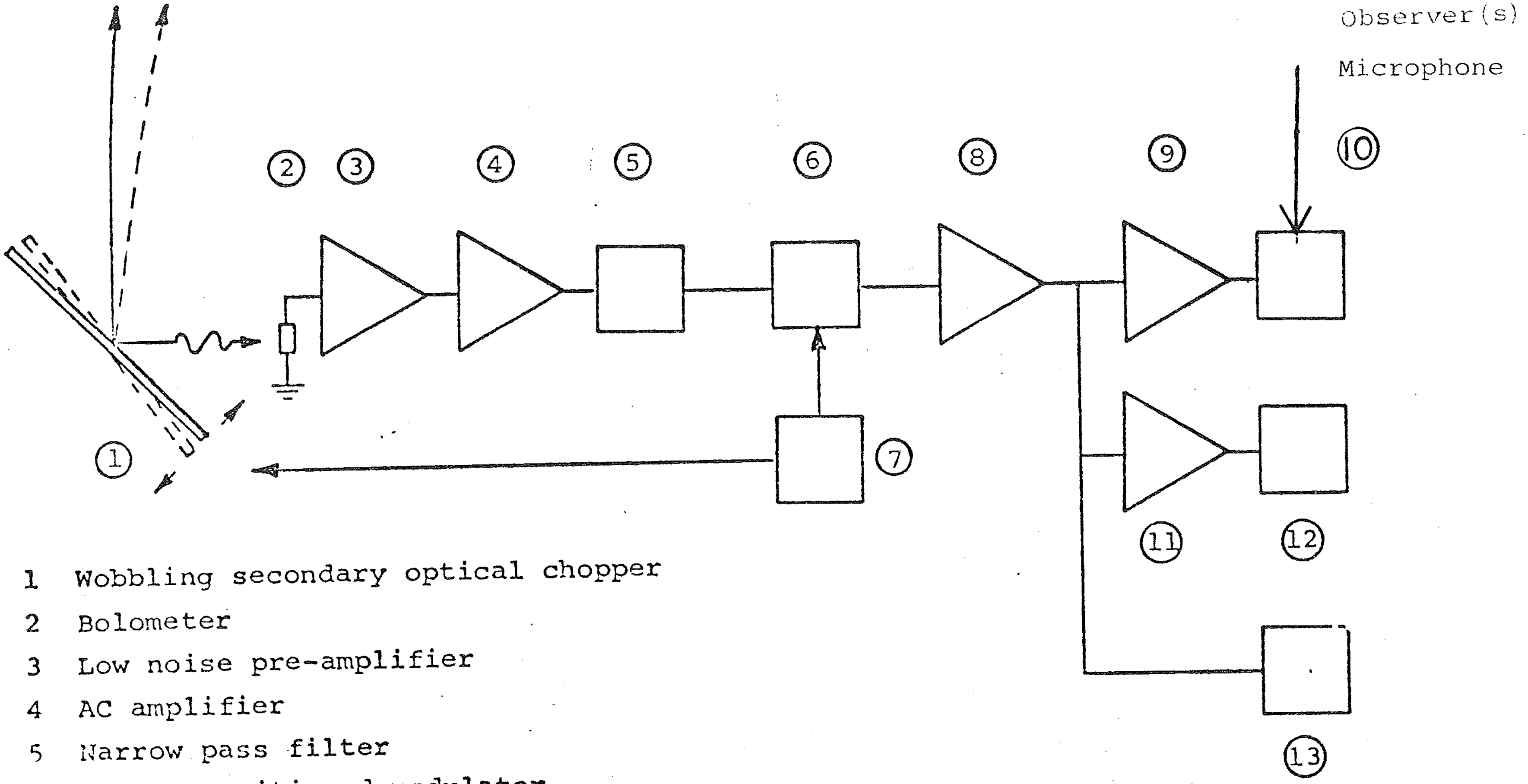
Increased spectral resolution can easily be achieved by means of metal mesh Fabry Perot filters using the cooled crystals as blocking filters. The attainable resolution will be determined solely by the source strength, the intrinsic detector noise, and the available observing time.

D. ELECTRONICS AND SUPPORTING SYSTEMS:

1. Signal Channel Electronics

A block diagram of the electronics is shown in Figure 11. The radiation incident on the detector is chopped with the wobbling secondary optical chopper (1), typically at 80Hz. The output of the bolometer (2) is amplified (3,4), filtered through a narrow pass filter (5), rectified with a phase-sensitive demodulator (6) and further amplified in a DC amplifier (8). The input level of the DC amplifier can be offset to subtract the signal component due to incomplete cancellation of the instrumental or sky background. The observer monitors the DC output directly with an earphone (12) by means of a DC voltage-audio frequency converter (11) and analog fashion on a strip-chart recorder (13). A voltage-to-frequency converter (9) converts the DC output to a frequency between 1 KHz and 5 KHz which is recorded on one channel of a two-channel magnetic tape recorder (10). The second channel is used to record settings of gain and other function switches of the electronics, voice comments of the observer and airplane communications.

The most important part of the electronics components is the low-noise preamplifier, specifically designed to have a lower noise contribution than the detector. It boosts the output of the detector to a level (typical gain x 1000) so that further amplification and conditioning of the signal in a fairly conventional manner does not degrade the signal-to-noise



1	Wobbling secondary optical chopper
2	Bolometer
3	Low noise pre-amplifier
4	AC amplifier
5	Narrow pass filter
6	Phase sensitive demodulator
7	Chopper driver and phase reference
8	DC amplifier
9	Voltage-frequency converter
10	Magnetic tape recorder
11	Voltage-audio converter
12	Audio monitor
13	Stripchart recorder

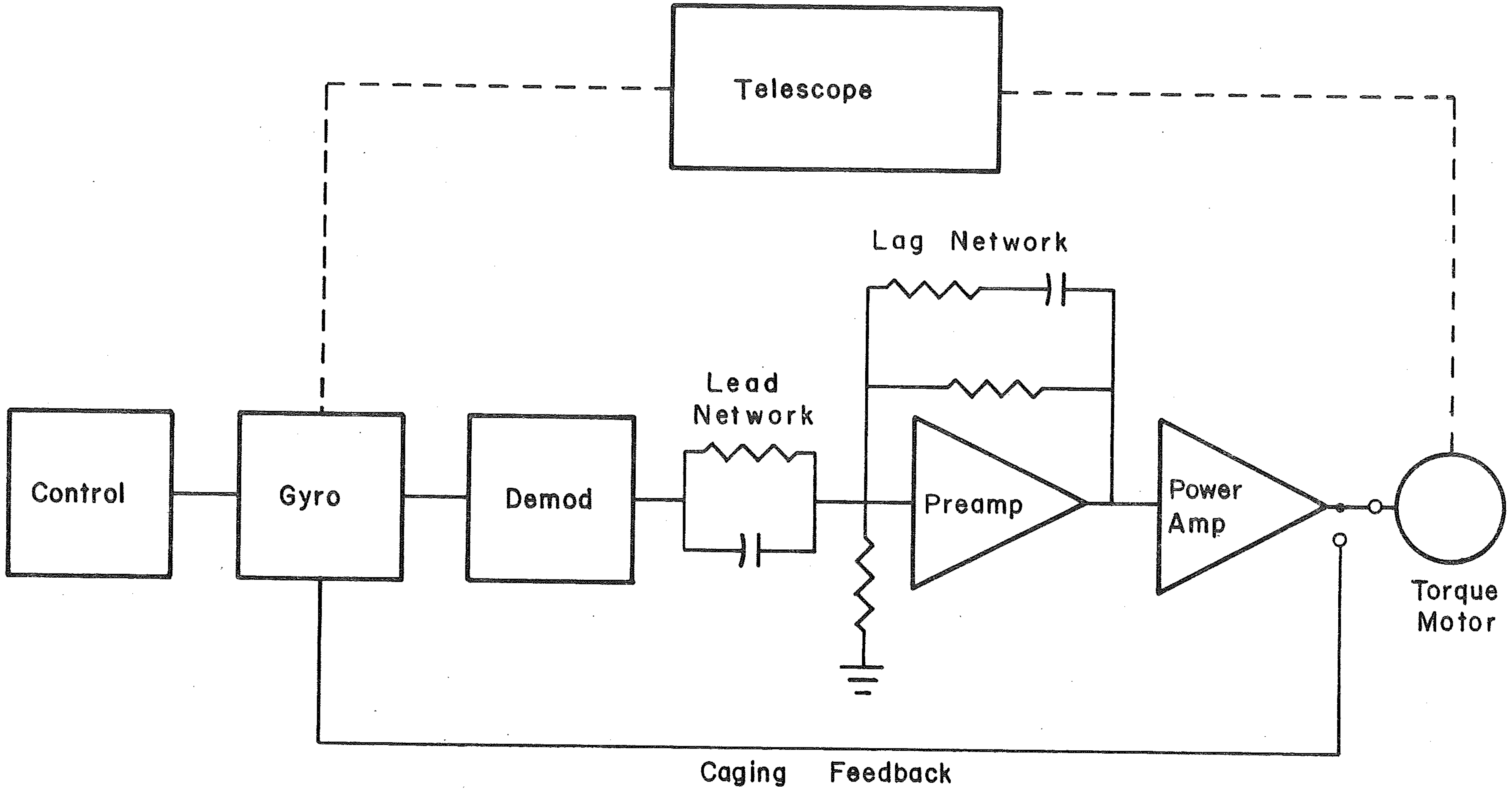
Figure 11 Telescope Signal Electronics Block Diagram

ratio available at the detector.

2. Telescope Drive Electronics

The Flying Infrared Telescope is inertially stabilized by two Honeywell GG49 rate-integrating gyros operating in identical roll and yaw axis servo feedback loops. A block diagram of one of the servosystems is shown in Figure 12. The output of the gyro is a 400 Hz signal whose amplitude is proportional to the angular displacement from an inertial null position. When the telescope feedback loop is closed, the gyro signal is demodulated, amplified and applied to a frameless torque motor (Inland T-5730-A) mounted on either the roll or yaw axis of the telescope. The telescope is pointed by redefining the null position of the gyro. This is accomplished by applying a current to the control winding of the gyro, which causes the gyro wheel to precess. In the caged mode, the output of the power amplifier is applied to the gyro control winding, causing the gyro wheel to remain fixed with respect to the gyro housing and allowing the telescope to move freely in its gymbals.

The performance of the system is determined by the feedback-loop gain, the frequency response and the noise level. For accurate tracking the high-frequency gain of the system should be as large as possible. However, if the loop gain exceeds unity at the point where the phase shifts produced by the elements of the loop (primarily the torque motor in this case) totals 180°, the system will be unstable. It is possible to increase the high-gain stability of the system by modifying the frequency response of the preamplifier, but this is useful only up to the point where the noise level of the system becomes comparable to the control signals. With second-order phase compensation of the type shown in Figure 12, noise-limited per-



TELESCOPE DRIVE ELECTRONICS BLOCK DIAGRAM

Figure 12

formance can be achieved. By redesigning the demodulator, the noise was significantly reduced, but the intrinsic limit set by the gyro itself has yet to be realized.

The large peak torque of the servo motors (7.0 ft-lb) is more than sufficient to produce the maximum angular acceleration required to cancel the aircraft motions. A smaller motor used initially on the roll axis only provided a proportional range of the restoring force too small to prevent excessive excursions caused by perturbations such as bumping the back of the telescope or moderate air turbulence.

3. Helium Pumping Apparatus

The Ge bolometer detector achieves its greatest sensitivity when the liquid helium cryogen temperature is maintained below the lambda transition (i.e. below 2.19°K). In the aircraft this condition is achieved by reducing the vapor pressure over the liquid with a mechanical vacuum pump connected through a throttle valve. The vacuum pump is exhausted to the outside through a fitting in the telescope window mount. Although not strictly required, our desire to be conservative in matters of safety has led to the use of a pump known to be non-explosive in an oxygen environment. It is driven by an explosion proof 28 volt DC motor. In practice, the helium vapor pressure is maintained at about 12 mm Hg (1.8°K).

4. Life Support Oxygen

The need for crew oxygen has been mentioned in section III A. The following brief discussion is given because it is not immediately evident why it is necessary to provide the crew with 100% oxygen when we are using a completely modern jet aircraft designed to provide safe transport of personnel in shirtsleeve comfort.

The aircraft will normally maintain a cabin environment equivalent to about 8000 feet or less when flying at an altitude of 41,000 feet. As the plane ascends above 41,000 up to 50,000 feet the cabin altitude will tend to rise. This rise (i.e. lowering of the air pressure) is accelerated by the fact that the Flying Infrared Telescope utilizes a controlled cabin air leak around the pseudo airbearing at the front of the telescope tube. The resulting cabin altitude is about 18,000 feet when flying at 50,000 feet.

Man can perform work at altitudes between 10,000 and 43,000 feet but must have supplemental oxygen. Therefore since the aircraft cabin altitude is running at 18,000 to 20,000 feet oxygen must be supplied to all the crew members. However breathing oxygen is supplied for two other reasons: (1) The operational ceiling with conventional oxygen equipment is 43,000 feet. For operation higher than 50,000 feet protective devices such as pressure suits must be used. It is this 7,000 foot region that provides the most concern in the event of an explosive decompression of the cabin. In such a case, the aircraft must immediately descend to 43,000 feet or below as the total useful consciousness of the crew memebers is measured in tens of seconds when exposed to the low ambient pressure above 43,000 feet. As the ship descends below this altitude, a crew using pressure breathing techniques would again start getting enough oxygen to be alert and active for a safe return to base. and (2) Pre-breathing of 100% oxygen before each flight greatly reduces the likelihood of crew members being affected by bends (a painful condition caused by nitrogen gas bubbles coming out of solution in fluids and tissues of the body at high altitude). Figure 13 shows the observer and telescope configured for a high altitude mission.

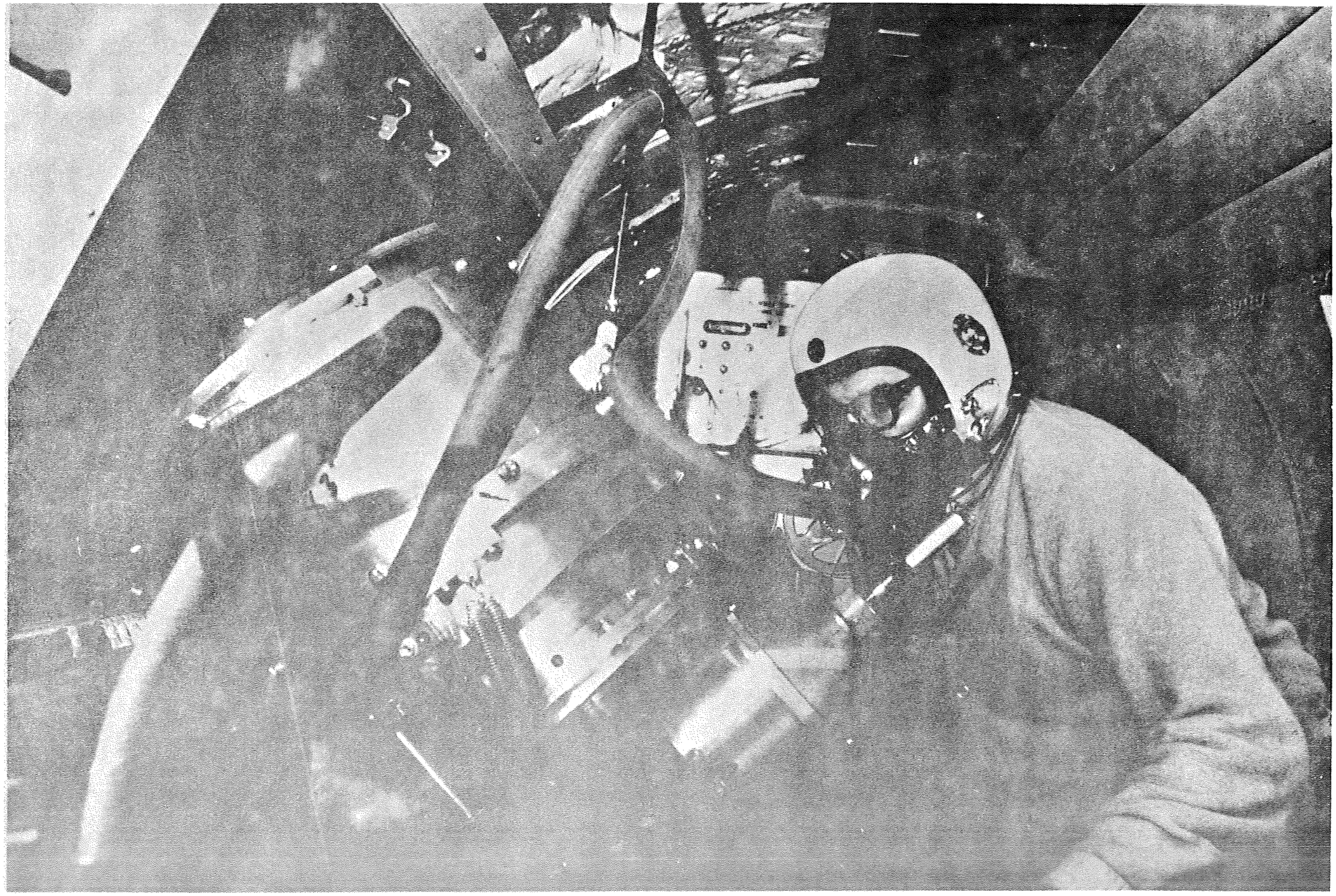


Figure 13

E. MISSION PLANNING :

The successful completion of a series of observational missions requires close coordination by the observers with several organizational groups within NASA Ames Research Center. The Flying Infrared Telescope program has been helped immensely from its inception by the attitude of helpful co-operation prevalent at Ames. On many occasions this has extended far beyond the usual amenities extended to a guest.

The nature of our mission demands night work. The program has been deliberately kept small so that an expensive standing support group at the Center would not be necessary. Consequently, there have been times when men who have already worked all day at their regular jobs have continued to assist us far into the night so that a mission could be launched. We are aware that the government cannot in all cases compensate individuals who have provided vital help under these circumstances but nevertheless we, the observers, are very grateful.

An observer's initial contact with the Center is through the Airborne Science office. Scheduling of the research observer time on the aircraft is handled through Robert Cameron of that office. He is responsible for liaison between the groups mentioned below. At the same time he has encouraged the observers to become well acquainted with the people involved within these groups. This policy has led to a mutual understanding of problems and almost certainly to a more efficient utilization of time.

(1) Navigation - the navigators, Jack Krupa and Robert Morrison, working within the Airborne Science Office provide

all mission parameters to the pilots in a form which minimizes the work required prior to filing a flight plan. For each mission or series of missions the observer(s) give the co-ordinates of the astronomical objects to the navigational team. A computer program initially written by Douglas Aircraft Co. under an Ames contract to provide aircraft flight path information for a solar eclipse has been modified to provide a print-out of Lear Jet heading vs time for each body to be observed. In preparation for a 3 body mission the navigators take the 3 printout sheets and plot the track lines on an aeronautical chart. At this point it may be necessary or desirable to shift the tracks in latitude and/or make slight changes in the observing time so that the entire mission, including climb out and let down, will be completed within the 3 hour block time Lear Jet range. The resulting flight plan is generally completed 12 to 24 hours before a mission and will take into consideration the terminal weather and upper winds forecast.

(2) Flight Operations - the flight operations office, under the direction of George Cooper has provided all pilot support for the Flying Infrared Telescope. Initially in 1967 and 1968 most of the flying was done by Glen Stinette and/or Gordon Hardy. During this period both of these pilots gave unstintingly of their time in the development of the operational techniques necessary for a successful Flying Infrared Telescope program. Beginning in 1969, as shown in Table I, the flying load increased and gradually all of the other pilots have been brought into the program. The pilots have other primary aeronautical research responsibilities but nevertheless have made a very substantial contribution to the program's success.

In section III D, we have discussed the need for supplemental breathing oxygen. Richard Gallant has very capably handled the personal equipment section (O_2 masks, helmets, rescue and safety equipment) during the period covered by this report.

(3) Aircraft Services - Aircraft ground maintenance support has been provided by Aircraft Services under Anthony Bengiveno. Three different aircraft have been used (Lear model 23) and it is impossible to credit everybody who has been involved. However the following men have served as crew chief on the Lear Jet for important periods at some time or another: Robert Tinkey, James Cox, Leroy Monroe, Victor Bravo, and Leslie Videll. Other mechanics have on a few occasions filled this very important position. Good maintenance, performed in a timely manner has been essential to a program that calls for take-off at a precisely stated time.

(4) Aircraft Inspection - the Aircraft Inspection Branch under Jacob Smith has the responsibility for independently inspecting all mechanical work done on the Lear Jet and certifying to the pilot that the aircraft is flight worthy. The inspection function, while sometimes a minor irritant to an impatient observer, serves as additional insurance that the mission will be safely and satisfactorily completed. Mr. Smith has on several occasions made suggestions which simplified the telescope installation.

F. THE MISSIONS:

The chronological record of Flying Infrared Telescope missions is contained in Table I. All flights have originated at NASA Ames Research Center with the exception of two expeditions. Missions 20 through 23 originated from Ellington AFB, Texas. Missions 100 through 107 originated from Howard AFB, Canal Zone.

The telescope was used by C. R. O'Dell early in 1970 and by the far infrared interferometer group at NASA-Ames under Fred Witteborn on several occasions in 1971.

TABLE 1

FLYING INFRARED TELESCOPE

FLIGHT RECORD

Mission Number	Date	Observational Objective	Observer(s)
(1)	10 Oct 68	γ Dra - Saturn	Gillespie
(2)	23 Oct 68	γ Dra - Saturn	Gillespie
(3)	24 Oct 68	γ Dra - Saturn	Gillespie
(4)	25 Oct 68	γ Dra - Saturn	Gillespie
(5)	19 Nov 68 (before dawn)	Jupiter - Mars	Gillespie
(6)	19 Nov 68 (evening)	α Orion - Orion Nebula	Gillespie
(7)	21 Nov 68	Jupiter - Mars	Gillespie
(8)	22 Nov 68	Jupiter - Mars	Gillespie
(9)	2 Dec 68	Saturn - α Orion - Orion Nebula	Gillespie
(10)	3 Dec 68	Jupiter - α Boo - Mars	Gillespie
(11)	4 Dec 68	Jupiter - α Boo - Mars	Aumann
(12)	6 Feb 69	Engineering Test Flight	Gillespie
(13)	10 Feb 69	Engineering Test Flight (Venus)	Aumann
(14)	10 Feb 69	Saturn - Orion Nebula - M-31	Gillespie

Mission Number	Date	Observational Objective	Observer(s)
(15)	12 Feb 69	Saturn - Orion Nebula - M-31	Aumann
(16)	21 Mar 69	3^{o}K Background Experiment (Flight Test)	Gillespie
(17)	24 Apr 69	Daylight Engineering Test Flight on Venus to check Gyro Roll Stabilization System	Gillespie
(18)	25 Apr 69	Engineering Test Flight on Moon	Gillespie & Aumann
(19)	6 Jun 69	Engineering Test Flight on Moon	Gillespie & Aumann
(20)	10 Jun 69	Galactic Center - Mars	Low
(21)	11 Jun 69	Galactic Center - Mars	Low & Aumann
(22)	12 Jun 69	Galactic Center - Mars	Low & Aumann
(23)	13 Jun 69	Galactic Center - Mars	Low & Gillespie
(24)	18 Aug 69	Engineering Test Flight on Moon	Gillespie & Aumann
(25)	19 Aug 69	Galactic Center - Mars	Low
(26)	20 Aug 69	Galactic Center - Mars	Low
(27)	21 Aug 69	Galactic Center - Mars	Gillespie & Aumann
(28)	22 Aug 69	Daylight Engineering Test Flight (Noise Tests)	Gillespie & Aumann
(29)	22 Aug 69	Galactic Center - Mars (2nd Flight)	Low
(30)	25 Aug 69	Galactic Center - Mars	Low & Aumann
(31)	26 Aug 69	Galactic Center - Mars	Low & Aumann
(32)	2 Sept 69	NGC 1068	Low
(33)	3 Sept 69	Engineering Test Flight	Low & Aumann
(34)	3 Sept 69	NGC 1068 (2nd Flight)	Low
(35)	3 Feb 70	Engineering Test Flight	Low & Gillespie
(36)	4 Feb 70	Saturn and Comet Tago-Sato-Koska	Low & O'Dell
(37)	5 Feb 70	Saturn and Comet Tago-Sato-Koska	Gillespie & O'Dell
(38)	11 Feb 70	Jupiter	Gillespie & Cauthen
(39)	11 Feb 70	IR Object in Orion and Jupiter (2nd Flight)	Gillespie & Cauthen
(40)	12 Feb 70	NGC-1068 and Saturn	Gillespie & Cauthen

Mission Number	Date	Observational Objective	Observer(s)
(41)	17 Feb 70	IR Object in Orion and Jupiter	Gillespie & Cauthen
(42)	18 Feb 70	NGC-1068, Mars, Saturn and IR Object in Leo	Low & Gillespie
(43)	19 Feb 70	NGC-1068, Mars, Saturn and IR Object in Leo	Low & Cauthen
(44)	19 Feb 70	Jupiter and altitude dependence study of the received IR signal	Gillespie & Low
(45)	24 Feb 70	NGC-1068, Mars, Saturn and IR Object in Leo	Low & Gillespie
(46)	25 Feb 70	Study of noise characteristics at high altitude	Gillespie
(47)	24 Mar 70	Engineering Test Flight to Evaluate Noise Characteristics	Gillespie & Cauthen
(48)	26 Mar 70	Orion Nebula - Jupiter	Cauthen
(49)	27 Mar 70	Comet Bennett - Jupiter	Gillespie
(50)	31 Mar 70	Comet Bennett - Jupiter	Gillespie & O'Dell
(51)	1 Apr 70	Comet Bennett - Jupiter - Moon with Investigation of LWIR Attenuation vs Altitude	Low & O'Dell
(52)	2 Apr 70	Orion Nebula - Jupiter	Gillespie
(53)	3 Apr 70	Galactic Center Region - Jupiter	Low
(54)	22 Apr 70	Galactic Center Region - Jupiter	Aumann & Gillespie
(55)	23 Apr 70	Galactic Center Region - Jupiter	Aumann & Gillespie
(56)	24 Apr 70	Galactic Center Region - Jupiter	Aumann & Gillespie
(57)	6 May 70	Galactic Center Region	Low & Aumann
(58)	7 May 70	Galactic Center Region - Jupiter	Low & Aumann
(59)	8 May 70	Galactic Center Region	Low & Harper
(60)	19 May 70	Galactic Center Region - Jupiter	Aumann & Gillespie
(61)	20 May 70 (morning)	Galactic Nebula M-17 - Jupiter	Aumann & Cauthen
(62)	20 May 70	Venus - Jupiter	Gillespie & Cauthen
(63)	17 June 70	Engineering Test Flight 2 Detector System	Low & Cauthen
(64)	23 June 70	Jupiter, Galactic Center, Moon	Aumann & Harper
(65)	24 June 70	Jupiter, Galactic Center, M82, Moon	Aumann & Low

Mission Number	Date	Observational Objective	Observer(s)
(66)	25 June 70	Jupiter, Galactic Center, M82	Low & Harper
(67)	25 June 70	Venus	Low & Harper
(68)	6 Oct 70	Engineering Test Flight Jupiter - Moon	Gillespie & Cauthen
(69)	7 Oct 70	Venus, Jupiter, Moon	Gillespie & Harper
(70)	8 Oct 70	Venus, Jupiter, Moon	Harper & Cauthen
(71)	12 Oct 70	M-17 Saturn	Low & Harper
(72)	13 Oct 70	M-17 Saturn	Low & Cauthen
(73)	15 Oct 70	Orion Nebula NGC 7027	Harper & Low
(74)	22 Oct 70	M-17 Saturn	Low & Gillespie
(75)	23 Oct 70	W-51 NGC 2024 Orion Neb	Harper & Low
(76)	26 Oct 70	K3-50 DR21 NGC 7027	Harper & Gillespie
(77)	27 Oct 70	W-49 - W-51 - Orion Nebula	Harper & Gillespie
(78)	1 Dec 70	Engineering Test Flight Dual Bolo System	Low & Cauthen
(79)	1 Dec 70	Saturn - NGC 1068	Gillespie & Cauthen
(80)	2 Dec 70	Saturn - NGC 1068-M82	Gillespie & Cauthen
(81)	3 Dec 70	Saturn - NGC 1068-M82	Low & Cauthen
(82)	7 Dec 70	Saturn - NGC 1068-M82	Gillespie & Cauthen
(83)	9 Dec 70	NGC 2024, Orion Nebula	Harper & Cauthen
(84)	11 Dec 70	Orion Nebula, W-3	Harper & Gillespie
(85)	4 Jan 71	Telescope Focus Flight	Gillespie & Harper
(86)	6 Jan 71	Mars - Venus - Jupiter	Gillespie & Cauthen
(87)	7 Jan 71	Saturn Orion	Harper & Cauthen
(88)	7 Jan 71	Mars - Venus - Jupiter	Gillespie & Patterson
(89)	7 Jan 71	Engineering Test Flight Low Altitude/Local Area Mylar evaluation	Gillespie & Cameron
(90)	29 Jan 71	Saturn	Gillespie & Carof
(91)	8 Feb 71 (morning)	Jupiter-Mars-Venus	Gillespie & Witteborn
(92)	8 Feb 71 (evening)	Saturn-Orion	Gillespie & Swift

Mission Number	Date	Observational Objective	Observer(s)
(93)	9 Feb 71	Training Flight for Ames Personnel	Witteborn & Swift
(94)	10 Feb 71	Training Flight for Ames Personnel	Caroff & Erickson
(95)	11 Feb 71	Training Flight for Ames Personnel	Caroff & Erickson
(96)	17 Feb 71	Training Flight for Ames Personnel	Witteborn & Erickson
(97)	9 March 71	Saturn - Orion	Low & Gillespie
(98)	10 March 71	Venus (daylight flight)	Gillespie & Swift
(99)	10 March 71	Saturn - Orion	Low & Boggess
(100)	17 March 71	Orion Nebula-Carinae Nebula Visual familiarization only	Low & Gillespie
(101)	18 March 71	Engineering Test Flight	Low & Gillespie
(102)	19 March 71	Orion Nebula-Carinae Nebula	Low & Gillespie
(103)	22 March 71	Orion Nebula	Low & Gillespie
(104)	24 March 71 (morning)	Mars	Low & Gillespie
(105)	24 March 71 (evening)	Orion Nebula-η Carinae and Carina Nebula	Low & Gillespie
(106)	25 March 71 (evening)	Orion Nebula - η Carinae and Carinae Nebula - Jupiter	Low & Gillespie
(107)	26 March 71 (morning)	Mars	Low & Gillespie
(108)	22 Apr 71	Jupiter - Venus	Erickson & Swift
(109)	24 Apr 71	Jupiter - Venus	Caroff & Erickson
(110)	29 Apr 71	Engineering Test Flight (1st Flight)	Caroff & Swift
(111)	29 Apr 71	Engineering Test Flight (2nd Flight)	Erickson & Swift
(112)	29 Apr 71	Moon (3rd Flight)	Witteborn & Erickson
(113)	18 May 71	Jupiter	Witteborn & Swift
(114)	19 May 71	Moon (1st Flight)	Caroff & Erickson
(115)	19 May 71	Jupiter (2nd Flight)	Caroff & Erickson
(116)	20 May 71	Jupiter	Witteborn & Swift
(117)	20 May 71	Moon	Witteborn & Swift
(118)	21 May 71	Moon	Witteborn & Erickson
(119)	25 May 1971	Galactic Center - Jupiter	Harper & Cauthen
(120)	26 May 1971	Galactic Center - Jupiter	Harper & Cauthen
(121)	27 May 1971	Galactic Center - Jupiter (1st Flight)	Harper & Cauthen
(122)	27 May 1971	Engineering Test Flight (2nd Flight)	Harper & Cauthen

IV. PROPERTY INVENTORY:

The following list of property has been purchased for use on the Flying Infrared Telescope program.

(1) Polaroid camera: model 88, complete with case.
Acquisition cost: $510.
Use: In regular use for preparation of telescope star finding charts.

(2) Lear Jet window (escape hatch modified as the telescope mount.
Acquisition cost: $821.
Use: To hang the Flying Infrared Telescope in the Lear Jet.

(3) Wallace and Tiernan Aneroid Monometer
Acquisition cost: $415.
Use: To monitor vapor pressure over the liquid helium used for detector cooling.

(4) Welch Scientific vacuum pump
Acquisition cost: $232.
Use: To reduce the vapor pressure (i.e. to provide cooling below the λ point) of the liquid helium used for flight Dewar cooling.

(5) Techni-Rite strip chart recorder
Acquisition cost: $456.
Use: To provide inflight real-time "quick look" capability and to serve as back up to magnetic recording system.

The Government has been asked for transfer of title on the above property items purchased on this NASA grant.

V. OBSERVATIONAL RESULTS:

A. Introduction

The observational program for the 30 cm Flying Infrared Telescope can be divided into two parts: (1) Study of the far-infrared emission of the planets, and (2) The study of the far-infrared emission of bright galactic and extragalactic sources. So far, our effort has been directed toward utilizing extremely large spectral band widths to cover the entire region between 25 and 300μ where observations with groundbased instruments are not possible. Thus, the spectral resolution for all of our studies is very low. However, it will be seen that because this portion of the electromagnetic spectrum was virtually unexplored at the outset of this program many new and fundamental results have been obtained.

Most of the results have already appeared in the literature and they will be summarized here by giving only the abstract of the publication and the reference. There are two exceptions to this; (1) a study of the spectra of Jupiter, Saturn, and Venus, and (2) a study of the Carinae Nebula and Eta Carinae made on a recent expedition to the Panama Canal Zone. Because these results are not yet published, they will be described in somewhat more detail in this report.

B. Planetary Studies

1. The Internal Powers and Effective Temperatures of Jupiter and Saturn. H. H. Aumann and C. M. Gillespie, Jr. (Department of Space Science, Rice University, Houston, Texas), and F. J. Low (Department of Space Science, Rice University, Houston, Texas; and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona). The Astrophysical Journal, Vol.157, 1969. The total power emitted by Jupiter and Saturn

has been measured by observing the planets from a jet aircraft at 15-km altitude with a telescope system open from 1.5 to 350μ. The two planets were found to radiate 2.7 and 2.4 times the amount of power they receive from the Sun, respectively. These new results put observational restraints on models for the internal structures and atmospheres of the two planets.

2. The Far Infrared Continuum of Venus, Jupiter, and Saturn

This paper by D. A. Harper Jr., K. R. Armstrong, and F. J. Low is in preparation. Here, we will give a brief account of the principal results. Aumann, Gillespie, and Low, Ap. J. Vol. 157, 1969 measured the total far-infrared flux emitted by Jupiter and Saturn and determined the absolute temperature of those bodies. We have now undertaken to determine the spectral character of the radiation from these three brightest planets. A similar study for Mars is still in progress, and those results will not be discussed at this time. The observations are summarized in Figures 14, 15, and 16. The horizontal error bars indicate the approximate width of the various filters utilized. The vertical error bars indicate uncertainties in the fluxes based primarily on uncertainties in the calibration procedures. In all cases, the signal-to-noise ratio was high and the observations were easily repeated. It can now be seen that for these three planetary bodies, departures from the Planck distribution given by the measured effective temperature and shown in these graphs as a solid curve, are small. Both published and nonpublished results at shorter wavelengths have been included.

A detailed account of the absolute calibration procedure employed in this study will be found in a Master's thesis submitted to Rice University by K. R. Armstrong in May, 1971.

This thesis also explains in some detail the various observational problems and the sources of error.

Many of the uncertainties in constructing models to describe the behavior of the atmospheres of Venus, Jupiter, and Saturn have now been removed by the actual measurement of the far infrared spectra of these planets. There do appear to be small but significant deviations from Planckian behavior which should be examined with higher spectral resolution and higher absolute precision.

Finally, it should be noted that these measurements constitute an absolute calibration of these bright far infrared sources enabling them to be utilized as standard sources for study of other celestial bodies.

The observed infrared surface brightness of Venus is shown in Figure 14. The black body emission corresponding to the temperature expected for a highly conductive sphere in radiative equilibrium with solar insolation at the orbit of Venus is indicated by the solid curve (Bond albedo A=0.77). The dashed curve represents the solar flux reflected from an intrinsically white sphere at the orbit of the planet. The dotted curve is taken from Gillett, Low, and Stein(9) and shows the monochromatic surface brightness between 2.8μ and 14μ. The open circles are the results of ground based photometry at 10.2μ and 22μ obtained by Low(10,11), and the far

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(9) Absolute Spectrum of Venus from 2.8 to 14 Microns, F. C. Gillett, F. J. Low, and W. A. Stein, J. Atm. Sci., 25, 594, 1968.

(10) Planetary Radiation at Infrared and Millimeter Wavelengths, F. J. Low, Bull. Lowell Obs., 184, 1965.

(11) Observations of Venus, Jupiter, and Saturn at λ20μ, F. J. Low, Ap. J., 71, 391, 1966.

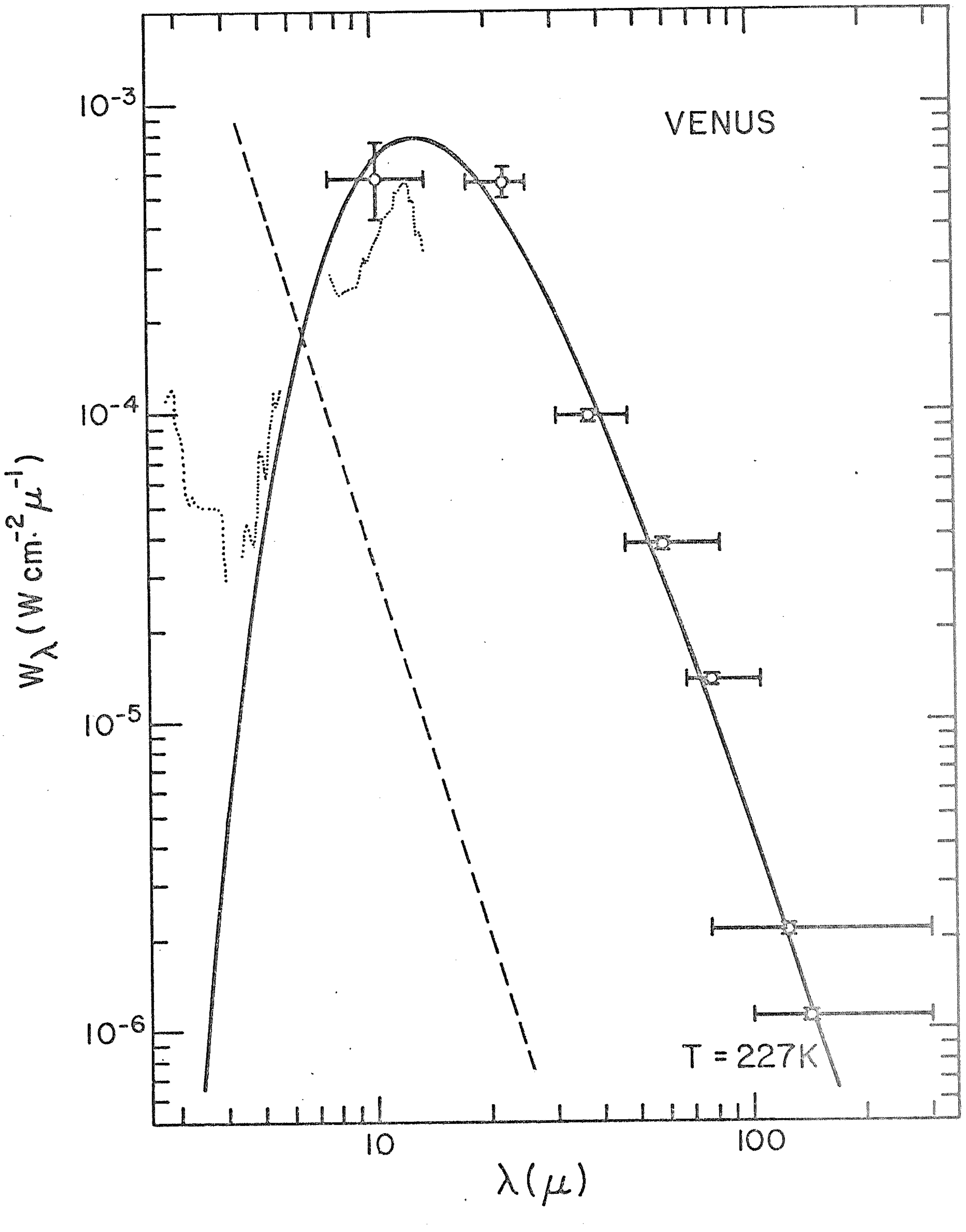

Figure 14

infrared airborne radiometry between 30μ and 300μ. Vertical error bars on the point beyond 30μ indicate variations from the mean of one standard deviation for several deflections obtained from the flight of 8 Feb. 1971. Horizontal error bars indicate half power transmission points of the system response. The calibration of the far infrared measurements is based on broadband observations of Mars from 30μ to 300μ using an assumed black body emission spectrum at an effective temperature of 234 K(12). Wide band fluxes were obtained from the broad band calibration and the measured response curves of the filters, and plotted as monochromatic fluxes at the effective wavelength of the filter.

Figure 15 shows the observed infrared brightness of Jupiter. In this case the solid curve represents the blackbody emission corresponding to Jupiter's measured effective temperature of 134 K(13). The dashed curve has the same meaning as for Venus, and the dotted curve is taken from the narrow band photometry of Gillett, Low and Stein(14). The open circles have the same meaning as in the case of Venus with the exception that the vertical error bars at 5.0, 10.2 and 22μ indicate upper and lower limits of observed fluxes in 1967 (5.0μ, 4 nights) and 1969 (10.2 and 22μ, 12 nights). Note that the photometry at 10.2μ and 22μ was obtained with telescope beam diameters smaller than the diameter of the disk, hence leading to possible errors and fluctuations due to beam size corrections and pointing.

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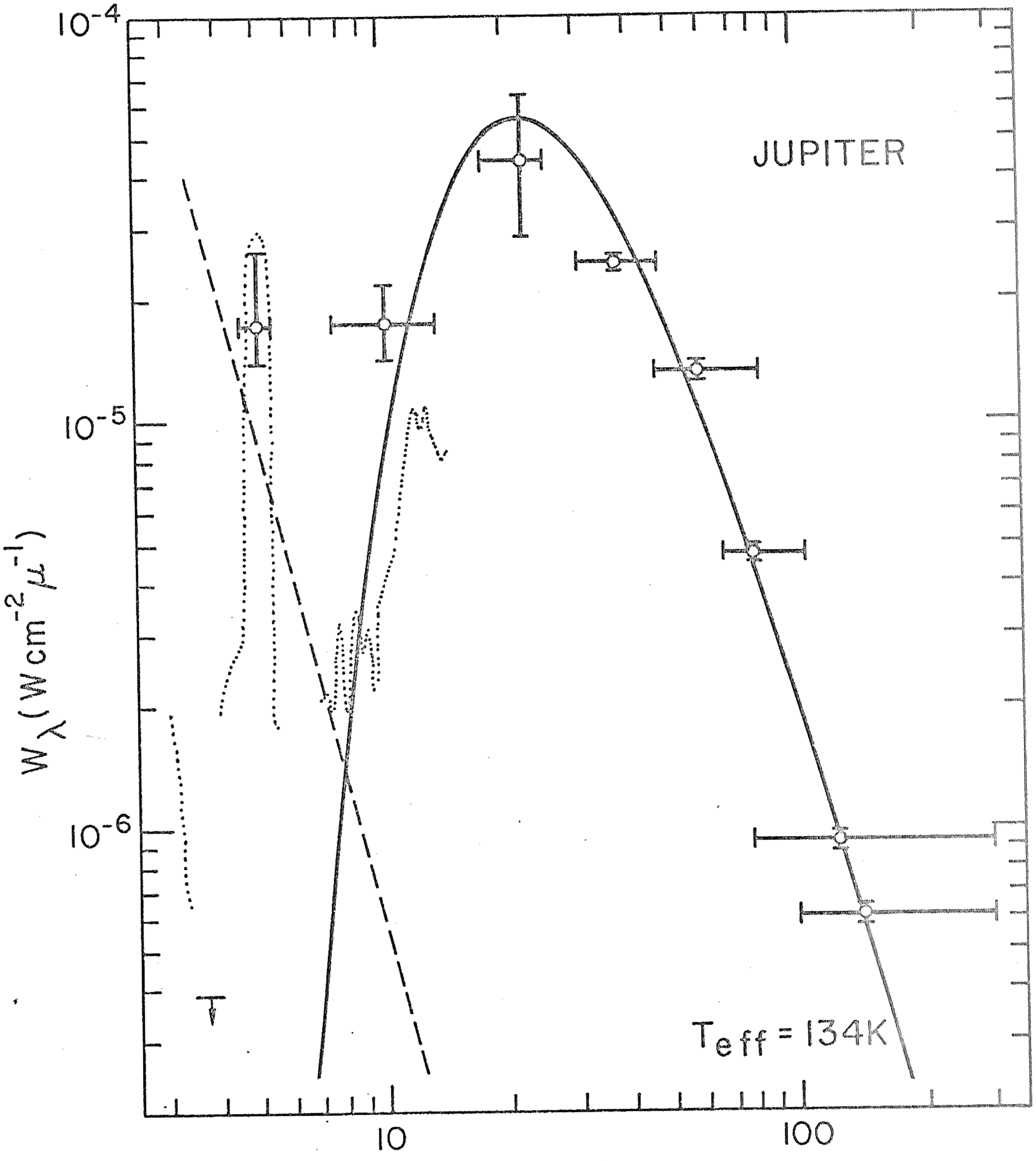
(12) The Internal Powers and Effective Temperatures of Jupiter and Saturn, H.H. Aumann, C.M. Gillespie, Jr. and F.J. Low, _Ap. J._, _157_, L69, 1969.

(13) H. H. Aumann, _et al._, op. cit.

(14) The 2.8 - 14 - Micron Spectrum of Jupiter, F. C. Gillett, F.J. Low, and W.A. Stein, _Ap. J._, _157_, 925, 1969.



10^{-4}
10^{-5}
10^{-6}
$W_\lambda (W cm^{-2} \mu^{-1})$
JUPITER
$T_{eff} = 134K$
10
100
$\lambda(\mu)$

Figure 15

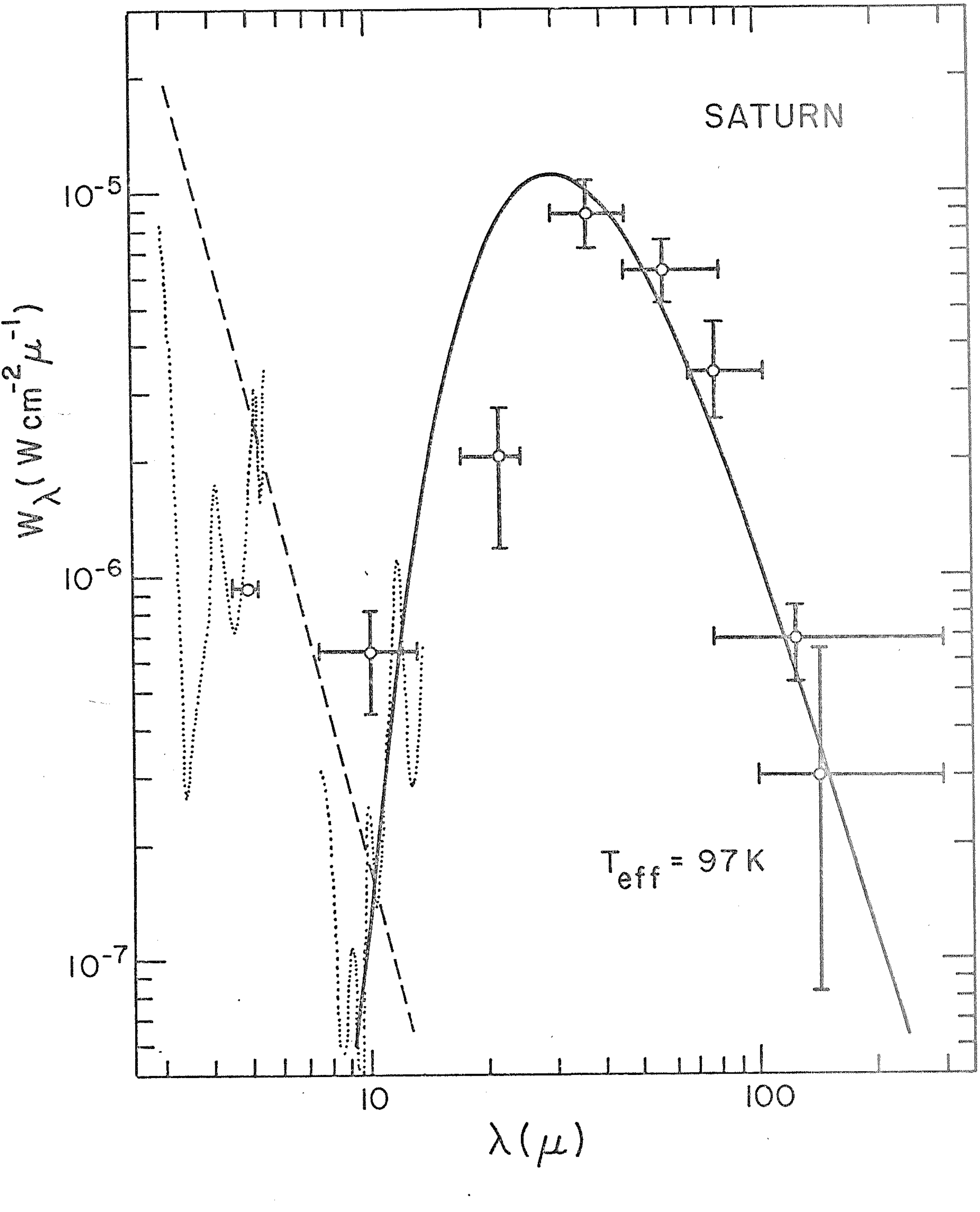


Figure 16

Figure 16 contains observations of the infrared brightness of Saturn. All curves have the same meaning as in the case of Jupiter, the 2.8 - 14μ photometry of Gillett, Low, and Stein being taken from unpublished observations obtained in November and December 1968. Vertical and horizontal bars have the same meaning as for Jupiter, and the calibration of the far infrared observations was obtained in the same manner as described above.

C. Galactic and Extragalactic Sources

1. Eta Carinae

Our observations may be divided into four parts: (A) Studies of galactic nebulae, principally HII regions, (B) Studies of infrared stars, (C) Studies of the infrared nucleus of our galaxy, (D) Studies of external galaxies and quasars.

The first infrared star to be observed at wavelengths beyond 25μ is the bright singular object in the southern sky known as Eta Carinae. The observations of this object have not been fully reduced. However, it appears that in the wavelength range between 30 and 100μ the spectrum drops below the extrapolated Planckian continuum fitted to the groundbased observations. This is, in general, what is expected for all infrared stars which are emitting by the process of thermal re-radiation from a circumstellar envelope of particulate matter. Further observation of such objects in this wavelength interval, in which the circumstellar envelopes are optically thin, should reveal important information about the particulate matter responsible for the thermal emission.

Eta Carinae is at the edge of a complex region known as the Carinae Nebula. We now have detailed studies of both the Carinae Nebula and the Orion Nebula as a function of spectral and spatial distribution. As shown by Harper and Low in their study of a number of galactic HII regions, these nebulae emit an enormous flux in the far-infrared. Most of the flux probably comes from the HII regions themselves by means of a universal mechanism of thermal reradiation. However, in both the Orion Nebula and the Carinae Nebula there is evidence of a separate class of object which is not necessarily associated with the highly ionized region. Angular resolution is the key to unraveling the nature of these objects. We have attempted to steadily improve the angular resolution of our small instrument and have been able to gain some insight into the structure of these complex extended sources. Work in this area is continuing.

2. Far-Infrared Emission From HII Regions. D. A. Harper (Department of Space Science, Rice University, Houston, Texas), and F. J. Low (Department of Space Science, Rice University, Houston, Texas; and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona). The Astrophysical Journal, Vol. 165,L9-L13, 1971. Large far-infrared (45 -750μ) fluxes have been measured from eight sources associated with galactic HII regions. The far-infrared objects are coincident with the thermal radio sources DR 21, K3-50, M17, M42, NGC 2024, W49, and W51. An upper limit was also obtained for the planetary nebula NGC 7027. The far-infrared luminosities of the sources range from 2×10^4 to 2×10^7 $L_\odot$. Measurements of M17, M42, NGC 2024, W49, and W51 indicate that the sources are extended, are optically thin, and have temperatures in the range 65° - 120°K.

3. Far-Infrared Observations of the Galactic Center. H. H. Aumann (Department of Space Science, Rice University, Houston, Texas), and F. J. Low (Department of Space Science, Rice University, Houston, Texas; and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona). The center of our Galaxy has been observed between 40 and 350μ. The measured peak flux of $(8 \pm 3) \times 10^{-21}$ W m^{-2} Hz^{-1} at $(4.2 \pm .2) \times 10^{12}$ Hz corresponds to a total integrated infrared flux at the Earth of $(2.8 \pm 1.0) \times 10^{-5}$ erg sec^{-1} cm^{-2}. If a distance of 10^4 pc is assumed, the total infrared luminosity

of the galactic nucleus is (8 ± 3) x $10^7 L_\odot$. The far-infrared diameter of the nucleus is less than 3' (10 pc), and its position agrees to within 6' with the position of Sag A. Size and luminosity considerations strongly favor a nonthermal model of the galactic nucleus which consists of multiple sources. A number of discrete sources with flux levels of about 1.5×10^{-21} W m^{-2} Hz^{-1} were found near the galactic nucleus.

4. The Infrared-Galaxy Phenomenon. F. J. Low (Department of Space Science, Rice University, Houston, Texas; and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona). The Astrophysical Journal, Vol. 159, 1970. An ensemble of identical infrared sources, called irtrons, radiates the quiescent infrared continuum now found to characterize the nuclei of all galaxies. Continuous creation of matter and antimatter within the irtrons releases energies greater than 10^{62} ergs. The observed infrared continuum results from coherent synchrotron decay of electrons and positrons produced by annihilation. The observed infrared luminosities form an evolutionary sequence beginning with QSOs, extending to Seyfert galaxies and exploding galaxies, and ending with large spirals like our own.

5. Observations of Galactic and Extragalactic Sources Between 50 and 300 Microns. F. J. Low (Department of Space Science, Rice University, Houston, Texas; and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona). and H. H. Aumann (Department of Space Science, Rice University, Houston, Texas). We report far-infrared observations of the galactic nucleus, of two discrete sources near the galactic nucleus, of two sources associated with HII regions, and of two extragalactic sources. All these objects have spectral distributions peaking between 50 and 300μ, and their luminosities range from 1.6×10^5 to $2 \times 10^{12} L_\odot$.

Reference should be made to the following review papers by F. J. Low which summarize a number of results obtained with the 30 cm. Flying Infrared Telescope and relate them to groundbased observations.

6. Infrared Emission of Galaxies
Semaine d'Etude on the Nuclei
of Galaxies, Vatican City, 1970.

7. Infrared Astrophysics
Science 164, No. 3879, 501, 1969.

8. Galactic Infrared Sources
Bok Symposium, Tucson, 1970.

V. SUMMARY AND CONCLUSIONS:

The twelve-inch (30 cm) Flying Infrared Telescope program has proven the idea that observational, far infrared astronomy could be performed from aircraft flying in the stratosphere. The implications of this fact are potentially far-reaching. Already under development by NASA is a substantially larger (36" diameter) airborne telescope which will be available to the scientific community for use during the middle years of this decade.

Our analysis in 1965-1966 indicated that possibly in the long run it would be more cost-effective to install far infrared telescopes on space craft but that for at least a decade aircraft would be more economical. Although it could not be foreseen at that time the Space Shuttle may fulfill this role by the late seventies, permitting a modestly funded individual investigator to perform his own far infrared experiments in space.

In this report the observational results have been discussed in section IV. Abstracts of the more significant scientific papers coming out of the program have been included.

These results are divided into two subject areas: planetary observations and the galactic and extragalactic observations. Engineering data and the historical background of the <u>Flying Infrared Telescope</u> have been covered. In the interest of completeness, a section (III-E MISSION PLANNING) has been included to show the teamwork required from the many people who have made possible the more than one hundred flights here reported.

Two Ph.D. theses and three M.S. theses in Space Science have emerged directly from this program with other graduate students receiving some support. Another development has been the emergence of an "in-house" far infrared group at NASA Ames under the direction of Dr. Fred Witteborn. This group has used the <u>Flying Infrared Telescope</u> on several occasions as a mount for a far infrared interferometer.

In addition to the basic NASA support, improvements to the telescope, including optics, stabilization and electronics systems, were funded by ARPA during FY'70 under the technical cognizance of the Air Force Cambridge Research Laboratories.

We wish to acknowledge the continuing interest and support of NASA Headquarters and the enthusiastic co-operation of many personnel at the Ames Research Center. The <u>Flying Infrared Telescope</u> has emerged as a unique and valuable scientific instrument in its own right and will serve as a test bed for even more powerful infrared telescopes working above the tropopause.