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FLYING INFRARED TELESCOPE OBSERVATIONS OF FAR INFRARED SOURCES

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Project No. 8692
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28 February 1971

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Contract Monitor: Stephan D. Price
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13. ABSTRACT

The Flying Infrared Telescope (described in Semi-Annual Technical Report No. 1) has been operational during the thirteen-month period ending 31 October 1970 with forty-six high altitude missions being flown. We have measured the total infrared luminosities of the galactic center and the Seyfert galaxy NGC-1068, the first extragalactic object to be observed at far-infrared wavelengths. Likewise, the long-wave infrared (45–750μ) fluxes have been measured from eight sources associated with galactic H_{II} regions. The development of far infrared transmission filters used during observation of the H_{II} regions is discussed.

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I. INTRODUCTION

The concept of operating a far infrared astronomical telescope system in the stratosphere above most of the obscuring water vapor was proven during a series of high altitude flights(1) made during October, November and December 1968. At that time, when the Flying Infrared Telescope became operational, it was evident that by combining these newly developed observing techniques with information gained from ground-based observations it should be possible to provide needed information leading to the number and spatial distribution of astronomical far infrared sources that are above a given level of flux.

A dual approach to the problem was proposed using ground-based facilities at the University of Arizona, Catalina Station (separate Arizona Proposal) for the basic survey and the Flying Infrared Telescope (Rice Proposal) with its unique ability to operate beyond the 25 micron atmospheric cut-off as a supporting facility.

The operational plan established at the start of this contract provided for modifications and improvements to the Flying Infrared Telescope to be followed by several series of high altitude research flights aboard a NASA operated Learjet. This plan has been followed and the scientific results of 46 flights conducted between the commencement date (1 September 1969) and 31 October 1970 are reported herein.

Emphasis has been placed on structuring the Flying Infrared Telescope missions to aid in understanding the nature of the far infrared radiation sources located in our galaxy as well as those of extragalactic origin.

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(1) The Internal Powers and Effective Temperatures of Jupiter and Saturn, H. H. Aumann, C. M. Gillespie, Jr. and F. J. Low, Astrophysical Journal, 157, L69-72, 1969.

II. DESCRIPTION OF THE RESEARCH MISSIONS

Table 1 lists chronologically the missions flown by the Flying Infrared Telescope during the period 1 September 1969 (contract commencement date) and 31 October 1970. These 46 missions were divided into five series as follows:

Series 1, September 1969:

These three flights (although technically flown within the period of this contract) actually came at the end of a series of missions primarily concerned with the galactic center and the planet Mars in late August 1969 and are mentioned here only for the sake of completeness.

Series 2, February 1970:

The series had three objectives: (a) observation of the Seyfert galaxy NGC-1068; (b) observation of the comet Tago-Sato-Koska; and (c) planetary observations.

Series 3, March-early April 1970:

The objectives during these missions were to observe Comet Bennett, make a study of the"in-flight" system noise characteristics, and to flight test and debug some instrumental improvements in preparation for a systematic survey of the galactic center region.

Series 4, late April-through June 1970

Ten of the fourteen missions in this series were devoted to galactic center observations. Two flights were made to obtain data from Venus and Jupiter so that it will be possible to directly establish the LWIR flux ratios for the four planets Jupiter, Mars, Saturn, and Venus. The galactic nebula M-17, an H_{II} region, was observed for the first time at far infrared wavelengths with inflight calibration of the radiometer on the planet Jupiter.

Series 5, October 1970

Ten missions were flown. Seven were devoted to the observation of galactic H_{II} regions, two were flown to obtain planetary information and one was an engineering test flight. The instrumentation used(2) and the observational techniques(3) unique to the <u>Flying Infrared Telescope</u> have already been described. The successful execution of a 2, 3, or 4 body mission requires careful and extensive preflight planning by the observers, the pilots and a navigator (who does not fly on the Learjet).

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(2) Investigation of Bright Sources of Long-Wave Infrared Radiation, F. J. Low, H. H. Aumann and C. M. Gillespie, Jr., Semi-Annual Technical Report No. 1, 1 December 1969, Contract No. F19628-69-C-0302.

(3) Closing Astronomy's Last Frontier -- Far Infrared, F. J. Low, H. H. Aumann and C. M. Gillespie, Jr., <u>Astronautics and Aeronautics</u>, <u>Vol. 8</u>, No. 7, July 1970.

III. SCIENTIFIC RESULTS

The scientific results of the work supported, in part, by this contract is reported in four sections, the first two of which are abstracts of scientific journal articles. Reprints of these two papers have been forwarded to the Air Force Technical Reports Distribution Center in accordance with the directive contained in "Outline of Reporting Procedures for Contractors".

A. Observations of Galactic and Extragalactic Sources between 50 and 300 microns. F. J. Low and H. H. Aumann, The Astrophysical Journal, 162: L79 - L85, November 1970.

ABSTRACT

We report far-infrared observations of the galactic nucleus, of two discrete sources near the galactic nucleus, of two sources associated with H_{II} regions, and of two extragalactic sources. All these objects have spectral distributions peaking between 50 and 300 microns and their luminosities range from 1.6×10^5 to $2 \times 10^{12} L_{\odot}$.

B. Far-Infrared Emission From H_{II} Regions.

D. A. Harper Jr. and F. J. Low, The Astrophysical Journal, 165: L9-L13, 1971 April 1

ABSTRACT

Large far-infrared (45-750μ) fluxes have been measured from eight sources associated with galactic H_{II} 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 $2 \times 10^7 L_\odot$. 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.

C. The Planetary Results

The airborne planetary observations were already underway before the start of this contract and will actively continue after its conclusion with the complete scientific results to be published in a journal article during calendar year 1971. Nevertheless, in the interest of completeness of this report, the following summary is presented.

Radiometric observations of Venus, Jupiter and Saturn have been made in spectral bands of moderate resolution over the wavelength interval 30 to 300 microns. Preliminary results for low resolution spectra of these three planets in the far infrared are shown in the following table.

Wavelength	Brightness Temperature (^{o}K)		
Interval	Venus	Jupiter	Saturn
30 - 300μ	254 (+4,-5)	136 (+3,-2)	103 (+4,-5)
30 - 45μ	208 (+3,-3)	124 (+2,-2)	94 (+3,-3)
45 - 80μ	270 (+5,-6)	149 (+4,-3)	107 (+5,-5)
60 - 100μ	273 (+6,-7)	140 (+2,-3)	117 (+7,-7)
75 - 300μ	246 (+6,-6)	134 (+3,-4)	110 (+8,-8)
95 - 300μ	220 (+5,-5)	140 (+4,-4)	88 (+7,-6)

Temperatures for the 30 - 300μ interval are brightness temperatures based on an adopted effective temperature of 234 ^{o}K for Mars.(1) Brightness temperatures for each of the remaining wavelength intervals are calculated from the measured transmission spectrum of the corresponding filter and the observed flux ratios between filters. The error limits indicated reflect only the statistical fluctuations in observed flux ratios.

Further observations of the planet Mars as it nears opposition will permit a direct comparison with a standard source outside the atmosphere for all wavelength intervals, thus eliminating possible variations in the planetary spectra due to differential absorption by water vapor.

D. Supporting Laboratory Research (The Far Infrared Filter Program)

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.

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 Flying Infrared Telescope 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 30-100μm 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 100μm. 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 at 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) The major source of noise in the Flying Infrared Telescope system has been 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 1). 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. 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 cutons when cooled to cryogenic temperatures. (For a summary of low temperature transmission data in the current literature, see Hadni 1967.)(4) The use of these materials in low pass and bandpass filters is illustrated in Figures 2 and 3. Their principal advantages as

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

low pass filters are a rapid cut-on and good stopband blocking. For example (Figure 2) 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).(5) 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 Figure 3 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).(6) Such a filter has been combined with sapphire, calcium fluoride, and 0.5 mm of teflon to produce the 80μ bandpass filter in Figure 3. 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 secondary onto the bolometer. By this means Fresnel reflection losses

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

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

associated with the separate filter elements can be eliminated.

The techniques outlined above have been applied successfully in observations described elsewhere in this report. These observations have demonstrated the feasability 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.

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 dectector noise, and the available observing time.

TABLE 1

Flying Infrared Telescope

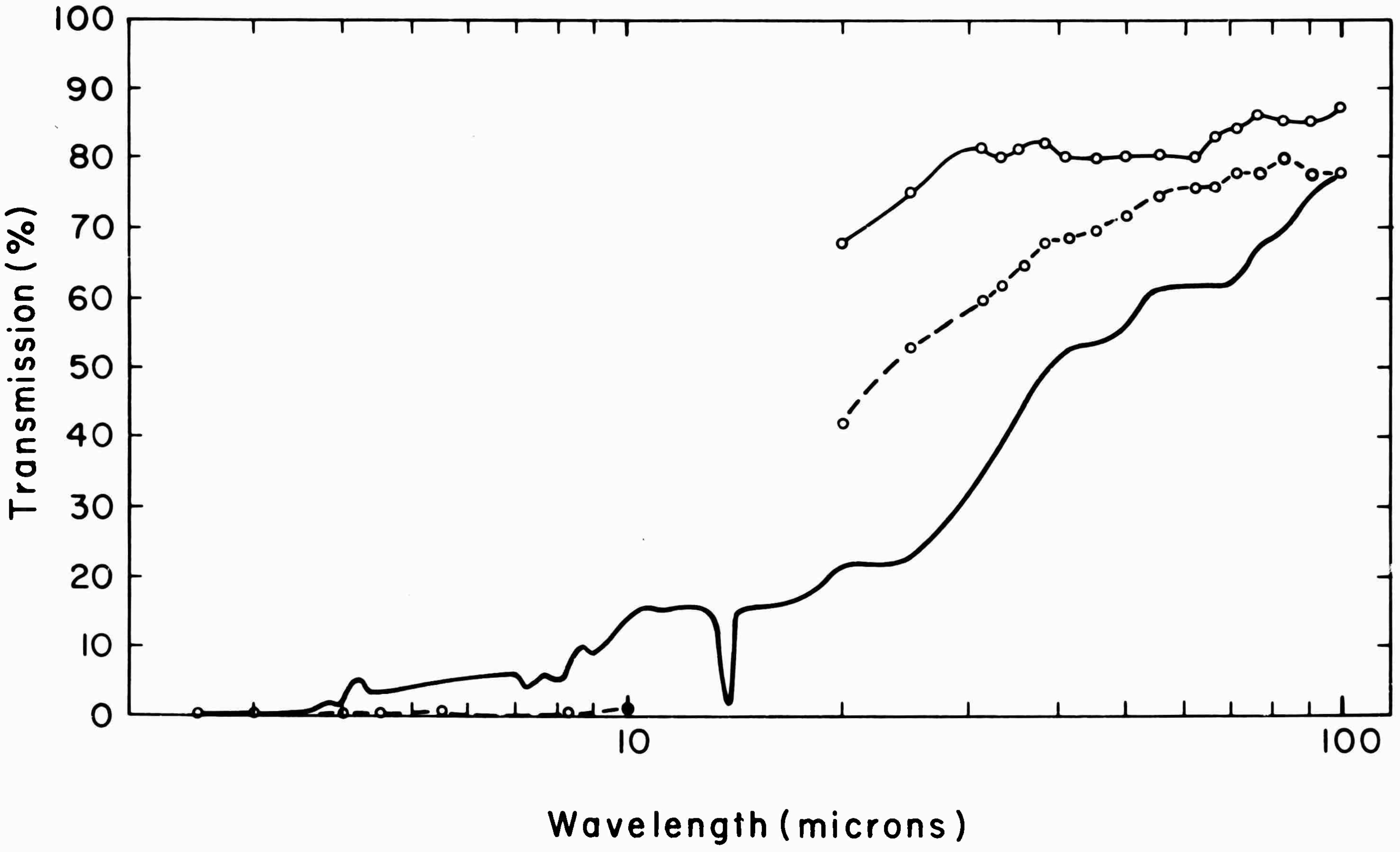
Flight Record

1 September 1969 - 31 October 1970

Series Number	Mission Number	Date	Mission Objective	Observer(s)
1	(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
2	(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
	(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	Gillespie & Low
	(46)	25 Feb 70	Study of Noise Characteristics at High Altitude	Gillespie
3	(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

TABLE 1, Continued:

Series Number	Mission Number	Date	Mission Objective	Observer(s)
	(52)	2 Apr 70	Orion Nebula - Jupiter	Gillespie
	(53)	3 Apr 70	Galactic Center Region - Jupiter	Low
4	(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
	(66)	25 June 70	Jupiter, Galactic Center, M82	Low & Harper
	(67)	25 June 70	Venus	Low & Harper
5	(68)	6 Oct 70	Engineering Test Flight Jupiter - Moon	Gillespie & Cauthen
	(69)	7 Oct 70	Engineering Test Flight 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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50
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30
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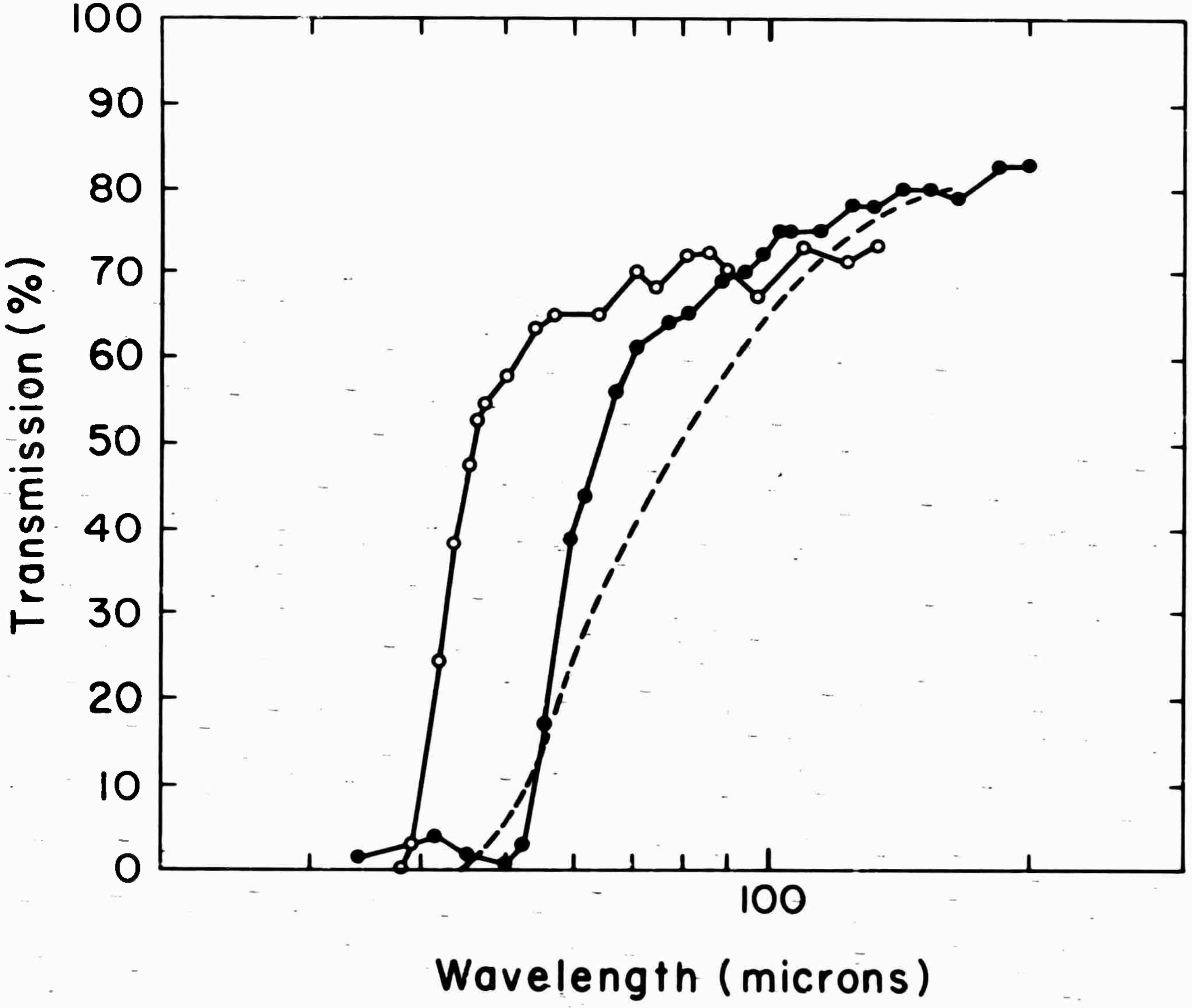
Transmission (%)
10
100
Wavelength (microns)

Figure 1


Transmission (%)
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90
80
70
60
50
40
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20
10
0
100
Wavelength (microns)

Figure 2

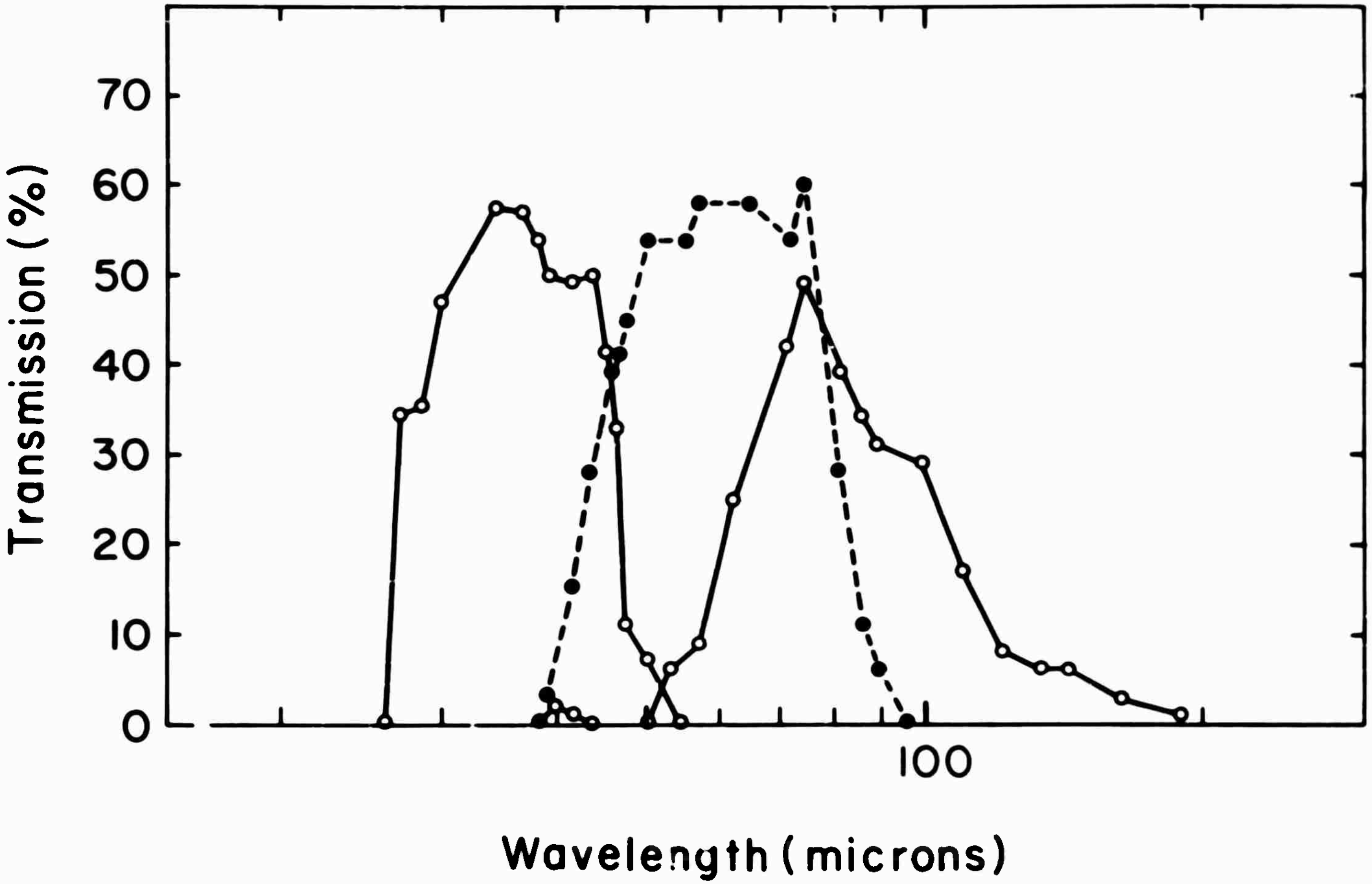

Figure 3

ERRATA

Flying Infrared Telescope Observations
of Far Infrared Sources

Rice University
Space Science Department
Houston, Texas 77001

Contract No. F19628-69-C-0302
Final Report
28 February 1971

This errata sheet should be inserted in the subject report to accomplish the following two corrections:

1. The following information was omitted from the inside of the cover:

Program Code No.	9E50
Effective Date of Contract	26 January 1969
Contract Expiration Date	30 April 1971
Principal Investigator and Phone No.	Dr. Frank J. Low/602 884-2727
Project Scientist or Engineer and Phone No.	Stephan D. Price/617 861-2501

2. On the cover and title page the task number, 869205, should be omitted.