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AIRBORNE INFRARED ASTRONOMY

by

HARTMUT H. AUMANN

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Frank J. Low

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1.0 INTRODUCTION

We describe the design, performance and results obtained with a 12" diameter telescope system operated from a Learjet at an altitude of approximately 50,000 feet. The system is capable of performing observations of discrete astronomical sources throughout the infrared from 1 micron to 1 mm.

A small portion of this part of the electromagnetic spectrum can at present be studied with ground-based infrared telescopes through a number of relatively narrow windows in the atmosphere between 1 micron and 25 microns. One of the most interesting results of these observations has been the realization that the infrared emission from a number of extra-galactic sources is orders of magnitude greater than the total power emitted by all the stars in the largest of galaxies (Low and Johnson 1965, Low and Kleinmann 1968, Kleinmann and Low 1970) and that the bulk of this energy is radiated in the far-infrared, between 25 microns and 1 mm. The peak of the spectral power distribution and the total amount of power radiated by these sources can, however, not be determined from the ground since the intense absorption of the atmospheric water vapor, about 2 mm of precipitable water at 7000 feet altitude under favorable conditions, blocks out the wavelength region from 25 microns to 1 mm.
Above the tropopause at about 50,000 feet altitude the residual amount of water vapor, of the order of 4 microns of precipitable water, attenuates at a number of narrow bands, but the average transmission between 25 microns and 1 mm is of the order of 60-80%. An infrared telescope operated at 50,000 feet altitude is thus a powerful tool for the observation of far-infrared sources. The first such telescope has been constructed at Rice University and has been operated from NASA 701, a Learjet operated by the NASA Ames Research Center at Moffett Field, California.

In the following, after a description of the telescope system, achieved and theoretically achievable noise equivalent flux levels and observation and calibration procedures, we present detailed analysis of observations of the infrared nebula in the Orion, the galactic center and the Seyfert galaxy NGC 1068. Model calculations for the infrared nebula in the Orion show that the radiation emitted by this object can be interpreted as thermal reradiation from a dust cloud. Unless beam size effects are important dust models have to be excluded in the case of the galactic center and NGC 1068.

Our observations of the galactic center and NGC 1068 lend support to the assumption that the infrared galaxy phenomenon, the steep rise of the flux density spectrum in the far-infrared, with a peak near $4 \times 10^{12}$ Hz, is common to all galaxies -- normal galaxies, infrared galaxies and quasars.
2.0 INSTRUMENTATION, ENVIRONMENT AND CALIBRATION

Our observations are carried out above the tropopause at an altitude of about 50,000 feet onboard a Lear jet operated by the NASA Ames Research Center at Moffett Field, California. The telescope, mounted in the emergency exit of the aircraft, has a 12" aperture and views the sky directly through an open port in the emergency exit of the aircraft. Figure 2.1 shows a general view of the plane with the telescope mount installed.

Following is a discussion of the design of the Lear jet telescope, its operating environment at 50,000 feet altitude and its theoretically achievable and actual performance. Our discussion pertains specifically to the Lear jet telescope. However, many comments regarding the background radiation, space filtering and noise apply in general to infrared telescopes installed in stratospheric aircraft. Detailed discussions of general infrared systems design topics such as optics, detector, infrared filters, cryogenics and electronics are referred to infrared technology handbooks (e.g., Wolfe 1965).

The telescope is used for relative broadband integrated energy flux measurements of discrete astronomical sources. Calibration procedures are developed to convert these measurements to absolute energy flux densities. Based on
Figure 2.1 General view of the Lear jet.
absolute flux calibrations it appears that the performance of the Lear jet infrared telescope in its present wide-beam design and used for extreme broadband integrated flux measurements is limited by extraneous noise.

2.1 The Atmosphere

In the infrared region beyond 20 microns the electromagnetic transmissivity of the atmosphere is dictated by water vapor absorption. The rotational vibrations of water effectively blot out vertical transmission from the ground through the atmosphere at wavelengths between 25 microns and 1 mm. With increasing altitude the amount of precipitable water vapor above the observing platform decreases. In addition, the decrease in pressure reduces the self-broadening of the spectral lines so that in general the windows become more transparent than one would expect from extrapolating sea level transmission curves. Figure 2.2 shows the wavelength attenuation coefficient for a vertical path from 10 km altitude through the remaining atmosphere as compiled by F. F. Hall (1967), using calculations by J. T. Hall (1967) and water vapor distributions measured by Mastenbrook (1966). No attempt has been made to draw the narrowness of the absorption lines to scale. The 10 km altitude absorption coefficients, assuming $1.7 \times 10^{-3}$ cm of precipitable $\text{H}_2\text{O}$, lie a factor 1000 below those at sea level.
ELECTROMAGNETIC ATTENUATION BY WATER VAPOR & CO₂

ATTENUATION AT 10KM ALTITUDE (DB/1.7 x 10³ CM PRECIP. H₂O)

10⁻²

10⁻¹

10⁰

10¹

10⁻²

WAVELENGTH

10μ

100μ

1mm

1cm

Figure 2.2
Measurements of the precipitable amount of water vapor above 15 km, the operating altitude of the Lear jet telescope, are uncertain because of instrumental contamination of the atmosphere. Estimates range from 2μ to 10μ H₂O in a vertical column (Sissenwine et al. 1966). From Figure 2.2 this corresponds to an average transmission of better than 85% for a 45° slant path and better than 60% for a 20° slant path in the 20μ-300μ region.

Recently Eddy et al. (1970) have measured the far-infrared atmospheric transmissivity at an altitude of 12 km. Based on their work we estimate that the transmissivity for a 20° slant path from 15 km altitude between 70 microns and 300 microns ranges from 70% to 95%, with a minimum near 100 microns.

While the residual amount of water vapor above 50,000 feet altitude does not appreciably affect broadband relative flux measurements, it gives rise to atmospheric background radiation. For a 45° slant path in the wavelength interval between 20μ and 45μ this background is dominated by the background due to the emissivity (≈ 10%) of the telescope optics. Hoffmann (1970) has measured a sky emissivity of ≈ 4% between 60μ-100μ for a vertical path from 80,000 feet altitude. At 50,000 feet altitude this corresponds to 20% emissivity for a 45° slant path, 40% emissivity for a 20° slant path, if we assume a constant
$H_2O$ mixing ratio above the tropopause (Mastenbrook 1966). The corresponding average transmissivities are 80% and 60%, respectively, somewhat lower than the numbers deduced from Figure 2.2 and the work by Eddy et al. (1970).

2.2 The Telescope

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, with a radius of curvature of approximately -14". 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 cross-sectional view, Figure 2.3, 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°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.
Figure 2.3 General telescope optics layout.
The details of the configuration inside the dewar were changed for almost every sequence of flights in order to achieve specific mission objectives or to optimize signal-to-noise ratio. Details of specific systems are discussed together with achievable noise equivalent flux levels in Section 2.4, System Performance.

Basic telescope components such as the dewar, the detector and the electronics closely follow designs developed for ground-based infrared telescopes at the Lunar and Planetary Laboratory, University of Arizona.

2.2.1 Mechanical Design

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 2.4). Two such window mounts have been fabricated, one centers the telescope viewing angle at 22 degrees, the other at 45 degrees above the horizon.

An exploded view of the telescope is shown in Figure 2.5. 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 degrees movement of the telescope in azimuth (yaw) and elevation (roll) relative to the airplane. The spacing of the pseudo air-bearing surfaces is carefully adjusted such that free movement is
Figure 2.4

Guide telescope view port

Air bearing surface permitting ±3° telescope movement
possible with up to 4 psi differential pressure across the
telescope-backup-plate which serves as the pressure bulkhead.

Attached to the front of the telescope tube and the
moving air-bearing is a four-leg spyder which provides a
rigid support for the secondary mirror and the optical
chopper. The primary mirror is attached to the back of the
telescope tube with the telescope-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 telescope tube. It is
aligned with the optical axis of the main telescope and per-
mits positive starfield identification and guiding (Section
2.3). 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. The roll-axis is gyro-
stabilized (Section 2.2.2). The weight of the telescope
unit, approximately 120 lbs., is kept low through the use
of light-weight aluminum in the construction, including the
primary mirror. The secondary mirror is made of polycry-
stelline silicon. Both mirrors are vacuum gold coated to
obtain mechanically stable and, in the infrared, highly
reflective surfaces. The high heat conductivity of the
mirror materials allows them to cool rapidly to ambient
temperature at altitude (≈ 220°K).
2.2.2 Gyro Roll Stabilization

The Lear jet exhibits, like most other swept wing design aircraft, a "dutch roll" characteristic with a roll amplitude of approximately 2° and a roll period of 5-10 sec. A roll stabilization has been installed on the telescope which largely offsets the roll instability. A block diagram of the roll stabilization servo is shown in Figure 2.6.

Briefly, the servo system operates as follows. With the caging feedback connected and the telescope pointing in a given direction the gyro-torquer adjusts the gyro output to zero and thus defines the "null position" of the telescope. The caging feedback is now opened and the power amplifier is connected to the torque motor. The torque motor acts on the telescope gimbal through a torque multiplier. A deviation of the telescope from its null position is sensed by the gyro and causes a proportional output which is amplified and phased such that the torque motor returns the telescope to its null position. The servo system cancels the dutchroll to approximately 1 arcmin. The incomplete cancellation is due to friction and restoring forces in the pseudo air-bearing as well as by the inherent softness of a null seeking servo system near its null position.
FIGURE 2.6
Roll Stabilization Servo
The telescope can be slewed in elevation by means of a joy stick which, acting through the gyro-torquer, redefines the null position of the telescope.

2.2.3 Helium Dewar

The dewar contains the liquid helium necessary to cool the detector to \( \approx 2^\circ\text{K} \). 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 use of helium-cooled detectors on a telescope onboard a high performance jet aircraft.

The dewar is shown in Figure 2.7. 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 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.
2.2.4 **Infrared Detector**

The detectors used throughout this work have been Ge:Ga bolometers. The detector, consisting of a single gallium doped germanium crystal, has been described in the literature (Low 1961). It operates at a temperature of approximately 1.8°K, achieved by pumping on liquid helium and has an essentially flat response from 1.5μ to beyond 500μ wavelength.

a) **Detector Sensitivity**

The sensitivity of cryogenic bolometers has been discussed in detail by Low and Hoffman (1963); 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 ($\ll 10^{17}$ watt) where a relatively slow response time can be tolerated ($\gg 2 \times 10^{-2}$ sec) values of $10^{-14} \frac{\text{watt}}{\text{Hz}^{1/2}}$ have been achieved.

b) Detector Size and Beam Size

For the 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 certain faint objects).

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 achieved through the use of additional lenses or mirrors which focus the energy in the beam onto the detector.
Two methods have been employed:

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 polyethylene have been used. The beam diameter of the telescope equals the aperture $d_F$ of the Fabry lens. Since aberrations make the use of spherical lenses with focal length $f_F < 2d_F$ 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 as shown in Figure 2.3. For detector magnification of less than 4 of 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 lack of transmission and reflection losses and ease of alignment with visual light make the mirror scheme preferable to a Fabry lens.
2.2.5 **Optical Chopper**

Our discussion of the atmospheric emissivity at 50,000 feet altitude shows that the atmosphere contributes a significant amount of background radiation in the 20\(\mu\) to 400\(\mu\) region. The background flux thus generally exceeds the flux from the astronomical object by several orders of magnitude. This holds true for most astronomical telescopes operated at wavelengths longer than a few microns unless the telescope is cooled to a sufficiently low temperature and operates well above the atmosphere, where the sky emissivity is negligible.

Schemes, which by electronic or mechanical means enhance the signal from the object and make it stand out above the background, are referred to as space filtering techniques. In an infrared telescope this function is accomplished by means of a electro-mechanically driven optical chopper.

The Lear jet telescope employs what is commonly referred to as a single detector, dual-beam chopper. The signal incident on the detector is modulated by rapidly wobbling the secondary mirror of the telescope between two fixed positions. The two resulting beams are separated in azimuth. The center-to-center beam separation, the chopper throw, is usually equal to the beam diameter. The telescope is thus sensitive to discrete sources of flux and flux gradients but not to constant and uniform instrumental and sky backgrounds.
The chopper assembly is shown in Figure 2.8. The secondary mirror is attached to striker arms which are fastened by means of two thin leaf springs to a plate containing two (Ledex-124910-036) solenoids. Chopping speed of up to 133 cps with beam separation of 10 arcmin have been achieved. The electronic chopper driver supplies an adjustable reference signal for the phase detector.

In principle the two telescope beams traverse identical paths through the telescope and the atmosphere, resulting in cancellation of the instrumental and sky background radiation. In practice, the background cancellation efficiency is of the order of 99%-99.9%. The residual signal, referred to as instrumental offset, consists of a signal with the chopper frequency with a constant amplitude superimposed on the noise component. The constant amplitude component can be balanced to zero electronically (Section 2.2.6). The residual noise component may exceed the intrinsic detector noise. This subject is discussed further in Section 2.4.

Cancellation of background radiation can occur only insofar as the background is common to both beams. The forward speed of the airplane, approximately 600 feet/sec, thus prevents complete cancellation of atmospheric background radiation unless chopping speeds of the order of 600 cps or faster are employed, i.e., the airplane moves
one telescope diameter or less during a time of the order of the chopper period.

2.2.6 **Electronics**

A block diagram of the electronics is shown in Figure 2.9. The radiation incident on the detector is chopped with the wobbling secondary optical chopper (1), typically at 80 Hz. 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 such as to subtract the signal component due to incomplete cancellation of the instrumental or sky background (Section 2.2.5). 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.
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

Telescope Electronics Block Diagram
The most important part of the electronics components is the low-noise preamplifier. It boosts the output of the detector to a level high enough that further amplification and conditioning of the signal in a fairly conventional manner does not degrade the signal-to-noise ratio available at the detector.

General design requirements regarding preamplifier input impedance are discussed by Wolfe (1965). A schematic of one of the preamplifiers used with the Lear jet telescope and its specifications are given in Figure 2.10. This amplifier has an equivalent input noise of less than $10^{-8}$ volt/Hz at frequencies of 10 Hz and higher, compared to a typical bolometer noise at 1.8°K of $2 \times 10^{-8}$ volt/Hz or more. Its input impedance is approximately 1000 MΩ. The preamplifier, its power supply battery and a bolometer bias battery are mounted inside a shielded container directly to the outside case of the helium dewar.

2.3 Observation and Calibration Procedures

2.3.1 Observations

Observations are carried out at approximately 50,000 feet altitude during the time when the object of interest is, depending on the window adapter used, rising or setting between 19-25 degrees or 42-48 degrees above the horizon. This limits the observation time for each object
Voltage gain:  500
Frequency Response:  \( \pm 0.8 \text{ db} \) 2Hz - 50 kHz
Equivalent Input Noise:  \(< 10^{-8} \text{ volt rms/Hz}^{1/2}\) at 10 Hz
Input Impedance:  1000 \( \Omega \)
Output Impedance:  \( \approx 2 \, \text{K} \Omega \)
Output Level:  3 volt p-p, output off-set +6.5 volt DC
Gain Stability:  \( \pm 0.8 \text{ db} \) \(-35^\circ \text{C} \) to \(+60^\circ \text{C}\)
\[ \pm 0.1 \text{ db} \] for 11 volt - 13 volt supply

Power Requirement:  200\( \mu \text{A} \) at 12 volt

FIGURE 2.10

Low Noise Pre-amplifier
to 20-30 minutes. Given the right ascension and declination of the object and the Greenwich sidereal time, a computer program developed by Douglas Aircraft Company (1967) provides the flight path and navigational data for the airplane. Since the Lear jet's time at altitude is limited to approximately 90 minutes, it is generally not possible to observe on one flight more than three objects, one of which is usually a calibration object.

Positive starfield identification and guiding are accomplished by means of a carefully boresighted 2" aperture, 10-power guide telescope with a 6" diameter field-of-view. The average density of stars with visual magnitudes brighter than $m_v = 6$ is .1/square degree (Allen 1962). The large field of view of the guide telescope thus assures that in most cases several reasonably bright stars forming easily identifiable patterns are in the field of view. This is particularly important as many far infrared sources are rather faint in the visual. A reticle in the eyepiece of the guide telescope, especially designed for each particular visually faint or invisible object, permits guiding on that object by positioning of the telescope beam relative to a bright star pattern with an accuracy of about 6 arcmin. This offset guiding technique has been used successfully with beams of 10 arcmin diameter and larger.
In order to measure the energy flux from an object the observer points the telescope at the sky near the object and then guides the object into either of the two beams. The deflections obtained by this procedure are directly proportional to the amount of power radiated by the object in the wavelengths passband of the filter system of the telescope.

2.3.2 Calibration

Full use has been made of the wide bandwidths achievable with a stratospheric infrared telescope. This permits the detection of a large number of faint sources with a telescope of rather limited collecting area. The absolute calibration of extremely broad passband systems is complicated. The concepts of effective wavelength and effective bandwidth, useful in the calibration of ground-based wideband photometry, are of little practical value in extremely wide passband systems. An effective bandwidth and wavelength could be defined, but both would depend on the filter characteristic of the system and the energy flux density spectrum of the source.
The signal produced by an object in the beam of the telescope, i.e., the observed deflection, is given by the voltage

\[ V = S \cdot A \cdot \eta \int T(\lambda) T_A(\lambda) F(\lambda) \, d\lambda \]  \hspace{1cm} (2.1)

where

- \( S \) = responsivity of the detector [volt/watt] derated, if necessary, for the appropriate chopping speed. For the Ge:Ga bolometer operated between 1.5\( \mu \) and 500\( \mu \) we assume \( S \) to be wavelength independent.
- \( A \) = telescope collecting area.
- \( \eta \) = wavelength independent efficiency factor of the chopper, the telescope optics, the electronics and the guiding efficiency of the observer.
- \( T(\lambda) \) = filter system transmissivity.
- \( T_A(\lambda) \) = transmissivity of the atmosphere.
- \( F(\lambda) \) = energy flux density spectrum of the object outside the earth's atmosphere.

In principle, the quantities \( S, A, \eta \) and \( T(\lambda) \) can be determined from laboratory calibrations. An estimate of \( T_A(\lambda) \) is possible, at least for broadband measurements. However, \( T_A(\lambda) \) and \( \eta \) may be in error by a not negligible factor.
Relative calibrations avoid these uncertainties and have been used throughout this work. For a relative calibration a source with a known energy flux density spectrum \( F_C(\lambda) \) is observed immediately before or after the observation of the unknown object. The signal from the calibration source is

\[
V_C = S \cdot A \cdot \eta \int T(\lambda) \cdot T_A(\lambda) \cdot F_C(\lambda) \, d\lambda . \tag{2.2}
\]

We set the integral, which can be numerically evaluated, equal to \( I \) and obtain from Equation 2.1,

\[
\int T(\lambda) \cdot T_A(\lambda) \cdot F(\lambda) \, d\lambda = \frac{IV}{V_C} . \tag{2.3}
\]

Possible scale factor errors in \( T_A(\lambda) \) and \( \eta \) appear on both sides of Equation 2.3 and hence cancel.

The planets Mars, Jupiter and Saturn with effective blackbody temperatures of 234\(^\circ\)K, 134\(^\circ\)K and 97\(^\circ\)K, respectively, (Aumann et al. 1969) are used as infrared calibration standards. This calibration has been checked for broadband integrated energy flux measurements at wavelengths beyond 50\(\mu\)m, where the use of Jupiter and Saturn as calibration standards appeared somewhat suspect because of the uncertainties in their atmospheric emissivities. Using a 60\(\mu\)m-300\(\mu\)m passband (System VI, Section 2.4), the measured deflection ratios Jupiter/Saturn and Saturn/Mars agree to
within ±10% with the ratios calculated from Equation 2.3 using the above quoted temperatures.

If \( F(\lambda) \) is known to within one unknown parameter, e.g., a blackbody of known size but unknown temperature, Equation 2.3 can be solved numerically. Otherwise, additional assumptions or measurements are required.

a) We can represent \( F(\lambda) \) in an analytic form containing \( n \) adjustable parameter and observe the unknown object and the calibration source with \( n \) different filter combinations. The resulting \( n \) equations in \( n \) unknowns can be solved numerically. If the general shape of \( F(\lambda) \) can be deduced from other observations or arguments about the radiation mechanisms, the procedure converges. It has been used, in the simple case of \( n = 2 \), to analyze our galactic center observations.

b) The integral in Equation 2.3 can be evaluated exactly if the combined transmission characteristics of the filter system and the atmosphere are representable by a constant amplitude bandpass function. If the combined transmission characteristics exhibit a fairly steep cut-on and cut-off we define an effective cut-on \( \lambda_1 \), an effective cut-off \( \lambda_2 \) and an average transmissivity \( \overline{T} \) weighted by the flux
density spectrum of the calibration source such that

\[ \bar{T} \int_{\lambda_1}^{\lambda_2} F_C(\lambda) \, d\lambda = \int_0^{\infty} T(\lambda) \, T_A(\lambda) \, F_C(\lambda) \, d\lambda. \]  

(2.4)

The amount of power radiated by the unknown source between \( \lambda_1 \) and \( \lambda_2 \) is then given by

\[ P(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} F(\lambda) \, d\lambda = \frac{IV}{TV_C} \left[ \text{watts} \right] \]  

(2.5)

If the filter cut-on and cut-off is not steep, i.e., \( \lambda_1 \) and \( \lambda_2 \) differ appreciably from the \( \frac{1}{2} \) peak transmission points, Equation 2.5 may be considerably in error.

2.4 Systems Performance

Only in the case of a perfect system is the performance of a telescope determined by the N.E.P. its detector achieves under laboratory conditions. The performance of any real system is degraded by inefficiencies in the optics, the filters and the chopper, and, possibly, additional sources of noise.

While the fundamental sources of noise in infrared detectors have been widely discussed (e.g., Wolfe 1965), possible sources of extraneous noise have not. The noise
originating from these sources may determine the limiting performance of aircraft-based infrared telescopes. We distinguish sky noise, infrared microphonics and chopper noise. Phase sensitive detection and narrow pass filtering in the electronics rejects all but the noise component with the chopper frequency.

Random fluctuations in the residual atmospheric background give rise to sky noise similar to the sky noise limiting the performance of ground-based telescopes in the 5μ, 10μ and 22μ atmospheric windows. This noise persists even in a single beam, i.e., if the optical chopper is switched off. The frequency power spectrum of sky noise, based on experience from ground-based observations in atmospheric windows, decreases rapidly above a "cut-off" frequency.

Infrared microphonics noise results from a modulation of the background incident on the detector due to vibrations of the detector itself or of the optical axis of the telescope. Such vibrations may be excited by the broad vibration spectrum generated by jet airplanes. Like sky noise, infrared microphonics noise persists even with the chopper switched off. It should be highly frequency dependent.

Chopper noise is due to fluctuations in the beam cancellation efficiency of the chopper. It may be a chopper vibration induced infrared microphonics noise, or, in the case
of a chopper using reciprocating or wobbling mirrors, may be due to mechanical bounce of the chopper in either or both of its rest positions. If present, chopper noise should be particularly noticeable in the presence of large instrumental offsets.

The performance of a system can be discussed in terms of the noise equivalent power measured at the detector under observing conditions (N.E.P.ₕ [watt/Hz¹/₂]) as compared to the detector N.E.P., i.e., the noise equivalent power the detector achieves at the appropriate chopping frequency under laboratory conditions. It is clear, however, that the result of such a comparison has no relation to the ability of a system to detect faint sources, if extraneous noise dominates the detector noise. The N.E.P.ₛ of such a system would approach the detector N.E.P. with decreasing throughput efficiency without a gain in the signal-to-noise ratio on a calibration object. It is more relevant to compare the amount of energy flux required to give unity signal-to-noise ratio, the noise equivalent flux N.E.F.ₛ of the actual system, with the noise equivalent flux achievable with a perfect system. A perfect system has unity efficiency and 100% transmissivity inside its design wavelength passband. Its N.E.F. equals the detector N.E.P. divided by the telescope collecting area.
An absolute flux calibration as discussed in Section 2.3.2 is required to evaluate the N.E.F. of a system. Figure 2.11 describes in tabulated form seven systems for which such absolute calibrations are available. The table lists for each system the $\frac{1}{2}$-peak beam width and the warm and cooled filters used to define the passband. All filters are long wavelength pass filters, but diffraction causes the response of the systems to roll off beyond 350$\mu$. The effective passband and average transmission is calculated from the method developed in Section 2.3.2.b. Systems IV through VII use the same detector and silicon Fabry lens.

We already mentioned that in low background applications, and where slow chopping speeds can be tolerated, Ge:Ga bolometers with N.E.P. values of $10^{-14}$ watt/Hz$^{\frac{1}{2}}$ can be built. Ideally, a 12" diameter telescope thus could achieve a N.E.P. of $1.6 \times 10^{-17}$ watt/cm$^2$ Hz$^{\frac{1}{2}}$.

The presence of significant amounts of background radiation at 50,000 feet altitude and the fast chopping speeds required to cancel fluctuations in this background prevent us from utilizing detectors with such a low N.E.P. in the Lear jet telescope, at least in its present broad bandwidth, wide beam configuration. With a background of about $3 \times 10^{-7}$ watt an N.E.P. of $1-2 \times 10^{-13}$ watt/Hz$^{\frac{1}{2}}$ at 80 Hz is possible. In order to achieve this speed the detector size is only 0.75 mm square and 0.3 mm thick.
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
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<td>15</td>
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<td>300°K 100°K 2°K</td>
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<tr>
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<td>Near Infrared Cut-on</td>
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<td>26μ</td>
<td>55μ</td>
<td>37μ</td>
<td>45μ</td>
<td>50μ</td>
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<td>80μ-300μ</td>
<td>60μ-300μ</td>
<td>75μ-300μ</td>
<td>65μ-300μ</td>
<td>60μ-300μ</td>
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<td>Average Transmission of Filters</td>
<td>25%</td>
<td>25%</td>
<td>10%</td>
<td>15%</td>
<td>11%</td>
<td>15%</td>
<td>19%</td>
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<td>N.E.P. (watt/Hz°)</td>
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<td>2x10^{-13}</td>
<td>2x10^{-13}</td>
<td>2x10^{-13}</td>
<td>2x10^{-13}</td>
<td>2x10^{-13}</td>
<td>2x10^{-13}</td>
</tr>
<tr>
<td>N.E.P.s (watt/Hz°)</td>
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<td>3x10^{-12}</td>
<td>3x10^{-13}</td>
<td>1x10^{-12}</td>
<td>4x10^{-13}</td>
<td>1x10^{-12}</td>
<td>1.8x10^{-12}</td>
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<tr>
<td>N.E.P. (watt/cm²Hz°)</td>
<td>5x10^{-16}</td>
<td>5x10^{-16}</td>
<td>5x10^{-16}</td>
<td>5x10^{-16}</td>
<td>5x10^{-16}</td>
<td>5x10^{-16}</td>
<td>5x10^{-16}</td>
</tr>
<tr>
<td>N.E.F. (watt/cm²Hz°)</td>
<td>2.5x10^{-14}</td>
<td>2.5x10^{-14}</td>
<td>1.7x10^{-14}</td>
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<td>1.7x10^{-14}</td>
<td>9x10^{-15}</td>
<td>1.7x10^{-14}</td>
</tr>
</tbody>
</table>

* Dewar Window

FIGURE 2.11
The noise equivalent flux achievable with a perfect system using such a detector is $5 \times 10^{-16} \text{ watt/cm}^2 \text{ Hz}^{1/2}$. This is 19 times better than the best actually achieved N.E.F.s, using System VI. The extraneous noise, N.E.P.s, in this system is only four times the detector noise, mainly because of its low through-put efficiency. We attribute the observed excess noise to incomplete background cancellation by the chopper and sky noise.

In its present wide beam, wide bandpass configuration, the Lear jet telescope appears to be limited by extraneous noise. Faster chopping speeds, smaller bandwidths and/or narrower beams should decrease the background noise problem. We do not feel that it presents a fundamental limitation to the performance of stratospheric infrared telescopes.
3.0 ASTRONOMICAL OBSERVATIONS

In this chapter we report the first observations of the infrared nebula in Orion, the galactic center and the Seyfert galaxy NGC 1068 at wavelengths between 25\(\mu\) and 300\(\mu\).

Our observations of the infrared nebula in Orion are interpreted as thermal reradiation from a dust cloud. The resulting spectral power distribution shows a striking similarity to the spectral power distributions deduced for the galactic center and NGC 1068. However, dust models of the galactic center and NGC 1068 have to be ruled out unless beam size effects are important. Synchrotron radiation models with a low frequency cut-off due to free-free absorption can explain the spectral power distribution of the galactic center and NGC 1068.

3.1 Far-infrared Observation of the Infrared Nebula in the Orion

3.1.1 Review

In 1967 Kleinmann and Low (1967), observing at 22\(\mu\), detected an extended infrared nebula, hereafter referred to as "KL source", approximately 1 arcmin north of \(\theta^1\) (c) in the Trapezium region of the Orion Nebula, at

\[
\alpha = 5^h 30^m 18.9 \pm 2^s \\
\delta = 5^\circ 26' 33 \pm 3'' 
\]

(1900.0)
The position of the source is about 14 arcsec SW of an infrared point source (Becklin and Neugebauer 1967), the BN source, and close to an OH radio source (Raymond 1967).

Various theories as to the nature of the KL source have been suggested. Kleinmann and Low proposed that the source is a collapsing protocluster with a mass of $10^2 - 10^3 M_\odot$. The possibility that gravitational contraction of the cloud as a whole may be the source of the then estimated luminosity of $10^5 L_\odot$, led to unreasonably large masses of the order of $10^5 M_\odot$ (Hartmann 1967).

From recent observations of the Trapezium region, Ney and Allen (1969) have concluded that the KL source is optically thin at 20µ. It thus could be interpreted as a thin shell of dust and gas, with a total mass of considerably less than 10 $M_\odot$, heated by a single hot star.

The observations which we present and analyze cover the wavelength range from 1.5µ to approximately 350µ, using the Lear jet telescope. The airborne observations are supplemented by high resolution scans from the ground to more accurately determine the size of the object at 10µ and 22µ.

We suggest as a model a thick spherical dust cloud heated by several luminous stars. The physical properties, especially in the far infrared, of interstellar dust grains and grains occurring in dense nebulae are uncertain
(Greenberg 1963, Wickramanighe 1967, Greenberg 1968). Model calculations based on our observations indicate that, at least in the KL-object, certain dust grains can be excluded from consideration because of excessive mass requirements alone. Rather than collapsing or contracting, the object appears to be in a state of slow expansion due to radiation pressure.

3.1.2 Observations

A. Ground-based Observations

The 28" telescope at the University of Arizona Catalina observing station was used to scan an area of 120 x 120 arcsec surrounding the KL-object with a 15 arcsec beam at 22μ. This telescope has an optical chopper similar to the one described in Section 2.2.5. A chopper throw of 67 arcsec in azimuth was used for the scans. The data were made available by Drs. F. J. Low (Rice University and University of Arizona) and D. E. Kleinmann (Rice University).

Figure 3.1 shows 22μ isophots with a contour spacing of 1/2 α-Ori \( [F_{22\mu}(\alpha\text{-Ori}) = 1.5 \times 10^{-15} \text{ watt/cm}^2\mu] \). The peak flux from the KL-source is 3.75 times that of α-Orion's. The peak contour diameter is 40 arcsec with cool wings extending to more than 90 arcsec diameter. The two dashed
Fig. 3.1 Cool wings of the KL source extend to more than 90 arc sec diameter.

(-- 22 μ R.A. scans)
lines represent 10μ contours. Only the immediate vicinity of the KL-source was scanned at that wavelength.

The 22μ brightness temperature averaged over a 52" beam is 68°K with the 2 arcmin diameter outer ring being at a cooler 61°K. The 10μ brightness temperature of 78°K (for a 52" beam) and the 22μ-10μ color temperature of 130°K is taken as evidence of a hot inner core. This is confirmed by the fact that the 10μ 3/4 peak contour diameter of 28" is significantly less than the 22μ diameter. The centers of the 22μ and 10μ contours are separated by no more than 4.5 arcsec.

The object shown in the 22μ scan centered at θ'(c) has been reported previously (Ney and Allen 1969). Its flux density spectrum differs substantially from that of the KL-object, decreasing by a factor of two between 10μ and 22μ, while the KL-object shows an increase of about a factor of six in the same wavelength interval.

B. Airborne Observations

Airborne observations were made with the Lear jet telescope described in Section 2. Using systems I, II and VI we obtained broadband relative flux measurements between 1.5μ-300μ, 30μ-300μ and 65μ-300μ.

Summarized in Figure 3.2 are the dates of the observations, the wavelength passbands and the calibration sources.
FIGURE 3.2 Summary of the K.L.-source Observations with the Lear jet Telescope.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>1.5μ-300μ</td>
<td>Nov 20, 68</td>
<td>α-Ori</td>
<td>3.9x10^{-12} watt/cm^2</td>
<td>0.6</td>
<td>2.3x10^{-12} watt/cm^2</td>
<td>1.5x10^5L_☉</td>
</tr>
<tr>
<td></td>
<td>Dec 03, 68</td>
<td>Saturn</td>
<td>8.7x10^{-13} watt/cm^2</td>
<td>2.5</td>
<td>2.2x10^{-12} watt/cm^2</td>
<td>1.4x10^5L_☉</td>
</tr>
<tr>
<td>30μ-300μ</td>
<td>Feb 10, 69</td>
<td>Saturn</td>
<td>5.2x10^{-13} watt/cm^2</td>
<td>3.5</td>
<td>1.8x10^{-12} watt/cm^2</td>
<td>1.2x10^5L_☉</td>
</tr>
<tr>
<td></td>
<td>Feb 12, 69</td>
<td>Saturn</td>
<td>5.2x10^{-13} watt/cm^2</td>
<td>3.8</td>
<td>2x10^{-12} watt/cm^2</td>
<td>1.3x10^5L_☉</td>
</tr>
<tr>
<td>65μ-300μ</td>
<td>Feb 12, 70</td>
<td>Jupiter</td>
<td>2x10^{-12} watt/cm^2</td>
<td>0.45</td>
<td>0.9x10^{-12} watt/cm^2</td>
<td>0.6x10^5L_☉</td>
</tr>
</tbody>
</table>
The ratios of the deflection obtained from the KL-source and the calibration sources allow us to calculate absolute broadband energy fluxes for the KL-source using the methods developed in Section 2.3.2. For Jupiter and Saturn these calculations are based on the semi-diameters published in the American Ephemeris and blackbody temperatures of 134±4°K and 97±4°K, respectively (Aumann et al. 1969). For α-Orionis we have used the published magnitudes between 1.5μ and 5μ (Johnson et al. 1966).

The relative accuracy of the flux measurements is reflected in the tabulation. The main uncertainties in the absolute calibration lie in the probable errors in the effective temperatures of Jupiter and Saturn and a slight uncertainty in the 1.5μ cut-on of System I. The absolute calibrations based on relative flux measurements are probably better than ±30%. The calculated deflections of the planets, based on the known characteristics of the telescope, the detector and the filters, using Equation 2.1, agree with the observed deflection to within a factor of two.

No systematic scans of the KL-source were made with the Lear jet telescope. The far-infrared diameter appears to be comparable to the 2 arcmin and 3 arcmin beams of systems I and II, and small compared to the 10 arcmin beam of system VI. A diameter of 2 arcmin is in rough agreement with the extent of the cool wings noted in the 22μ scans.
The large difference in the beam diameter of systems I, II and VI introduces two possible sources of error:

1) All three beams cover portions or all of the \( \theta \)' (c) object and the BN-source. However, since the luminosity of the BN-source is only \( 1.4 \times 10^3 \) L\(_\odot\) (Kleinmann and Low 1967) and the energy flux density spectrum of the \( \theta \)' (c) object drops off steeply beyond 10\( \mu \) (Ney and Allen 1969), we do not believe that significant errors are introduced into our measurements.

2) A considerable free-free emission background has been observed from the region of the KL-source. MacLeod and Doherty (1968) measured 419 F.U. (1 F.U. = \( 10^{-26} \) watt/m\(^2\) Hz) at \( \lambda = 2.8 \) cm with a 3 arcmin beam, Ney and Allen (1969) reported 260 F.U. with a 4 arcmin beam at \( \lambda = 3.5 \mu \) and more recently (Low 1970a) has measured 500 F.U. at \( \lambda = 5 \mu \) with a 5 arcmin beam. Scaling to the appropriate beam diameters and bandwidths we can show that free-free emission contributes no more than \( 10^{-14} \) watt/cm\(^2\) into the beam of any of the three systems and can then be neglected.

Taking 500 pc for the distance of the KL-source (Kleinmann and Low 1967) we arrive at a total infrared luminosity of \( 1.5 \times 10^5 \) L\(_\odot\), of which \( 1.25 \times 10^5 \) L\(_\odot\) is
radiated between 30μ-300μ and 0.6 \times 10^5 L_\odot is radiated between 65μ and 300μ. The far infrared linear diameter is approximately $10^{18}$ cm or $7 \times 10^4$ A.U.

3.1.3 Model Calculation

As a model of the infrared nebula in the Orion we assume that the observed energy flux originates from a spherical cloud of dust heated by several highly luminous stars. Hartmann (1967) proposed that these stars are formed as the first results of sub-fragmentation of the cloud. However, several old stars similar to VY CMa or NML Cyg, with luminosities of $2-3 \times 10^4 \ L_\odot$ each (Low et al. 1970) could also be the source of the observed energy flux, as well as possibly the source of the dust.

A model calculation can answer the question, "if the observed energy flux density spectrum and size can be approximated by a dust model, what are the physical properties of the dust grains and how much mass is required?" The parameters which a successful model has to match are summarized in column 1 of Figure 3.8. $L_{1.5-300}$, $L_{30-300}$ and $L_{65-300}$ are the infrared luminosities measured between 1.5μ-300μ, 30μ-300μ and 65μ-300μ, respectively. $F_{10}$ and $F_{22}$ are 10μ and 22μ energy flux densities for a 2 arcmin beam, calculated from 10μ and 22μ scans. The far infrared radius
\( R_2 \approx 5 \times 10^{17} \text{ cm} \) and an estimate of \( R_1 \approx 10^{17} \text{ cm} \), the radius of the hot inner core, specify the size of the model.

The simplest kind of dust model produces a blackbody spectrum. The model consists of an optically thick, spherical shell of dust particles, all heated to the same temperature. The dust grains are sufficiently large so that their radiation and absorption efficiencies are independent of wavelength. An 80°K blackbody sphere at 500 pc distance fits most of the observed values; however,

a) In order to produce the observed luminosity the outer radius of the sphere, \( R_2 \), has to be 3.3 times smaller than the observed value.

b) The model does not exhibit the limb-darkening evident in the 22\( \mu \) scans.

c) Particles, such as the required dust particles, showing only neutral extinction, have never been observed.

In the following we construct a dust model using two different, but what are considered fairly typical, interstellar dust particles: pure spherical graphite grains and impure graphite grains, with average radii \( a = 5 \times 10^{-6} \text{ cm} \). The absorption cross section \( \sigma(\lambda) = Q(\lambda) \pi a^2 \) for pure graphite grains is given by Werner and Salpeter (1969). For impure graphite grains we assume \( Q(\lambda) \approx 2\pi a/\lambda \).
Rees \textit{et al.} (1969) have recently used such dust grains in calculations of dust models of NGC 1068. The absorption efficiency of impure graphite grains is similar to that of core-mantle grains, grains with a graphite core of 5 \times 10^{-6} \text{ cm} radius surrounded by a dirty ice mantle of outer radius a = 1.5 \times 10^{-5} \text{ cm}. We assume that at wavelengths shorter than 1\mu the absorption efficiency can be averaged and made wavelength independent, \( Q(\lambda < 1\mu) = Q_s = 1 \). This choice makes the model insensitive to the temperature of the central source, as long as it emits most of its energy below 1\mu. Figure 3.3 shows the absorption efficiencies \( Q(\lambda) \) as functions of wavelengths.

We assume that these dust grains are uniformly distributed inside a thick spherical shell of inner radius \( R_1 \) and outer radius \( R_2 \), with a density \( n_d[\text{cm}^{-3}] \). This, of course, is only an approximation. In a more realistic dust grain model, the dust grain density would be a function of \( R \), \( n_d(R) \). Radiation pressure and/or excessive temperature would make the grains unstable inside of \( R_1 \). From there the dust grain density would rise steeply, reach a maximum and decrease, perhaps at a lesser rate, to zero. In our approximation \( R_1 \) and \( R_2 \) represent the peak points of \( n_d(R) \) and \( n_d \) is the average density. Model calculations assuming various analytic forms for \( n_d(R) \) have confirmed the general validity of the
Fig. 3.3 Absorption efficiency as a function of wavelength for the grain models studied:

- $0.05\mu$ pure graphite grains
- $0.05\mu$ pure graphite grains
conclusions drawn from models using the simplified dust distribution.

The total optical depth $\tau$ of the model is wavelength dependent, but is constant at its maximum below 1\mu ,

$$\tau_s = Q_s \pi a^2 n_d (R_2 - R_1) \quad (3.1)$$

$\tau_s$ must be considerably greater than one since photographs of the KL-source region (e.g., Ney and Allen 1969) show no evidence of a central star or stars.

With increasing $\tau_s$, i.e., with increasing grain density, the total optical depth $\tau(\lambda)$ in the infrared increases and a larger fraction of the total power is radiated in the far-infrared. Subject to the constraints that the distance $R_1$, $R_2$ and the total power output $L_{1.5-300}$ are fixed, the model calculations amount to finding, for each type of dust grain, the total optical depth $\tau_s$ at which the model achieves the best fit to $L_{30-300}$ and $L_{65-300}$.

The numerical solution of the energy transfer equation through a thick dust cloud is accomplished by dividing the cloud into a large number of shells, each with short wavelength optical depth $\Delta \tau_s$. If $\tau_s(R)$ is the short wavelengths optical depth of the dust cloud such that $\tau_s(R_1) = 0$ and $\tau_s(R_2) = \tau_s$, we choose
\[ \Delta T_s = \begin{cases} 
0.1 & 0 < T_s(R) < 3 \\
0.25 & 3 < T_s(R) < 10 \\
0.5 & 10 < T_s(R) < 30 \\
1.0 & 30 < T_s(R) 
\end{cases} \] (3.2)

The temperature \( T_D \) of the dust grains in a shell at the distance \( R \) is given by a generalization of the energy balance equation as stated by Van de Hulst (1946):

\[ \int_{\lambda_0}^{\infty} Q(\lambda) F_s(\lambda, R) \, d\lambda = \int_{\lambda_0}^{\infty} Q(\lambda) B(\lambda, T_D) \, d\lambda, \] (3.3)

where \( F_s(\lambda, R) \) is the energy flux density spectrum incident on the dust at the distance \( R \), \( Q(\lambda) \) is the absorption efficiency of the dust grain and \( B(\lambda, T_D) \) is the Plank distribution function for the temperature \( T_D \). The appearance of the same factor \( Q(\lambda) \) in the integral over the emitted radiation as well as the absorbed radiation is based on a generalization of Kirchhoff's law. Its correctness is immediately proven from the requirement that at the surface of the central star, at \( R = R_o \), the temperature of the dust \( T_d = T_s \), the surface temperature of the star, since \( F_s(\lambda, R_o) = B(\lambda, T_s) \).

At \( R > R_o \), \( F_s(\lambda, R) \) consists of two parts, the flux from the central source, attenuated by the dust inside the radius \( R \), and the infrared flux emitted by the dust inside the radius \( R \).
For $\tau_s(R) \geq 3$ the infrared flux emitted from the dust grains inside the radius $R$ makes the dominant contribution to the heating of the outer shells.

Numerically, $F_s(\lambda, R)$ is represented by a 200 point grid, extending from 0.05$\mu$m to 500$\mu$m. Thus central source temperatures of up to 20,000$^\circ$K can be handled. Equation 3.3 is solved by iteration for each shell. A computer program has been written which carries out the numerical calculations. The complete listing of the program, written in Fortran IV, is included in the Appendix.

Computations were carried out for the two types of dust grains described above for models with value of $\tau_s = 3$ to $\tau_s = 1000$, assuming a stellar source blackbody temperature of 10,000$^\circ$K. Figure 3.4 shows how the fraction of the total power radiated in the far infrared between 30$\mu$m-300$\mu$m and 65$\mu$m-300$\mu$m increases with the optical depth $\tau_s$ of impure graphite models. For $\tau_s \approx 150$, 84% of the power is radiated between 30$\mu$m-300$\mu$m, 37% is radiated between 65$\mu$m-300$\mu$m, very close to the observed 83% and 40%, respectively.

A total short wavelength optical depth of $\tau_s = 150$ certainly suffices to obscure any stars buried in the cloud. The energy flux density spectrum calculated for the impure graphite grain model with $\tau = 150$ is plotted in Figure 3.5. Superimposed are the 10$\mu$m and 22$\mu$m observations, adjusted for a 2 arcmin beam diameter. The spectrum is plotted in units
Fig. 3.4 Fraction of the total power $f$ radiated between $\lambda = 30\mu$ and $\lambda = 65\mu$. Impure Graphite Grains.
Fig. 3.5 Infrared Nebula in Orion. Calculated spectral power distribution of the impure graphite grain model.

- observed at 10µ and 22µ (beam adjusted to 2 arcmin)
- calculated
of watt/m$^2$/Hz as a function of frequency. Note that, for \( \lambda > 200 \mu \), \( F_\nu \sim \nu^{2.5} \), while the spectral power distribution of a blackbody decreases with \( F_\nu \sim \nu^2 \).

The temperature of the dust grains, shown in Figure 3.6, decreases rapidly from \( T_D(R_1) = 250^\circ K \) to approximately \( 100^\circ K \) at \( R = 1.5 \times 10^{17} \) cm and then falls off essentially as \( R^{-0.5} \) to \( T_D(R_2) = 50^\circ K \). Changing \( R_1 \), the somewhat uncertain radius of the hot inner core, from \( 1 \times 10^{17} \) cm to \( 5 \times 10^{16} \) cm increases \( T_D(R_1) \) to approximately \( 330^\circ K \). However, the strong near-infrared radiation emitted by the hot, innermost shells is almost completely reabsorbed by the outer shells since \( \tau(5\mu) \approx 10 \) and \( \tau(10\mu) \approx 5 \). Thus only a small increase in the flux below \( 10\mu \) results. The spectral power distribution at wavelengths above \( 10\mu \) and \( T_D(R_2) \) are not affected.

With \( \tau_s = 150 \) and a grain density of \( 5 \times 10^{-6} \) cm$^{-3}$, the total mass of the dust grains alone is \( 1.5 \, M_\odot \). If we assume, following Van de Hulst (1949), that the normal cosmic abundances of elements are maintained in the dust cloud, we can calculate its total mass. Since the ratio of the total number density of particles, \( n_H \), in the form of hydrogen atoms, to the dust grain number density, \( n_d \), \( n_H/n_d \approx 1.3 \times 10^{11} \) for 0.05\( \mu \) graphite grains, \( n_H \approx 6.5 \times 10^5 \) hydrogen atoms per cm$^3$, corresponding to a total mass of \( 200 \, M_\odot \). The mean mass of interstellar clouds is \( 1000 \, M_\odot \) (Allen 1962), with a mean
IMPURE GRAPHITE GRAIN TEMP °K

TEMPERATURE OF IMPURE GRAPHITE GRAINS AS FUNCTION OF THEIR RADIAL DISTANCES FROM THE CENTER OF THE DUST CLOUD

FIGURE 3.6
density of 10 atoms/cm$^3$. The physical conditions permitting dust grain formation in interstellar clouds and the KL-source are thus rather different.

The total mass of the dust cloud is insensitive to the assumed grain size as long as it does not deviate too much from 0.05$\mu$. If we had assumed 0.15$\mu$ for the radius of a typical dust grain, 27 times fewer dust grains would have been required. The reason is that, in addition to the increase in cross-section (by a factor of 9), the absorption efficiency would have increased by a factor of 3 [$Q(\lambda) \approx 2\pi a/\lambda$, proportional to the radius]. However, in order to maintain normal cosmic abundances, the hydrogen atom to dust grain ratio has to be increased by a factor of 27 to \( \left( n_H/n_d \right) = 3.6 \times 10^{12} \).

No satisfactory model could be constructed with pure graphite grains. For a mean optical depth $\tau_s = 1000$ a pure graphite grain model radiates 29% of the total power between 30$\mu$-300$\mu$, 1.2% between 65$\mu$-300$\mu$, as compared to the observed 83% and 40%, respectively. The grain temperatures are much higher than those of impure graphite grains, $T_D(R_1) \approx 450^\circ$K, $T_D(R_2) \approx 70^\circ$K. The steep decrease of the infrared absorption efficiencies of pure graphite grains forces them to radiate with an extremely narrow spectral power distribution. The superposition of a large number of
dust shells at different temperatures does not broaden the resulting spectral power distribution sufficiently to approximate the observed spectrum.

From Figure 3.7 we estimate that for a pure graphite grain model with $\tau_s \approx 4000 \ L_{30-300}$ can be matched, but that $\tau_s \gg 10,000$ is required to match $L_{65-300}$. With $\tau_s = 4000$, 40 $M_\odot$ of grains and a total mass of $\approx 5500 \ M_\odot$ are required; but $L_{65-300}$ would be a factor six below the observed value.

The observed and calculated parameters of the KL-object are summarized in Figure 3.8.

3.1.4 Discussion

We have shown that a dust model containing impure graphite grains produces a good fit to the observations of the KL-source over a wide range of the spectrum. Models composed entirely of pure graphite grains have to be rejected. However, because of their high temperature stability, pure graphite grains may exist inside $R < 1.5 \times 10^{17} \ cm$. The reason is that our impure graphite grain model may contain core-mantle grains or dirty ice grains which have radiative properties below 100$\mu$ similar to those attributed to impure graphite. Since ice grains at the densities of interest, near $n_H = 10^6 \ cm^{-3}$, are unstable at temperatures above $\approx 100^\circ K$ (Gaustad 1963), they can exist only at $R > 1.5 \times 10^{17} \ cm$. 
Fig. 3.7 Fraction of the total power $f$ radiated between $\lambda = 300 \mu$. 
<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>80°K Blackbody</th>
<th>Impure Graphite Grains</th>
<th>Pure Graphite Grains</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance [cm]</strong></td>
<td></td>
<td>$1.5 \times 10^{21}$ cm $= 500$ pc</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$R_1$ [cm]</strong></td>
<td></td>
<td>$\approx 1 \times 10^{17}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$R_2$ [cm]</strong></td>
<td></td>
<td>$\approx 5 \times 10^{17}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$L_{1.5-300}$</strong></td>
<td></td>
<td>$1.5 \times 10^5 L_\odot = 6.25 \times 10^{38}$ ergs sec $^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$L_{30-300}$</strong></td>
<td>$1.25 \times 10^5 L_\odot$</td>
<td>$1.27 \times 10^5 L_\odot$</td>
<td>$1.25 \times 10^5 L_\odot$</td>
<td>$\approx 1.2 \times 10^5 L_\odot$</td>
</tr>
<tr>
<td><strong>$L_{65-300}$</strong></td>
<td>$0.6 \times 10^5 L_\odot$</td>
<td>$0.5 \times 10^5 L_\odot$</td>
<td>$0.54 \times 10^5 L_\odot$</td>
<td>$\approx 0.0 \times 10^5 L_\odot$</td>
</tr>
<tr>
<td><strong>$F_{10}$ [watt cm$^{-2}$ µ]$^{-1}$</strong></td>
<td>$2 \times 10^{-15}$</td>
<td>$8 \times 10^{-16}$</td>
<td>$1.5 \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td><strong>$F_{22}$ [watt cm$^{-2}$ µ]$^{-1}$</strong></td>
<td>$1.6 \times 10^{-14}$</td>
<td>$2.1 \times 10^{-14}$</td>
<td>$2.1 \times 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td><strong>Short Wavelengths Optical Depth</strong></td>
<td>?</td>
<td>Very Large</td>
<td>150</td>
<td>4000</td>
</tr>
<tr>
<td><strong>Grain Density [cm$^{-3}$]</strong></td>
<td>?</td>
<td>?</td>
<td>$5 \times 10^{-6}$</td>
<td>$&gt;1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td><strong>Mass$_{Dust}$</strong></td>
<td>?</td>
<td>?</td>
<td>$1.5 M_\odot$</td>
<td>$&gt;40 M_\odot$</td>
</tr>
<tr>
<td><strong>Mass$_{Gas}$</strong></td>
<td>?</td>
<td>?</td>
<td>$200 M_\odot$</td>
<td>$5500 M_\odot$</td>
</tr>
</tbody>
</table>

**FIGURE 3.8** Observed and Calculated Parameters of the Infrared Nebula in the Orion.
A thin shell of pure graphite at $R < 1.5 \times 10^{17}$ cm would be at a temperature above $300^\circ$K. It thus would enhance the energy flux below $10\mu$, but should have little effect above $10\mu$.

Since our observations of the KL-source were broadband energy flux measurements, biased relative to the 10-100$\mu$ region, the model calculation is sensitive only to the radiative properties of the dust below 100$\mu$. Recently the KL-source has been observed at 1 mm with a one arcmin beam. The measured 100 F.U. (F. J. Low, private communication), well below the 1000 F.U. extrapolated from our model, may indicate that the radiation efficiency of the impure graphite grains above 100$\mu$ drops steeper than shown in Figure 3.3. If we assume that the absorption efficiency of impure graphite grains decreases beyond 100$\mu$ proportional to $\lambda^{-2}$ (dashed line in Figure 3.3), the spectral power distribution of the model drops as $\nu^{3.75}$ at wavelengths beyond 200$\mu$ and reaches 100 F.U. at 1 mm (Figure 3.9).

The impure graphite grain model with a total short wavelength optical depth of 150 closely resembles the infrared object in the Orion. Assuming that the model is stable with respect to rotation, i.e., its rotation period is longer than $10^5$ years, the question arises if this model is stable under its own radiation pressure. The radiation pressure on a
Figure 3.9 Infrared Nebula in Orion
Calculated spectral power distribution of the modified impure graphite grain model.
- observed at 10\(\mu\) and 22\(\mu\)
  (adjusted to a 2 arcmin beam)
- calculated
dust grain exceeds the gravitational attraction if

$$\frac{Q_s L_s (R)}{4\pi R^2 c} \frac{\pi a^2}{M(R) m} > \frac{GM(R)m}{R^2} ,$$

(3.4)

where $L_s (R)$ and $M(R)$ are the short wavelength luminosity and the mass inside the radius R. $Q_s$, $m$ and $a$ are the short wavelengths absorption efficiency, the mass and the radius of the dust grain; $c$ is the velocity of light; and $G$ is the gravitational constant. This inequality is easily satisfied for our model, even if the mass of a central object is an order-of-magnitude larger than the total mass of the dust cloud. The radiation pressure is much larger than gravitational attraction. The dust grains would thus be rapidly ejected were it not for the braking provided by the ambient gas. Collision of the dust grains with the ambient gas cause the grains to drift outward relative to the gas with velocity $v_D$, given approximately by

$$v_D \approx \left( \frac{Q_s L_s (R)}{8\pi R^2 c n_H m_H} \right)^{1/2} ,$$

(3.5)

where $m_H$ and $n_H$ are the mass and number density of the gas particles (mostly in the form of hydrogen). Inserting numbers appropriate for the impure graphite grain model we obtain at $R = R_1$, where $v_D$ is largest,
\[ v_D \approx 3 \times 10^5 \text{ cm/sec} \]

\[ = 10^{13} \text{ cm/year} \]

Changes in the appearance of the infrared nebula in the Orion due to radiation pressure will occur with a time scale of the order of \(10^5\) years.

3.2 Far-infrared Observations of the Galactic Center and NGC 1068

3.2.1 Review

The dynamical center of the Galaxy lies at a distance of \(10^4\) pc from the sun in the direction of the constellation Sagittarius (Oort and Rougoor 1960). In 1966 Becklin and Neugebauer (1968) detected infrared radiation from the galactic center at 2.2\(\mu\). Since then the galactic center region has been observed extensively with ground-based telescopes at wavelengths between 1.6\(\mu\) and 22\(\mu\).

Based on such observations, Becklin and Neugebauer (1969) have concluded that within 2 arcmin (\(\approx 1.8 \times 10^{19}\) cm) of the galactic center there are at least three distinguishable sources of radiation: (a) a general background with an intrinsic spectrum of \(\approx 4000^\circ\)K; (b) a point-like source (< 5 arcsec diameter) with a spectral power distribution peaking near 2\(\mu\); and (c) a core that stands out predominantly at 5\(\mu\), 10\(\mu\) and 22\(\mu\), 20 arcsec in diameter, in agreement
with Low et al. (1969), who reported a 15 arcsec diameter with wings. Its spectral power distribution, $F_\nu$, rises proportionally to $\nu^{-2}$ in this region of the infrared spectrum. A small amount of polarization, less than 2%, has been found at 10\(\mu\) (Low et al. 1969).

It is this core, the galactic nucleus, that we have observed in the far-infrared. Because the spectral power distribution of the point source beyond 2.2\(\mu\) follows that of the general background, rather than that of the 20 arcsec nucleus, it is interpreted by Becklin and Neugebauer (1969) as a very luminous star at the galactic center.

A striking feature of the energy flux density spectrum of the galactic nucleus is its similarity to the energy flux density spectrum of the Seyfert galaxy NGC 1068 (Low and Kleinmann 1968). By observing the galactic nucleus and NGC 1068 with the Lear jet telescope, we have confirmed that this similarity extends through the region from 50\(\mu\)-300\(\mu\).

The large amount of infrared radiation, which Low and Kleinmann have shown to be a common feature of many Seyfert galaxies, is thus shared by the nucleus of this galaxy and therefore perhaps by the nuclei of other normal galaxies.

If the similarities of the energy flux density distributions are indicative of a common type of energy generation, the galactic center shares with NGC 1068 and other extragalactic sources a mechanism for producing an enormous amount of far-infrared radiation.
3.2.2 Far-infrared Observations of the Galactic Center

The galactic center was observed with the Lear jet telescope during flights in June 1969, when it was marginally detected, and in August 1969. These flights are summarized in Figure 3.10. Of a total of ten flights, two were completely successful. During the flights in August a special reticle was installed in the guide telescope permitting offset guiding on Sag X, a third magnitude star, with more than 6 arcmin, i.e., $\approx 1/3$ beam diameter, accuracy. The far-infrared position of the galactic center agrees to within this offset guiding accuracy with the position given by Becklin and Neugebauer (1968) for the 2.2\(\mu\) source and the radio source Sagittarius A (Downes and Maxwell 1966).

Observations of Mars provided an absolute calibration and a check of the bore-sighting. Using the polyethylene-quartz filter combination (system IV) the galactic center produced (2.0 ± 0.1) times the deflection observed from Mars; the galactic center/Mars ratio was 2.1 ± 0.1 for the polystyrene filter combination (system V). Both objects were observed on all flights within 30 minutes from each other and were at that time 20-24 degrees above the horizon.

An area of about ten square degrees around the galactic center was scanned, essentially perpendicular to the galactic plane. A typical scan through the galactic center, using the polystyrene filter, is shown in Figure 3.11. The
FIGURE 3.10  Summary of the Flights on the Galactic Center

<table>
<thead>
<tr>
<th>Date</th>
<th>System</th>
<th>Chopper Speed [Hz]</th>
<th>Chopper Throw [arcmin]</th>
<th>Major Results</th>
<th>Major Problems</th>
<th>Observer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Jun 69</td>
<td>III</td>
<td>20</td>
<td>24</td>
<td>None</td>
<td>Oxygen</td>
<td>Low</td>
</tr>
<tr>
<td>11 Jun 69</td>
<td>III</td>
<td>20</td>
<td>24</td>
<td>None</td>
<td>Large base line shifts.</td>
<td>Low Aumann</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chopper failure</td>
<td></td>
</tr>
<tr>
<td>12 Jun 69</td>
<td>III</td>
<td>20</td>
<td>20</td>
<td>Detection of Galactic Ctr.</td>
<td>Large base line drifts</td>
<td>Low</td>
</tr>
<tr>
<td>13 Jun 69</td>
<td>III</td>
<td>20</td>
<td>20</td>
<td>Detection of Galactic Ctr.</td>
<td>Large base line drifts</td>
<td>Low Gillespie</td>
</tr>
<tr>
<td>19 Aug 69</td>
<td>III</td>
<td>40</td>
<td>20</td>
<td>None</td>
<td>Excessive DC offset</td>
<td>Low</td>
</tr>
<tr>
<td>20 Aug 69</td>
<td>III</td>
<td>40</td>
<td>20</td>
<td>None</td>
<td>Intermit.Chopper</td>
<td>Low</td>
</tr>
<tr>
<td>21 Aug 69</td>
<td>III</td>
<td>40</td>
<td>20</td>
<td>None</td>
<td>Moon 4° from Galactic Center</td>
<td>Gillespie Aumann</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Intermit.Chopper</td>
<td></td>
</tr>
<tr>
<td>22 Aug 69</td>
<td>IV</td>
<td>80</td>
<td>14</td>
<td>None</td>
<td>Voice Channel Failure</td>
<td>Low</td>
</tr>
<tr>
<td>25 Aug 69</td>
<td>IV</td>
<td>80</td>
<td>14</td>
<td>Measurements 60μ-300μ</td>
<td>None</td>
<td>Low Aumann</td>
</tr>
<tr>
<td>26 Aug 69</td>
<td>V</td>
<td>80</td>
<td>14</td>
<td>Measurements 75μ-300μ Horiz. Scans</td>
<td>None</td>
<td>Low Aumann</td>
</tr>
</tbody>
</table>
Fig. 3.11 A scan through the galactic center perpendicular to the galactic plane.
separation of the two peaks is equal to the chopper throw of 14 arcmin. The scans do not differ significantly from scans through a point source. The far-infrared diameter of the galactic nucleus is thus comparable to or smaller than our 15 arcmin beam. Measurements at 5μ-22μ (Low et al. 1969, Becklin and Neugebauer 1969) have shown that the source consists of a 15 arcsec core with wings. At the noise level indicated in Figure 3.11 point sources or gradients indicative of extended sources producing more than one-eighth the peak-to-peak deflection observed for the galactic center would have been detectable. Scans approximately 1/4 degree to the north and south of the galactic center yielded no visible deflections. However, several discrete sources were found along the galactic plane approximately 1/2 degree south of the galactic center. Specifically, there appears to be a source, which produced about 1/5 the deflection observed from the galactic center, approximately 40 arcmin to the southwest at

$$\alpha = 17^h 41^{±0.6}_m$$

$$\delta = -29^° 30^{±8}_1$$

(1950.0)

These sources may be satellites of the galactic nucleus or members of a new class of cool objects distributed throughout the galactic plane. Whatever their nature, it
seems that they may contribute significantly to the infrared luminosity of the galaxy. The extended source reported by Hoffmann and Fredrick (1969) was not detected.

The differential atmospheric extinction correction for the observed Mars/galactic center ratio was small and could be neglected. The absolute signal measured for Mars, assuming a far-infrared spectrum corresponding to a black-body temperature of 234°K (Aumann et al. 1969), agrees to within a factor of two with calculations based on the known characteristics of the telescope, the filters and the bolometer.

Although our system is primarily designed to measure the total power received over a wide spectral bandwidth, limited information about the flux density spectrum $F_\nu(\nu)$ of the galactic center can be obtained by utilizing the known spectral response of the two different filter systems. This has been discussed in Section 2.3.2.

Since the observations of the galactic center were made with only two filter systems, Equation 2.3 corresponds to two equations in two unknowns, the location of the peak of the flux density spectrum, $\nu_{\text{max}}$, and its peak value $F_\nu(\nu_{\text{max}})$. For the analytic form of $F_\nu(\nu)$ necessary to perform the integrations, we assumed various spikes. This is roughly the behavior expected from extrapolations of previous ground-based observations at 10μ and 20μ (Low et al. 1969, Becklin
and Neugebauer 1969) and at 3.3 mm (Dworetsky et al. 1969). At 1 mm there is an unpublished upper limit of $5 \times 10^{-25}$ watt/m²Hz obtained recently with a 1 arcmin beam (Low, private communication).

Calculations were made for three spectra:

a) Power-law spectrum:

$$
F_*(\nu) = \begin{cases}
F_{\text{max}} \left( \frac{\nu}{\nu_{\text{max}}} \right)^{-\alpha} & \nu \geq \nu_{\text{max}} \\
F_{\text{max}} \left( \frac{\nu}{\nu_{\text{max}}} \right)^{2.5} & \nu < \nu_{\text{max}}.
\end{cases}
$$

(3.6)

$F_*(\nu)$ was forced through the 10μ observations and the 1 mm upper limit.

b) The same power-law spectrum as above, but $F_*(\nu)$ was forced through the 22μ observation and the 1 mm upper limit.

c) A spectrum resembling that produced by a mono-energetic electron synchrotron self-absorption cut-off,

$$
F_*(\nu) = \begin{cases}
F_{\text{max}} \left( \frac{\nu}{\nu_{\text{max}}} \right)^2 \left( 1 - \frac{\nu}{\nu_{\text{max}}} \right) & \nu \geq \nu_{\text{max}} \\
F_{\text{max}} \left( \frac{\nu}{\nu_{\text{max}}} \right)^{2.5} & \nu < \nu_{\text{max}}.
\end{cases}
$$

(3.7)
The results are listed in Figure 3.12. The location and the peak value of the flux, \((8\pm3) \times 10^{-21} \text{ watt/m}^2\text{Hz}\) at \((4.2\pm2) \times 10^{12} \text{ Hz}\), do not depend strongly on the assumed shape of the spectrum.

Assuming a distance of \(10^4 \text{ pc}\), the total integrated infrared flux from the galactic center, \((2.8\pm1.0) \times 10^{-5} \text{ erg/sec cm}^2\), corresponds to a total power output \(L_{\text{Tot}} = (8\pm3) \times 10^7 \text{ L}_\odot\), approximately 50% of which contributes to the observed signal \(L_{50\mu-300\mu}\). The present results, along with previously published data (Low et al. 1969) are plotted in Figure 3.13.

The indicated error bars reflect the uncertainties in the assumed spectra; they do not include the uncertainty in the absolute calibration which is probably accurate to better than 50%.

The spectral power distribution shown in Figure 3.13 may not represent the intrinsic radiative properties of the source but may be affected by beam size effects and by absorption in the intervening medium. The ground-based observations between 5 and 25 microns were made with a 25\(^\circ\) beam, the new upper limit of \(50 \times 10^{-26} \text{ watt/m}^2\text{Hz}\) at 1 mm was established with a 60\(^\circ\) beam, while the 3 mm point is based on a 180\(^\circ\) beam (Dworetsky et al. 1969). The beam used in our observations with the airborne infrared telescope had
<table>
<thead>
<tr>
<th>F.U.</th>
<th>Observed</th>
<th>$\nu_{\text{max}}$</th>
<th>$F_*(\nu_{\text{max}})$</th>
<th>Synchrotron Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F(10\mu)$F.U.*</td>
<td>$1 \times 10^3$</td>
<td>$10^3$</td>
<td>40</td>
<td>$2.5 \times 10^3$</td>
</tr>
<tr>
<td>$F(22\mu)$F.U.*</td>
<td>$2 \times 10^3$</td>
<td>$1 \times 10^4$</td>
<td>$2 \times 10^3$</td>
<td>$8 \times 10^4$</td>
</tr>
<tr>
<td>$F(1\text{mm})$F.U.*</td>
<td>&lt; 50</td>
<td>50</td>
<td>50</td>
<td>$1.1 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_{\text{max}}$</td>
<td>----</td>
<td>$4.1 \times 10^{12}$</td>
<td>$4.2 \times 10^{12}$</td>
<td>$4.2 \times 10^5$</td>
</tr>
<tr>
<td>$F_<em>(\nu_{\text{max}})$F.U.</em></td>
<td>----</td>
<td>$9.5 \times 10^5$</td>
<td>$1.1 \times 10^6$</td>
<td>$6.5 \times 10^5$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>----</td>
<td>3.5</td>
<td>5.05</td>
<td>expon.</td>
</tr>
<tr>
<td>$\beta$</td>
<td>----</td>
<td>3.8</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>$L_{\text{Tot}}[L_\odot]$</td>
<td>----</td>
<td>$6 \times 10^7$</td>
<td>$5.2 \times 10^7$</td>
<td>$1.1 \times 10^8$</td>
</tr>
<tr>
<td>$L_{50\mu-350\mu}[L_\odot]$</td>
<td>----</td>
<td>$2.8 \times 10^7$</td>
<td>$3 \times 10^7$</td>
<td>$5 \times 10^7$</td>
</tr>
</tbody>
</table>

* 1 F.U. = $10^{-26}$ watt/m$^2$Hz

**FIGURE 3.12**
Fig. 3.13 The Fluxdensity Spectrum of the Galactic Nucleus peaks steeply near 70 microns.

- $25^\circ\text{ beam}$
- $180^\circ\text{ beam}$
- $720^\circ\text{ beam}$
- $60^\circ\text{ beam}$
an effective diameter of 720 arcsec. Beam size effects thus need to be investigated. This is particularly important in view of the high luminosity reported by Hoffmann and Fredrick (1969) with an ≈ 2 degree diameter beam, 7 x 10^8 L☉ near 100μ, and because cooler wings extending beyond a 15 arcsec diameter were noted at 10μ and 22μ (Low et al. 1969). Becklin and Neugebauer (1969) have found that the flux density of the galactic nucleus at 5μ and 10μ is proportional to (beam diameter)^{0.6±0.2} for beam diameters larger than 20 arcsec. Assuming that the scans (Figure 3.11) indicate an upper limit of 3 arcmin for the far-infrared diameter of the galactic nucleus, the luminosity originating from the 20 arcsec core may be a factor of four below the luminosity measured with our large beam. Further far-infrared observations of the galactic nucleus with increased spatial resolution are clearly needed.

The apparent structure in the spectrum may be produced by solid-state absorption in the particulate matter which produces the ~ 25 magnitudes of visual extinction (Becklin and Neugebauer 1968). Again this needs to be investigated by further observations.

The calculated luminosity of the galactic nucleus, 8 x 10^7 L☉, originating from a region of less than 10 pc in diameter, corresponds to ≈ 1% of the total galactic luminosity. Stars contained in the same volume account for
no more than 10% of this calculated luminosity (Becklin and Neugebauer 1968).

Although a considerable effort was made, the bright extended 2°x6° source reported by Hoffmann and Fredrick (1969) was not detected. A scan through an extended source, with a \( \frac{1}{2} \) peak width of \( \leq 2 \) degrees, would appear with our instrument as a deflection proportional to the gradient of the luminosity profile. No evidence of such a gradient can be seen on scans such as the one shown in Figure 3.11. As an upper limit estimate we assume that a deflection indicative of a gradient would have to be less than \( \approx \) one-eighth the deflection obtained from the galactic center, \( F_{G.C.} \). With a chopper throw of \( \approx \frac{1}{2} \) degree, the gradient must thus be less than \( \frac{1}{2} F_{G.C.}/\text{degree} \). Assuming a triangular luminosity profile with a \( \frac{1}{2} \) peak width of less than 2 degrees and a linear extent of \( \approx 6 \) degrees, the resultant luminosity would be less than six times the luminosity deduced for the galactic center or less than half the luminosity claimed by Hoffmann and Fredrick (1969).

3.2.3 Far-infrared Observations of NGC 1068

The Seyfert galaxy NGC 1068 was observed in the far-infrared during flights in September 1969, when it was marginally detected, and in February 1970. The flight dates
and the equipment used are summarized in Figure 3.14. Saturn and Mars were used as calibration objects. The signal from Saturn was sufficiently large so that the planet provided a check of the bore-sighting. However, the signals from Mars and NGC 1068 were both below the peak-to-peak noise level so that a substantial amount of integration time was required. On 18 and 19 February 1970 flux measurements of NGC 1068 relative to Mars and Saturn were obtained. The resulting ratios are:

\[
\frac{\text{Mars/NGC 1068}}{} = 3.3 \pm 0.9 \\
\frac{\text{Saturn/Mars}}{} = 2.2 \pm 0.33 ,
\]

where the error bars indicate the 2\(\sigma\) confidence level. The observed Saturn/Mars ratio is in excellent agreement with a ratio of 2.15, calculated from the known transmission characteristics of the filters. The above quoted ratios have been corrected for an instrumental signal, producing approximately 20\% of the observed NGC 1068 deflection.

Using methods for data analysis outlined in Section 2.3.2 we find by direct integration that Mars radiates \(8.3 \times 10^{-14}\) watt/cm\(^2\) between 60\(\mu\) and 300\(\mu\). Given the flux ratio Mars/NGC 1068 = 3.3 ± .9, it follows that

\[
F_{60\mu-300\mu}^{\text{(NGC 1068)}} = (2.5 \pm .7) \times 10^{-14} \text{ watt/cm}^2 .
\]
**FIGURE 3.14  Summary of the Flights on NGC 1068**

<table>
<thead>
<tr>
<th>Date</th>
<th>System</th>
<th>Chopper Speed [Hz]</th>
<th>Chopper Throw [arcmin]</th>
<th>Major Results</th>
<th>Major Problems</th>
<th>Observer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02 Sept 69</td>
<td>V</td>
<td>80</td>
<td>14</td>
<td>None</td>
<td>Cracked Filter causing Excess Noise</td>
<td>Low</td>
</tr>
<tr>
<td>03 Sept 69</td>
<td>V*</td>
<td>80</td>
<td>14</td>
<td>Marginal Detection of NGC 1068</td>
<td>Base Line Oscillation</td>
<td>Low</td>
</tr>
<tr>
<td>12 Feb 70</td>
<td>VI</td>
<td>80</td>
<td>10</td>
<td>None</td>
<td>Insufficient Integration</td>
<td>Gillespie Cauthen</td>
</tr>
<tr>
<td>18 Feb 70</td>
<td>VII</td>
<td>80</td>
<td>8</td>
<td>Measurements of NGC 1068 65μ-300μ</td>
<td>None</td>
<td>Low Gillespie</td>
</tr>
<tr>
<td>19 Feb 70</td>
<td>VII</td>
<td>80</td>
<td>8</td>
<td>Measurements of NGC 1068 60μ-300μ</td>
<td>None</td>
<td>Low Cauthen</td>
</tr>
<tr>
<td>24 Feb 70</td>
<td>VII</td>
<td>80</td>
<td>8</td>
<td>None</td>
<td>Insufficient Integration</td>
<td>Low Gillespie</td>
</tr>
</tbody>
</table>

* Beam Diameter decreased to 10 arcmin.
At a distance of 11 Mpc (≈ 3.3 \times 10^{25} \text{ cm}) [Sandage 1963], NGC 1068 thus radiates $10^{12} \ L_\odot$, or 100 times the total luminosity of a giant spiral galaxy, between 60μ and 300μ. Since a conservative estimate of the luminosity of the 20 arcsec diameter nucleus, based on ground-based observations up to a wavelength of 25 micron, indicates "only" $6 \times 10^{10} \ L_\odot$ (Kleinmann 1968), we are forced to the conclusion that, just as in the case of the galactic center, the energy flux density spectrum of NGC 1068 peaks well beyond 25 microns.

Using the method developed in Section 2.3.2.a, we obtain a first order energy flux density spectrum, $F(\nu)$, of NGC 1068 by assuming that $F(\nu)$ peaks at a frequency $\nu_{\text{max}}$ with a value $F(\nu_{\text{max}})$ and drops off on the high frequency and the low frequency side according to a power law (Equation 3.6). At 22μ and 3.4 mm $F(\nu)$ is matched with ground-based observations [$F_{22\mu} = 80 \text{ F.U.}$ (Kleinmann and Low 1970); $F_{3.4 \text{ mm}} \approx 0.1 \text{ F.U.}$ (Epstein, E. E., private communication); during millimeter outbursts $F_{3.4 \text{ mm}} \approx 10 \text{ F.U.}$ have been observed (Schorn et al. 1968)].

Assuming $\nu_{\text{max}} = 4 \times 10^{12} \text{ Hz}$ as determined for the galactic center, Equation 2.3 can be solved numerically for $F(\nu_{\text{max}})$,

$$F(\nu_{\text{max}}) = (1.5 \pm .5) \times 10^{-22} \ \text{watt} \ \text{m}^{-2} \ \text{Hz}^{-1}.$$
The total luminosity integrated from 25µ to 300µ is $1.5 \times 10^{12} \ L_\odot$, compatible with the 60µ-300µ luminosity deduced directly without knowledge of $F(\nu)$.

The assumption $\nu_{\text{max}} = 4 \times 10^{12} \ \text{Hz}$ is not critical. Assuming $\nu_{\text{max}} = 3 \times 10^{12} \ \text{Hz}$ causes an insignificant change in $F(\nu_{\text{max}})$ and a 10% decrease in the total luminosity.

The resulting energy flux density spectrum of NGC 1068 is plotted together with previous ground-based observations (Kleinmann and Low 1970) in Figure 3.15. The error bars at 50µ and 300µ indicate the uncertainty of the spectral power distribution outside of the passband of the filter system. This uncertainty is especially severe beyond 200µ since only a small fraction of the total power output is radiated at these wavelengths.

The spectral power distribution shown in Figure 3.15 may be affected by beam size effects. With beam diameters up to 35 arcsec, no beam size effects were noted, to within experimental errors, at 5µ, 10µ and 22µ with beams larger than 5 arcsec (Kleinmann and Low 1970). A beam of 600 arcsec diameter was used for the far-infrared observations considerably larger than the largest beam used for the 5µ, 10µ and 22µ observations. Beam size effects in the far-infrared may thus not be negligible, but quantitative
**Figure 3.15 Spectral Power Distribution of NGC 1068**

- **Log Flux Density (Watt/M² Hz)**
- **Log Frequency (Hz)**

Symbols:
- ○ $5\pi$ - $35\pi$ Beams
- ○ $600\pi$ Beam

Frequency: $\nu 3.5$
estimates have to wait until far-infrared observations with increased spatial resolution become available.

It is interesting to note at this point that the noise equivalent flux, N.E.F.ₕ, of system VII is $1.7 \times 10^{-14}$ watt/cm² Hz¹/₂ (Figure 2.11). Thus, theoretically, a flux of $1.7 \times 10^{-14}$ watt/cm² should be detectable by the telescope system with unity signal/noise ratio and of the order of one second integration time. However, in order to measure the flux from NGC 1068, ≈ 2 N.E.F.ₕ, approximately forty 10-second blocks of integration time were required.

3.2.4 Discussion

A discussion of our observations of the galactic center and NGC 1068 can be divided into two parts: The question of the ultimate energy source and the question of the radiation mechanism which converts this energy into the observed far-infrared radiation.

For the radiation mechanisms we consider thermal reradiation by dust particles and synchrotron radiation. Dust models very efficiently convert energy in the form of short wavelength photons ($0.1 \mu \lesssim \lambda \lesssim 1 \mu$) into infrared radiation. However, in some cases a prohibitively large amount of dust may be required. Synchrotron radiation is efficient provided the source radiates most of its energy...
in the form of relativistic particles and excessive inverse Compton losses can be avoided.

In the following we show that the sources in the \( \approx 20 \) arcsec diameter nucleus of this galaxy and the \( \approx 5 \) arcsec diameter nucleus of NGC 1068 are very likely non-thermal and dust models have to be ruled out, if far-infrared beam size effects are insignificant. However, dust may play an important role, if the existence of considerable beam size effects should be confirmed.

3.2.4.1 Synchrotron Models

Since both the radio emission and part of the optical continuum from the nuclei of Seyfert galaxies are known to be due to the synchrotron process, it is natural to consider the possibility that the infrared flux is emitted directly by the same process. This question has most recently been considered in detail by Burbidge and Stein (1970) who concluded that the spectra of the galactic center and Seyfert galaxies could be explained in terms of an optically thick synchrotron radiation model. The asymptotic form of the spectral power distribution, \( F(\nu) \), of such a model is given in Equation 3.7. At frequencies \( \nu < \nu_{\text{max}} \), the frequency where the spectral power distribution reaches its peak, \( F(\nu) \) is proportional to \( \nu^{2.5} \), characteristic of synchrotron self-absorption. However, the first order energy flux density spectra deduced from our observations of the galactic center and NGC 1068 indicate
that, for $\nu < \nu_{\text{max}}$, $F(\nu)$ drops off substantially steeper than synchrotron self-absorption would permit, $F(\nu) \sim \nu^{3.5}$ to $\nu^4$. Thus, the question whether plasma effects could contribute to the steep low frequency roll-off of $F(\nu)$ has to be reexamined. Negative synchrotron self absorption, free-free absorption and the Razin effect are considered. We confine our discussion to electrons with narrow ("monoenergetic") energy spectra.

a) Synchrotron Radiation with a Free-Free Absorption Cut-off

The free-free absorption coefficient $\alpha(\nu)$ is given by (Ginzburg et al., 1964)

$$\alpha(\nu) = \frac{10^{-2} n_e^2}{T_e^{3/2} \nu^2} \left( 17.5 + \ln \frac{T_e^{3/2}}{\nu} \right), \quad (3.8)$$

where $n_e$ and $T_e$ are the density and temperature of the thermal electrons. Free-free absorption is important if $\alpha(\nu) R > 1$, where $R$ is the size of the source relative to the line of sight. For frequencies $\nu < \nu_{\text{ff}}$, with

$$\nu_{\text{ff}} \approx \left( 1.5 \times 10^{-1} T_e^{-3/2} n_e^2 R \right)^{1/3}, \quad (3.9)$$

the cut-off is exponential.
The peak of the spectral power distribution of synchrotron radiation with monoenergetic electrons of energy $\gamma m_0 c^2$ occurs at

$$\nu_{\text{max}} = 1.2 \times 10^6 B \gamma^2$$  \hspace{1cm} (3.10)

(Ginzburg et al., 1964). With $\nu_{\text{ff}} = \nu_{\text{max}} = 4 \times 10^{12}$ Hz we obtain from Equation (3.10)

$$B = 3 \times 10^6 \gamma^{-2}$$  \hspace{1cm} (3.11)

and from Equation (3.11)

$$n_e^2 R = 10^{25} T_e^{3/2} .$$  \hspace{1cm} (3.12)

For electrons with energies between 1 MeV - 100 MeV, magnetic fields ranging from 80 - 8 x $10^5$ gauss are required.

b) Synchrotron Radiation with Razin Cut-off

The Razin effect (Razin 1960) was actually first noted by Tsytovich (1951). A heuristic discussion is given by Scheuer (1966). In the presence of a plasma the index of refraction

$$n(\nu) = \sqrt{1 - (\nu_p/\nu)^2}$$  \hspace{1cm} (3.13)
is less than 1. Thus, in effect, the Lorentz factor $\gamma$ has to be replaced by $\gamma' = \left(1 - n(\nu)^2 \nu^2/c^2\right)^{-\frac{1}{2}}$. For frequencies $\nu < \nu_R$, with
\[ \nu_R \approx 20 \frac{n_e}{B}, \] (3.14)
where $n_e$ is the non-relativistic electron density and $B$ is the magnetic field strength, the Razin effect causes an exponential cut-off in the energy flux density spectrum.
In order to obtain the observed sharp peak in the spectral power distribution, we assume that the Razin cut-off starts at $\nu_R \approx \nu_{\text{max}}$, given in Equation 3.10. The Razin effect for $\nu > \nu_R$ is weak (Hornby and Williams 1966). With $\nu_R = 4 \times 10^{12}$ Hz, we obtain
\[ n_e = 2 \times 10^{11} B \] (3.15)
and
\[ B = 3 \times 10^6 \nu^{-2}. \]

With electron energies ranging between 1 MeV and 100 MeV, very high thermal electron densities, $10^{13}$ cm$^{-3}$ - $10^{17}$ cm$^{-3}$, are required. Free-free absorption then becomes important unless the size of the sources is kept rather small, $< 10^9 - 10^{11}$ cm, assuming $T_e = 10^8$K.
c) Negative Synchrotron Self-Absorption
   (Coherent Synchrotron Radiation)

Zheleznyakov (1967) has shown that in contrast to vacuum, in which reabsorption of synchrotron radiation by a system of relativistic electrons is always positive, reabsorption in a medium may be negative. For a system of electrons with a narrow energy spectrum with a maximum at $E_0$, negative reabsorption reaches a maximum value at the frequency

$$\nu_{\text{max}} \approx \left(6.25 \times 10^4 \frac{n_e^{3/2} \nu}{B}\right)^{1/2}$$  \hspace{1cm} (3.16)

if

$$n_e \ll 3.6 \times 10^5 B^2 \nu^2.$$  \hspace{1cm} (3.17)

$$\nu = \frac{E_0}{m_e c^2}$$  \hspace{1cm} (3.18)

In these equations $m_e$ and $n_e$ are the non-relativistic electron mass and density and $B$ is the magnetic field strength, all in cgs units.

If Equation (3.17) is satisfied, the region of appreciable negative reabsorption is quite narrow and lies within the limits of $\pm 0.3 \nu_{\text{max}}$. The reabsorption coefficient at $\nu = \nu_{\text{max}}$ in that case is given by
\[ \mu = \frac{-2.3 \times 10^{-2}}{a} \frac{e^2}{m_e c} \frac{v_p^2}{\nu_{\text{max}}} n_r , \quad (3.19) \]

where \((a)\) is a factor of order unity, \(v_p = 9 \times 10^{-3} \sqrt{n_e}\) is the plasma frequency and \(n_r\) is the relativistic electron density. If \(R\) is the dimension of the source and \(-\mu R > 1\), the intensity of the outward radiation exceeds the level of radiation in the absence of coherent radiation by the amplification factor

\[ A = \frac{e^{-\mu R} - 1}{-\mu R} . \quad (3.20) \]

In principle, very large amplification factors can be achieved. However, Zheleznyakov (1967) points out that if \(-\mu R >> 1\), non-linear equations have to be used to evaluate \(\mu\) and \(A\).

With \(\nu_{\text{max}} = 4 \times 10^{12} \text{ Hz}\) the condition (3.17) for coherent synchrotron radiation can be rewritten using Equation (3.16)

\[ n_e > \frac{4.3 \times 10^{17}}{\nu^2} . \quad (3.21) \]

Unless very high energy electrons are used, the lower limit on the required non-relativistic electron density \(n_e\) is
very high, $10^{13} - 10^{17}$ cm$^{-3}$ for relativistic electrons in
the 1 MeV - 100 MeV range. Free-free absorption then
limits the size of the source just as in the case of Razin
effect models.

The dominant energy loss mechanism of the relativistic
electrons competing with synchrotron losses is inverse
compton scattering. From Jones (1965)

$$\frac{dE}{dt}_{\text{inverse compton}} = 2.6 \times 10^{-14} \gamma^2 w_{\text{ph}}, \quad (3.22)$$

where $w_{\text{ph}}$ [ergs/cm$^3$] is the energy density of the photon
field. Since

$$\frac{dE}{dt}_{\text{synchrotron}} = 2 \times 10^{-15} \gamma^2 B^2 \quad (3.23)$$

(Ginzburg et al., 1964) synchrotron losses dominate inverse
compton losses if

$$\frac{\frac{dE}{dt}_{\text{inverse compton}}}{\frac{dE}{dt}_{\text{synchrotron}}} \ll 1 \quad (3.24)$$

i.e., $L \ll 10^{10} B^2 R^2 \quad (3.25)$

$L$, $R$ and $B$ are the luminosity, radius and magnetic field
strength of the source. For coherent synchrotron radiation
Equation (3.25) has to be replaced approximately by

\[ L \ll 10^{10} A B R^2 \]

(3.26)

where \( A \) is the amplification factor.

In the case of free-free absorption models, inverse Compton losses can be minimized by increasing \( R \), up to the point when free-free emission (proportional to \( n_e^2 \)) becomes unacceptably large. This assumes that the free-free absorption occurs in a shell surrounding the source. The maximum size of the source in coherent synchrotron radiation and Razin effect models is dictated by free-free absorption. However, in coherent synchrotron models inverse Compton losses can be decreased by increasing the amplification factor.

A large number of synchrotron radiation models are possible. However, building quantitative models that radiate with reasonable efficiency and meet all additional observational requirements such as upper limits on free-free emission, \( \gamma \)-ray and x-ray fluxes, is difficult.

Rieke (1970) has considered in detail synchrotron models of the galactic nucleus. He concludes that fairly efficient coherent synchrotron radiation models can be devised using 100 MeV electrons. Assuming an amplification factor of \( 10^9 \), the energy contained in the 100 MeV electrons is converted
with $\approx 50\%$ efficiency into far-infrared radiation. The remaining energy appears after double inverse Compton scattering in the form of $\approx 100$ MeV $\gamma$-rays. The resulting flux of $\gamma$-rays, $\approx 10^{-1} \gamma/\text{cm}^2 \ \text{sec}$, lies a factor $3 \times 10^3$ above the flux observed in this energy range, coming from the direction of the galactic center (Hutchinson et al., 1969, Fichtel et al., 1969). Approximately 400 gr/cm$^2$ of absorbing gas in the line of sight would provide the required attenuation. (The range of 100 MeV $\gamma$-rays is $\approx 50$ gr/cm$^2$, Johnson 1963.) Since the amount of gas distributed near the galactic center is less than 150 gr/cm$^2$, most of the attenuation would have to occur in a shell surrounding the source.

The efficiency of free-free absorption models is small. Rieke (1970) concludes that only 1% of the energy available in the relativistic electrons is radiated in the infrared. Most of the losses are due to inverse Compton scattering. The efficiency of Razin effect models is lower than that of free-free absorption models.

Regardless of which synchrotron model is considered, the upper limit imposed on the source luminosity (Equation 3.25 and 3.26) and the requirement that excessive free-free emission has to be avoided demands that the sources in the galactic nucleus and NGC 1068 consist of a large number of small infrared synchrotron, irtron (Low 1970) sources.
3.2.4.2 Thermal Models

The spectral power distributions deduced for the Galactic Center and NGC 1068 can be approximated by 75°K plank curves. The minimum radius of a thermal model with luminosity L is thus given by the radius of the equivalent 75°K blackbody sphere,

$$R_{\text{min}} = 6.7 \times 10^{-3} \sqrt{L}$$  \hspace{1cm} (3.27)

Assuming that these thermal models consist of dust grains similar to the impure graphite grains used in models of the infrared nebula in Orion, the masses of such dust models as function of their luminosities can be estimated. If we choose \( R \approx 2 \times R_{\text{min}} \), a total mass of

$$M = 1.2 \times 10^{-3} L$$  \hspace{1cm} (3.28)

in the form of dust grains and hydrogen gas approximates the observed spectral power distribution.

A small amount of polarization has been noted in the galactic center at 10\(\mu\) (\(\approx 2\%, \text{Low et al., 1969}\)). Could polarization be produced by dust grains? It is thought that the polarization of starlight at visible wavelengths is due to absorption of light by elongated grains that are aligned by magnetic fields. If this is the true source of
polarization, Stein (1966) concludes that the far infrared emission from these elongated grains should also be polarized, as much as 30-70%. Observed infrared polarizations (Forbes 1967) are much smaller, possibly due to irregularities in the large scale structure of the magnetic fields.

a) Galactic Nucleus

The minimum radius of a thermal model of the galactic nucleus is given by Equation (3.27). With $L = 3 \times 10^{41}$ ergs/sec, $R_{\text{min}} = 3.7 \times 10^{18}$ cm. At a distance of $10^4$ pc this corresponds to a sphere of 50 arcsec diameter, 2.5 times larger than the diameters observed at 5, 10 and 22μ. This rules out thermal models unless beam size effects are important.

Indications of beam size effects at 5, 10 and 22μ have already been discussed. The only far-infrared observations of the galactic center other than those reported here are by Hoffman and Fredrick (1969) who, with an $\approx 12$ times larger beam, found a nine times greater luminosity.

In order to make a quantitative estimate of the consequences of beam size effects, we assume that the far-infrared flux from the galactic center is proportional to the (beam diameter)$^{0.6}$, for beams larger than 20 arcsec, as suggested by the work of Becklin and Neugebauer (1969) at 5 and 10 microns.
Since we have measured $8 \times 10^7 \ L_\odot$ with a 15 arcmin beam, it is, under these assumptions, easy to show that 20 arcsec diameter contains $\approx 8 \times 10^6 \ L_\odot$ and the $2^\circ \times 6^\circ$ Hoffmann source (Hoffmann and Fredrick 1969) contains $4 \times 10^8 \ L_\odot$, in agreement with the upper limit deduced from the galactic center scans.

The minimum diameter of a dust model radiating $8 \times 10^6 \ L_\odot$, from Equation (3.27), is $2.4 \times 10^{18} \text{cm}$, equivalent to approximately 15 arcsec at the distance of the galactic center. Such a 15 arcsec diameter source would be completely opaque to visible and near infrared radiation. 25 Magnitudes of visual absorption by interstellar dust hide the center of this galaxy from direct views. The 2.2 micron point source (Becklin and Neugebauer 1969) has to lie outside of this 15 arcsec diameter source. Such a "dark spot" in the nucleus of the Andromeda galaxy, generally believed to be a carbon copy of this (our) galaxy, would be only 1/4 arcsec in diameter and could thus not be resolved on short exposure photographs.

We conclude that the 20 arcsec diameter galactic nucleus is very likely a non-thermal source, unless considerable far-infrared beam size effects are assumed. In that case the luminosity of the 20 arcsec core may be rather modest, perhaps of the order of $8 \times 10^6 \ L_\odot$, but still a factor 7 larger than
previous conservative estimates based on ground-based observations out to a wavelength of 25 microns (Low et al. 1969). The remaining luminosity would be distributed in a large volume in the form of many small sources with the appropriate spatial density distribution to produce the assumed luminosity-beam size dependence.

b) NGC 1068

The observed luminosity of NGC 1068 is $6 \times 10^{45}$ ergs/sec. The minimum radius of a thermal model of NGC 1068 is then, from Equation (3.27), $5.2 \times 10^{20}$ cm. At a distance of 11 Mpc = $3.3 \times 10^{25}$ cm this radius corresponds to an angular diameter of 6.5 arcsec. Kleinmann and Low (1970) have reported an upper limit of 5 arcsec for the diameter of the nucleus of NGC 1068 at 5, 10 and 22μ. A dust model with a 5 arcsec diameter could radiate, with the observed spectral power distribution, no more than 60% of the luminosity measured with our 10 arcmin diameter beam. However, such a model has to be ruled out because the resultant "dark spot" on photographs of the nucleus of NGC 1068 is not observed. On plates with short exposure times the nucleus of NGC 1068 is approximately $1.2'' \times 1.5''$ in size (resolution $\approx 0.9''$ ) and increases in size on plates with longer
exposures to about $3'' \times 4''$ (Walker 1968). A single "dark spot" with a diameter of 1 arcsec or a large number of small "dark spots", if they they occult more than 25% of the cross-section of the 5 arcsec nucleus, should be detectable. Significant variations, with time scales of the order of days, noted in the flux level of the nucleus of NGC 1068 at 2.2 microns (Pacholczyk and Weymann 1968), 5, 10 and 22 microns (Kleinmann and Low 1970), imply source dimensions of the order of light days and multiple structure.

We conclude that the infrared radiation originating from the 5 arcsec nucleus of NGC 1068 cannot be thermal, i.e. is very likely non-thermal, unless we assume that far-infrared beam size effects are important. A dust model of the 5 arcsec nucleus cannot radiate more than 12% of the observed far-infrared luminosity of NGC 1068 of $1.5 \times 10^{12} L_\odot$. How much of this luminosity actually originates in the $5''$ nucleus is, at present, difficult to estimate. (The 10 arcmin diameter beam used for the measurement contains the entire galaxy NGC 1068!) The estimate of $6 \times 10^{10} L_\odot$ (Kleinmann 1968), based on a conservative extrapolation of narrow beam ground-based observations out to a wavelength of 25 microns, is a lower limit.
3.2.4.3. The Energy Source

Thermonuclear reactions, supernova explosions, gravitational collapse, stellar collisions and matter-antimatter annihilation have, by various authorities, been considered as the energy sources in the nuclei of galaxies. A summary of these mechanisms is given by Burbidge and Burbidge (1967). A total of $10^{59}$ ergs, $5 \times 10^4 M_\odot c^2$, is released in the galactic center in the form of far-infrared radiation, assuming that the lifetime of the galaxy is of the order of $10^{10}$ years. NGC 1068 radiates $2 \times 10^{62}$ ergs, $\approx 10^8 M_\odot c^2$, in the far-infrared, assuming a lifetime of the order of $10^9$ years. Unless the mass-to-energy conversion efficiency of the energy source is high, a considerable amount of matter has to be processed to provide the required energy.

The mass-to-energy conversion efficiency of thermonuclear reactions is of the order of 1% at the maximum, $10^{52}$ ergs/$M_\odot$, the energy appearing mostly in the form of ultraviolet photons. Gravitational collapse is in principle capable of releasing an amount of energy equal to $M c^2$. In order to release energy by this mechanism it is necessary to consider collapse nearly to the size of the Schwarzschild radius, $R_s = GM/c^2$. At this stage
general relativity shows that it is very difficult for energy to be emitted. Colgate and White (1966) have considered gravitational collapse as part of supernova explosions. They conclude that $10^{-3}$ of the total mass-energy could be ejected, $\approx 80\%$ in the form of kinetic energy of gas and $\approx 20\%$ in the form of relativistic particles.

The most efficient mass-to-energy conversion mechanism known at present is matter-antimatter annihilation. Of the energy released in the average proton-antiproton annihilation 50% goes into 95 MeV neutrinos, 33% into 180 MeV $\gamma$-rays and 17% into electrons and positrons with a mean energy of $\approx 100$ MeV (Ekspeng et al. 1966). Alfven and Klein (1962) have suggested that matter and antimatter exist in every galaxy. If a large amount of matter and antimatter is concentrated in the center of a galaxy, the resulting electrons and positrons may radiate coherent synchrotron radiation. The total mass-to-infrared energy conversion efficiency of this process would be $\approx 8\%$.

It is doubtful whether a mass-to infrared radiation conversion mechanism can be conceived which is significantly more efficient than the 8% efficiency deduced for the proton-antiproton coherent synchrotron radiation model. With this
efficiency a total mass of $6 \times 10^5 \, M_\odot$ has to be processed in the galactic nucleus, a fraction of the $3 \times 10^6 \, M_\odot$ contained in the same volume. The total amount of mass which has to be processed in NGC 1068 is $\sim 1.2 \times 10^9 \, M_\odot$. Walker (1968) has found, from rotation curves, that less than $7 \times 10^9 \, M_\odot$ are contained in the nucleus of NGC 1068 inside a diameter of 80 arcsec. If we assume that the mass density falls off from the nucleus approximately as $(\text{distance})^{-1.8}$, as Becklin and Neugebauer (1968) have shown for the galactic nucleus, of the order of $3 \times 10^8 \, M_\odot$ should be contained inside the 5 arcsec diameter from which the observed far-infrared luminosity is believed to originate.

It is this mass problem which has led Low (1970) to suggest that matter is continuously created in the nuclei of galaxies. The alternatives to this possibility are:

a) Mass collapses into the nucleus where it is transformed into radiation. An outflow of mass is actually observed.

b) The volume from which the observed far-infrared radiation originates has been underestimated. The possibility of beam size effects and the difficulty of estimating their importance from ground-based observations have already been discussed. Less than 5% of the observed luminosity is located below 25 microns.
4.0. Conclusions

An airborne infrared telescope has been developed that allows observations of astronomical objects between 25 microns and 1 mm, a region of the electromagnetic spectrum where the earth's atmosphere is completely opaque. The infrared nebula in Orion, the galactic center and the Seyfert galaxy NGC 1068 have been observed. NGC 1068 is the first object outside of this galaxy to be detected in the wavelength range between 25 microns and 1 mm.

The infrared nebula in Orion

The infrared luminosity of the infrared nebula in Orion is $1.5 \times 10^5 L_\odot$, equivalent to $6.25 \times 10^{38}$ ergs/sec. We suggest that it is thermal in origin and is emitted from a dust cloud surrounding one or a number of highly luminous stars which may have formed at the center. The total amount of mass contained in the dust cloud is of the order of $200 M_\odot$ in the form of hydrogen gas and dust grains. The infrared absorption efficiency of the dustgrains, $Q_\lambda$, is very nearly proportional to $2\pi a/\lambda$, where $a$ is the dust grain radius, but may decrease as fast as $1/\lambda^2$ at wavelengths beyond 100 microns. This wavelength
dependence of the infrared absorption efficiency suggests impure graphite grains, core-mantle grains - small graphite grains surrounded by a mantle of ice -, or dirty ice grains. Ice grains cannot be ruled out in the cooler regions of the dust cloud since the density of hydrogen gas is high enough to permit stable ice grains. This is in contrast to typical interstellar dust clouds where the density of hydrogen gas is several orders of magnitude lower and stable ice grains cannot form.

The spectral power distribution deduced for the infrared nebula in Orion can be generated with an arbitrary infrared luminosity L, if an amount of mass of the order of $1.2 \times 10^{-3} L$ in the form of dust and impure graphite grains is distributed in a sphere of radius $R \approx 1.3 \times 10^{-2} \sqrt{L}$, surrounding the energy source. The bulk of its energy output has to be in the form of ultraviolet photons.

**Galactic Center and NGC 1068**

We have measured total infrared luminosities of $3 \times 10^{41}$ ergs/sec for the galactic center using a 15 arcmin beam and $6 \times 10^{45}$ ergs/sec for NGC 1068 using a 10 arcmin beam. Although the deduced spectral power distributions bear striking resemblances to that deduced for the infrared nebula in Orion,
models are much more complex.

Synchrotron models using 1 - 100 MeV electrons (and positrons) approximate the observed spectral power distributions of the galactic center and NGC 1068. They require magnetic fields of the order of $10^{-2}-10^{-5}$ gauss and non-relativistic electron densities between $10^{10}$ and $10^{13}$ electrons/cm$^3$. The low frequency roll-off of the spectral power distribution is due to coherent radiation, free-free absorption or the Razin effect. Inverse compton losses and free-free emission are minimized by assuming that the infrared source has multiple structure.

The surface brightness of synchrotron radiation models is sufficient to radiate the observed infrared luminosities from the small volumes indicated by ground-based observations at 5, 10 and 22 microns. However, their modest mass-to-infrared energy conversion efficiencies, of the order of 8% or less, lead in the case of NGC 1068, and presumably in the case of other Seyfert galaxies, to a mass problem. At least four times more mass must have been processed in the 5 arcsec diameter nucleus of NGC 1068 than is at present contained in it. This has led Low(1970) to reiterate the suggestion of Jeans that mass is continuously created in the nuclei of galaxies.
The observed high infrared luminosities cannot be radiated from thermal dust models occupying the small 20 arcsec nucleus of the galactic center and 5 arcsec nucleus of NGC 1068. Dust models of the galactic center and NGC 1068 have to be ruled out, unless the existence of considerable beam size effects in the far-infrared is confirmed. Of the order of 90% of the measured i.r. luminosities must originate from outside of the small nuclei of this galaxy and that of NGC 1068. The mass-energy problem noted in the case of NGC 1068 would thus be avoided. There are indications of beam size effects in the case of the galactic center, but quantitative estimates of their importance are difficult at present, due to the lack of far-infrared observations with high spatial resolution. If beam size effects should be confirmed, non-thermal as well as dust models may play a role in the centers of galaxies.

Our observations of the galactic center and the Seyfert galaxy NGC 1068, regardless of the radiation mechanism, lend additional support to the assumption, based on considerable previous evidence (Kleinmann and Low 1970), that the quiescent spectral flux distributions are similar, if not identical,
for all galaxies. In fact, the observed infrared luminosities seem to form an evolutionary sequence -- quasars, Seyfert galaxies and normal, large spiral galaxies (Low 1970), with luminosities ranging from $\sim 10^{48}$ ergs/sec for the quasar 3C273B (at a distance of 500 Mpc), $6 \times 10^{45}$ ergs/sec for the Seyfert galaxy NGC 1068, to approximately $3 \times 10^{41}$ ergs/sec originating from the center of the local galaxy. The nature of the ultimate energy source is still uncertain.
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APPENDIX I

A complete listing of the computer program for the numerical solution of the energy transfer equation through a dust cloud is given in Fortran IV. Explanatory comments are scattered throughout the program.

The program checks for each shell the accuracy of the temperature iteration (Loop 100) and of the total luminosity. If, after 50 iterations, the temperature equation cannot be solved with less than 0.3% error, statement 115 is printed out and the iteration is terminated. At the end of each shell building loop the total luminosity is checked. If it differs by more than 5% from the input luminosity (XLIN), the program is terminated with statement 113.

As stated the program calculates a model of the infrared nebula in Orion with an input luminosity of $1.5 \times 10^5 \, L_\odot$ using modified impure graphite particles with $a = 5 \times 10^{-6} \, \text{cm}$ and a total mean short wavelength optical depth $\tau_s = 150$. Total Burroughs 5500 time required is 93 seconds, corresponding to an average of 0.43 seconds per dust shell.
C**** MODEL CALCULATION OF THE ORION OBJECT.
C**** TERMINAL RADIUS RT
C**** LUMINOSITY IS 1.5E+5 SOLAR LUMINOSITIES
 **COMMON/XLIN, ROBS, RT, RI
 XLIN=6.25E+38
C**** OBSERVER DISTANCE = ROBS
 ROBS=7.5E+21
C**** OPTICAL DEPTH IN UV AND VISUAL TAU
C**** PARTICLE CROSS SECTION AP
C**** GRAPHITE GRAINS
C**** ALPHA=1, FOR GRAPHITE GRAINS
C**** ALPHA=2, FOR IMPURE GRAPHITE GRAIN CALCULATION
C**** SHORT WAVELENGTH ABSORPTION EFFICIENCY EFF
C**** (LAMBDA) PROPORTIONAL TO LAMBDA**2
C**** FOR LAMBDA > 100 MICRONS
C**** INNER SHELL RADIUS RI
C**** XN = DUST GRAIN NUMBER DENSITY
 XC=1.4E-4
 AP=7.5E-11
 EFF=1.0
 ALPHA=2.
 RI=5.5E+16
 RT=5.5E+17
 TAU=150.
 XN= (EFF*AP*(RT-RI))
 CALL RADI00(XN, ALPHA, AP, EFF, XC, TAU)
 PRINT 1
 1 FORMAT(1H1)
 ELT=TIME(2)/60.
 PRINT 1000, ELT
 1000 FORMAT(/F14.2, 23H SECONDS EXECUTION TIME)
 OUTT=TIME(3)/60.
 PRINT 1001, OUTT
 1001 FORMAT(F14.2, 26H SECONDS INPUT/OUTPUT TIME)
 STOP
 END

SUBROUTINE RADI00(XN, ALPHA, AP, EFF, XC, TAU)
C**** RADIATIVE TRANSFER THROUGH A DUST CLOUD.
C**** H. H. AUMANN 17 JULY 1969
C****
C**** SUBROUTINES REQUIRED
C**** PLANKFUNCTION PLANK(F, XL, T)
C**** ABSORPTION EFFICIENCY ADUST(A, XL, ALPHA, EFF, XC)
C**** SIMPSON INTEGRATION FORMULA SIMP(F, VAL, H, N)
C****
C**** RI=INNER RADIUS OF THE DUST CLOUD
C**** ALPHA, EFF AND XC
C**** DETERMINE THE RADIATIVE PROPERTIES OF THE DUST
C**** AP=GEOMETRIC DUST GRAIN CROSS SECTION
C**** OPTICAL DEPTH IN VISUAL TAU
C**** OBSERVER DISTANCE = ROBS
C**** DUST GRAIN NUMBER DENSITY XN
C**** XLIN=TOTAL LUMINOSITY INPUT
COMMON/A/ XLIN,ROBS,RT,RI
C**** TS=CENTRAL SOURCE B.B. TEMPERATURE
C**** THIS PROGRAM HANDLES
C**** SOURCE TEMPERATURES BETWEEN 2300 AND 14000 DEGREES KELVIN
TS=10000.
C****
C**** OPTICAL DEPTH PER SHELL IN THE VISUAL
C**** DTAU = .1 FOR TAU LESS THAN 3
C**** DTAU = .25 FOR TAU LARGER THAN 3
C**** DTAU = .5 FOR TAU LARGER THAN 10.
C**** DTAU = 1. FOR TAU LARGER THAN 30.
KTAU=10.0+TAU
IFCTAU,GT,3.0KTAU=30.0+4.0*TAU
IFCTAU,GT,10.0KTAU=50.0+2.0*TAU
IFCTAU,GT,30.0KTAU=98.0+4.0*TAU
C**** THE SPECTRUM IS DESCRIBED BY TWO GRIDS OF NGRID POINTS.
NGRID=100
C**** SHORT WAVELENGTH GRID STARTS AT .1 MICRON.
C**** LONG WAVELENGTH GRID START AT 5 MICRONS.
XLIST=5.0-4.
XSST=1.0-5.
DIMENSION AS(100),AL(100),FS(100),FL(100),SFS(100),SFL(100)
XNUM=0.
R=RI
TL=400.
TP=100.
SIGMA=5.67E-5
C**** UNITS ERGS/CM**2 DEGREES**4 SEC
C**** RS=CENTRAL SOURCE RADIUS
RS=SQR(XLIN/(12.6*SIGMA*TS**4))
XLS=XSSST
XLL=XLST
DO 1 I=1,NGRID
CALL RQUST(AL(I),XLL,ALPHA,EFF,XC)
CALL AQUST(AS(I),XLS,ALPHA,EFF,XC)
CALL PLANK(DFS,XLS,TS)
FS(I)=DFS*(RS/R)**2
SFS(I)=AS(I)*FS(I)
CALL PLANK(DFL,XLL,TL)
SFL(I)=AL(I)*DFL
FL(I)=0.
XLS=XLS+XSST
XLL=XLL+XLST
1 CONTINUE
CALL SIMP(FS,XLUM,XSST,NGRID)
CALL SIMP(SFL,TESTO,XLST,NGRID)
TL=TL
TEST1=TESTO
XL=XLST
DO 117 I=1,NGRID
CALL PLANK(DFL,XL,TL2)
SFL(I)=DFL*AL(I)
117 XL=XL+XLST
CALL SIMPS(SFL,TEST2,XLST,NGRID)
C***** TL1=TEST1 AND TL2=TEST2 PROVIDE THE STARTING POINT
C***** FOR THE ITERATIVE SOLUTION FOR TL.
XLTOT=XLUM+12.6*R*R
C***** XLIN=XLTOT AS CHECK OF INTEGRAL
PRINT 44,R,TS,XLIN,XLTOT,RS,XN,ALPHA,EFF,XC,AP
44 FORMAT(10E9,3)
PRINT 46
46 FORMAT(9E9,3)
PRINT 6,(AL(I),I=1,NGRID)
6 FORMAT(8E9,3)
DO 9 I=1,NGRID
FL(I)=0.
9 SFL(I)=0.
PRINT 46
46 FORMAT(/)
C***** START BUILDING SHELLS
DO 3 KKK=1,KTAU
DTAU=1
IF(KKK,GT,30) DTAU=.25
IF(KKK,GT,50) DTAU=5
IF(KKK,GT,90) DTAU=1.
CALL SIMPS(SFS,VAL1,XSTT,NGRID)
CALL SIMPS(SFL,VAL2,XLST,NGRID)
GT=VAL1+VAL2
C***** SOLVE FOR THE DUST TEMPERATURE BY ITERATION.
DO 100 MH=1,50
CHECK=TEST2/GT
IF(CHECK,LT,997) GO TO 12
IF(CHECK,GT,1,003) GO TO 12
C***** ITERATION TERMINATED AT 0.3 PERCENT ERROR
GO TO 11
12 IF(KKK,EQ,1) GO TO 200
TL=(TL1-TL2)*(GT-TEST2)/(TEST1-TEST2)+TL2
C***** GRADIENT METHOD.
IF(TL,LE,0.) GO TO 200
GO TO 201
200 CNEX=ALOG10(TEST1/TEST2)/ALOG10(TL1/TL2)
A=TEST2/TL2**CNEX
C***** POWERLAW INTERPOLATION FOR THE FIRST SHELL:
TL=(GT/A)**(1./CNEX)
201 CONTINUE
 TL1=TL2
 TEST1=TEST2
 TL2=TL
C***** GENERATE THE DUST SPECTRUM
XL=XLST
DO 5 T=1, NGRID
CALL PLANK(FLLL, XL, TL)
SFLC(I)=FLLL*AL(I)
XL=XL+XLSL
5 CONTINUE
CALL SIMP(SFL, TEST2, XSLST, NGRID)
C**** THE UNITS OF TEST ARE ERGS/SEC CM**2
DO 10 CONTINUE
PRINT 115
115 FORMAT(" BAD TEMPERATURE ITERATION ")
10 TL=TL2
C**** DR=NEW LENGTH
XNR=XN
IF(XNR.LE.0.) GO TO 114
DR=DTAU/(EFF*AP*XNR)
C**** THIS CHOICE OF DR MAKES THE OPTICAL DEPTH
C**** PER SHELL EQUAL TO DTAU.
SCALE=AP*XNR+DR
RSCAL=(R/(R+DR))**2
DO 2 I=1, NGRID
C**** UPDATE THE FLUX VALUES
FS(I)=(FSC(I)*SFLC(I)*SCALE)*RSCAL
FL(I)=(FLC(I)+AL(I)*SCALE)+SFLC(I)*SCALE)*RSCAL
SFLC(I)=ASC(I)*FSC(I)
SFL(I)=FLC(I)+AL(I)
2 CONTINUE
CALL SIMP(FS, XSL, XSST, NGRID)
CALL SIMP(FL, XL, XSLST, NGRID)
R=R+DR
AREA=12.64*R*R
TXSL=XSL*AREA
TXLL=XLL*AREA
C**** TXSL=INTEGRATED SHORT WAVE LENGTH LUMINOSITY
C**** TXLL=INTEGRATED LONG WAVELENGTH LUMINOSITY
XNUM=XNUM+XNR+DR*AREA
C**** XNUM COUNTS THE TOTAL NUMBER OF DUST GRAINS
C**** INSIDE THE RADIUS R;
PRINT 45, R, TL, TXSL, TXLL, XNUM, CHECK, FL(1), FL(2), FL(3), FL(4), FL(5)
C**** 5, 10, 20 AND 30 MICRON FLUXES ERG/SEC CM**2
CTEST=TXLL+TXSL
C**** CONVERGENCE TEST, TERMINATION AT 5 PERCENT DIVERGENCE.
IF(CTEST.GT.1.05*XLIN) GO TO 112
IF(CTEST.LT.0.95*XLIN) GO TO 112
3 CONTINUE
C**** END OF THE SHELL BUILDING LOOP.
114 CONTINUE
CALL SIMP(FL, F30, XLSL, 6)
F033=F30*AREA
C**** F033 = FLUX INTEGRATED TO 30 MICRONS
CALL SIMP(FL, F62, XLSL, 12)
C**** F062 = FLUX INTEGRATED TO 60 MICRONS
F062=F62*AREA
RATIO=TXLL/FO33
PRINT 45
PRINT 66,FS(10),FS(20),FS(30),FS(50),FS(70),FS(100)
PRINT 6,(FL(I),I=1,NGRID)
PRINT 45
C***** ABSORPTION COEFFICIENT IN THE VISUAL EFF*AP*XN=ABSOR
ABSOR=AP*EFF*XN
XNO=(1,E-11)*(R/ROBS)**2
C***** XNO NORMALIZES THE FLUXES TO WATT/CM**2 MICRON
C***** OBSERVED AT THE EARTH
PRINT 44,FO33,RATIO,CTEST,VAL1,VAL2,GT,XNO,AREA,ABSOR
F05=FL(1)*XNO
F11=FL(2)*XNO
F23=FL(4)*XNO
F32=FL(6)*XNO
PRINT 40,F05,F11,F23,F32,FO62
40 FORMAT(5E9.3)
PRINT 45
45 FORMAT(/)
C***** CONVERSION TO WATT/M**2 HZ OBSERVED AT EARTH
XL=XLST
DO 2000 I=1,NGRID
FL(I)=FL(I)*R/ROBS*(R/ROBS)*(XL/XL/(3,E+13))
2000 XL=XL+XLST
PRINT 6,(FL(I),I=1,NGRID)
RETURN
112 PRINT 113
113 FORMAT(" TERMINATION AT 5 PERCENT DIVERGENCE ")
GO TO 114
END

SUBROUTINE QDUST(A,XL,ALPHA,EFF,XC)
C***** ABSORPTION EFFICIENCY OF DUST GRAINS.
C***** ALPHA = 1 FOR GRAPHITE GRAINS.
C***** ALPHA=1 FOR DIRTY ICEGRAIN CALCULATION.
   IF(ALPHA,EQ.,1.) GO TO 3
C***** ALPHA=2, FOR IMPURE GRAPHITE GRAIN CALCULATION.
   IF(ALPHA,EQ.,2.) GO TO 5
C***** THE ABSORPTION EFFICIENCY IS CONSTANT BELOW XC MICRONS.
C***** EFF IS THE SHORT WAVE LENGTH ABSORPTION EFFICIENCY.
   IF(XL=XC)1,1,2
1 A=EFF
RETURN
2 CONTINUE
   IF(XL.GT.(1,E=4)*A=3,E=9/XL**2
   IF(XL.GT.(1,E=3)) A=5,E=12/XL**3
RETURN
3 IF(XL.LE.XC) GO TO 4
   A=(4,5E-2)*EXP(-238,*,XL)
C***** DIRTY ICE CROSS SECTION AP=1.2E+9
RETURN
4 A=EFF
RETURN
5 A=EFF
IF(XL.GT.(1.E-4)) A=3.F-5/XL
IF(XL.GT.1.E-2)A=A*(1.E-2)/XL
RETURN
END

SUBROUTINE SIMP(F,VAL,H,N)
C***SIOPH RULE INTEGRATION OF THE FUNCTION F
C***EVALUATED BY THE CALLING PROGRAM AT N EVENLY SP
C***H=STEP LENGTH
C***N=NUMBER OF STEPS
C***IF N IS EVEN
C***THE LAST POINT IS INTEGRATED WITH A TRAPEZOIDAL
DIMENSION F(I)
VAL=0,
C***TEST FOR N=ODD
NO2=N/2
NT02=2*NO2
IF(NT02=N-1)*4+1
4 VAL=H*(F(N)+F(N-1))/2,
J=N-1
GO TO 3
C
EQUATION GIVEN IN WILDFRANP NUMERICAL ANALYSIS
1 J=N
3 IK=J-1
SUM=0.0
DO 5 I=2,1K+2
5 SUM=SUM+F(I)*4.0
IM=J-2
DO 2 I=3,1M+2
2 SUM=SUM+F(I)*2.0
VAL=(SUM+F(I)+F(J))*H/3.0+VAL
RETURN
END

SUBROUTINE PLANK(F,XL,T)
C***PLANK FUNCTION
C***CGS UNITS F=ERGS/SEC CM**2 CM 1/2 SPHERE
C1=3.7412E-5
C2=1.43879
XP=C2/(XL*T)
IF(XP=100.1)*2+2
1 CONTINUE
F=C1/(XL**5*(EXP(XP)-1.))
RETURN
2 F=0.
RETURN
END