63-3-5

—FINAL REPORT—

Prepared for

AEROSPACE CORPORATION
SUBCONTRACT NO. 62-151

STELLAR IRRADIANCE MEASUREMENTS

JANUARY 1963

ITT Federal LABORATORIES
A DIVISION OF INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION
15151 BLEDSOE STREET, SAN FERNANDO, CALIFORNIA

The contract for the measurement program reported on herein was let to provide an initial assessment of the stellar background for IR systems research. The major tasks were:

(1) A gross mapping ($\frac{1}{4}^{\circ} \times \frac{1}{4}^{\circ}$) of stellar irradiancies in the near, intermediate and far infrared.

(2) A test of the validity of extrapolation of stellar irradiancies from the visual to the infrared on the basis of assumed gray body distributions at established stellar effective surface temperatures.

Time requirements limited the program to the use of an existing telescope, low ground site, available infrared detectors and coverage of 1300 to 0200 hours in right ascension and -10° to 70° in declination. Cost of the program was approximately $25,000.

M. Ritter

FINAL REPORT

—STELLAR IRRADIANCE MEASUREMENTS—

by

Freeman F. Hall, Jr.

Prepared for:

AEROSPACE CORPORATION

SUBCONTRACT NO. ͜2—151

January 1963

I T T   F E D E R A L   L A B O R A T O R I E S

a Division of International Telephone & Telegraph Corporation
15151 Bledsoe Street   San Fernando, California

TABLE OF CONTENTS

1.0 FOREWORD 1

2.0 ABSTRACT 2

3.0 INTRODUCTION 3

4.0 SUMMARY AND CONCLUSIONS 6

5.0 METHOD USED TO SCAN THE IR STELLAR BACKGROUND 8

- 5.1 Radiometer Description 8
- 5.2 Experimental Procedure 10
- 5.3 Radiometer Calibration 15
- 5.4 Region of the Sky Scanned 18
- 5.5 Experimental Limitations 18

6.0 RESULTS OF THE MEASUREMENT PROGRAM 24

- 6.1 PbS Scans, 1.3–3.0 μ 24
- 6.2 Te Scans, 3.0–4.0 μ 42
- 6.3 Ge:Hg Scans, 8.0–13.0 μ 43

7.0 RECOMMENDATIONS 44

APPENDIX A: STATUS OF INFRARED ASTRONOMY 46

LIST OF REFERENCES 50

LIST OF ILLUSTRATIONS

FIGURE 1	INFRARED RADIOMETER, 50.8 CM APERTURE	8
FIGURE 2	FILLING THE Ge:Hg DETECTOR WITH LIQUID HELIUM	10
FIGURE 3	MEMORY OSCILLOSCOPE DISPLAY IN THE ABSENCE (a) AND PRESENCE (b) OF A STAR SIGNAL	11
FIGURE 4	SAMPLE OF PAPER TAPE RECORDING FORMAT USED DURING THE PROGRAM	13
FIGURE 5	RELATIVE SPECTRAL RESPONSE CURVES FOR THE THREE DETECTORS USED	16
FIGURE 6	AREA OF SKY SCANNED IN 1.3–3.0 μ REGION	19
FIGURE 7	TRACE OBTAINED WITH FLUCTUATING AIRGLOW BACKGROUND	21
FIGURE 8	1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1300 TO 1600 HOURS, $-10°$ TO $25°$ DECLINATION	25
FIGURE 9	1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1600 TO 2000 HOURS, $-10°$ TO $25°$ DECLINATION	26
FIGURE 10	1.3–3.0 μ INFRARED SOURCES DETECTED FROM 2000 TO 2400 HOURS, $-10°$ TO $20°$ DECLINATION	27
FIGURE 11	1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1300 TO 1800 HOURS, $20°$ TO $60°$ DECLINATION	28
FIGURE 12	1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1800 TO 2400 HOURS, $20°$ TO $60°$ DECLINATION	29
FIGURE 13	IRRADIANCE TO INFRARED MAGNITUDE RELATION FOR THE THREE SPECTRAL REGIONS	41

TABLE I	NOISE EQUIVALENT POWER DENSITY OF THE RADIOMETER	18
TABLE II	COMPARISON OF EK – ITTFL ~ 0 MAG SOURCES	31
TABLE III	LIST OF "PROBABLE" STELLAR SOURCES IN SURVEY	33
TABLE IV	LIST OF "POSSIBLE" STELLAR SOURCES ON TWO TAPES OR CONFIRMED	39

1.0 FOREWORD

This is the Final Report on Aerospace Corporation subcontract No. 62-151 (Government prime contract No. AF04(695)-169) entitled "Stellar Irradiance Measurements." This report completes the requirements of Item III.B. of the contract.

ITT Federal Laboratories' personnel who have contributed to the study, in addition to the author, include: G. E. Axtelle and P. V. Deibel, who performed cell detectivity and filter transmission measurements and radiometer calibrations; H. D. Coombes, who provided invaluable assistance with the electrical and electronic subsystems; and R. S. Chaldu and T. J. Townsend, who performed much of the measurement and data reduction tedium.

Acknowledgment is made of the helpful technical direction by Milton Ritter of the Aerospace Corporation.

Discussions with R. B. Leighton, B. C. Murray, and G. Neugebauer of the California Institute of Technology, and with A. J. Deutsch of the Mount Wilson and Palomar Observatories were highly beneficial.

The cooperation of the Geophysics Research Directorate, Air Force Cambridge Research Laboratories, in extending the availability of the radiometer developed under Contract AF19(604)-4971 was essential to the measurement program.

2.0 ABSTRACT

The results of a scan of the night sky in three spectral regions of the infrared, 1.3–3.0 μ, 3.0–4.0 μ, and 8.0–13.0 μ, are presented. A 50.8 cm aperture radiometer with instantaneous field-of-view 1/4 x 1/4 degrees and a nodding Newtonian secondary mirror was used in the study to obtain the results over a six weeks observation period in which eighteen per cent of the sky was scanned in the near IR. Several bright IR sources were detected which would not have been expected on the basis of extrapolation of their visual properties and assumed temperatures. It is shown that such extrapolation of the supposed blackbody properties of stars to predict infrared magnitudes becomes progressively less reliable for the cooler stars and may fail by many magnitudes for the M7 and M8 classifications. A number of sources were detected which do not correlate with the position of any known stars brighter than eighth visual magnitude; some stars show much greater IR brightness than expected, which may indicate the presence of cool companion stars. Scans in the intermediate and far infrared detected those few sources which were predicted to be bright in these spectral regions. This allowed setting the upper limit where troublesome backgrounds may be encountered on the order of 10^{-13} watts/cm^2. The method of data recording and an assessment of accuracy and reliability of the results are presented and recommendations made for a more comprehensive survey to allow a proper understanding of the infrared background which might be experienced in space. The ground-based radiometer used on the program was shown to have been limited in its usefulness by the presence of high altitude tenuous clouds, near IR OH airglow emission, and thermal emission of the atmosphere in the intermediate and far IR.

3.0 INTRODUCTION

The purpose of this study was to measure the radiance characteristics of the clear night sky in the infrared in order to more accurately predict the infrared background in space. A number of scientific and military instruments responsive to infrared radiation have already been placed in satellites and planetary probes, with every indication that infrared instrumentation will become increasingly important in the future. Mission applications may include detection and surveillance of other space vehicles by virtue of their passive infrared radiance or that due to reflected sunlight. It may be required further to track and rendezvous with or intercept such targets. Although visual and radio frequencies will play important roles in these functions, certain classes of vehicles may be expected to employ low reflectance paints in the visual region and passive or active radio frequency countermeasures. This will require operating tracking devices over as wide a spectrum as possible.

Since the passive peak spectral radiance of space vehicles naturally lies in the intermediate or far IR by virtue of the temperature of the target, this radiation is the most difficult to suppress or countermeasure and may well prove to be of crucial military interest. But as with any surveillance system, the background radiance characteristics must be entirely understood to avoid false alarms or tracking losses in the presence of such clutter. With our knowledge of the infrared stellar background based primarily on spectral extrapolation from ground-based measurements, there is a great deal of uncertainty involved in predicting the infrared background as seen from space. Certain of these extrapolation dangers, which will be discussed more fully in the text, can be eliminated by measuring the infrared stellar background with an earth-based radiometer. Although necessarily limited in its utility by the influence of the intervening earth's atmosphere with partially known absorption and emission characteristics, the possibility of accomplishing a preliminary survey of the background with an existing radiometer in an inexpensive program was the primary consideration leading to this measurement program. This report is, therefore, a preliminary assessment of the infrared stellar irradiance background from a limited portion of the sky, measured at the surface of the earth, and to limited noise equivalent power densities (NEPD) in spectral regions extending from 1.3–13 μ.

The method of measurement used in the present study is discussed in Section 5, with the results of the measurements presented in Section 6. A summary of the most important findings and predictions and recommendations for further work are also given. In Appendix A the report briefly reviews the present status of infrared astronomy, showing how previous investigations fall short of meeting the requirements of allowing accurate predictions of the infrared background as viewed from space.

It should be noted that although the impetus for this program was due to military requirements, a beneficial side effect is the recording of new astrophysical data which may lead to a clearer understanding of the structure of the physical universe. It is also important to remember that the results are presented as observed; no corrections for atmospheric transmission or emission have been applied. The measurement site at San Fernando, California, provided for a vertical transmission path through the atmosphere with 2 cm or less of precipitable water in a vertical column on most occasions. Thus, a near IR transmittance of 50–70% should have prevailed with even higher values in the intermediate and far IR.

Rather than measure specific stars or small areas in the sky, as has been done on previous infrared astronomy studies, it was desired to rapidly scan a large area of the sky and to obtain preliminary results very quickly. Surveying the sky with a narrow field radiometer would have required a prohibitive expenditure of time; what was needed was a Schmidt type survey, using the analogy to photographic astronomy. A scanning radiometer previously developed at ITTFL for tracking orbiting satellite vehicles was well suited for the job.[1,2] This instrument, which will be more fully described in Section 4, was available to start measurements immediately during midsummer of 1962. The Optical Physics Laboratory of Air Force Cambridge Research Laboratories, which sponsored development of the instrument, kindly extended its availability for this program, so that six weeks were expended in gathering the raw survey data and in submitting a preliminary report.

This Final Report on the study represents a more careful analysis of the data, together with several spot checks of high radiance areas. It should be noted, however, that the immediate goal of the project was attained: surveying nearly 20% of the night sky in the 1–3 μ region with smaller areas scanned in the 3–4 μ and 8–13 μ windows within a six week period of time.

Although a more complete summary and recommendation are given in later sections of this report, it is pointed out here that even this preliminary survey has proven the existence of stars with a much lower temperature than usually assumed, the possible existence of diffuse areas of infrared radiance—especially in the Milky Way—and the partial failure of the extrapolation of visually obtained data to accurately predict the spatial characteristics of the infrared stellar background. Further measurement programs, both ground based and in space, will be required to completely understand the infrared clutter which will influence the performance of optical devices in space.

The abbreviations m_V for visual stellar magnitude and m_{Si} for 1.3–3.0 μ stellar magnitude are frequently used in the report. Since the Si subscript refers to a silicon filter which passes wavelengths longer than 1.1 μ, this nomenclature is slightly inaccurate, but the 1.3 μ filter used did cut-on rather slowly. This dictated in favor of using this more common terminology.

In a specialized report such as this, combining the terminology of astronomy and radiometry, it is necessary to describe the project using language perhaps not entirely familiar to all who may read the report. It has been attempted to follow as closely as possible standard astronomical usage as given in R. H. Baker's Astronomy (D. Van Nostrand Company, Inc., New York, 1955) and the radiometric terminology proposed by the ONR-sponsored Working Group on Infrared Backgrounds. The pertinent points for those entirely unfamiliar with this field are that +5 magnitude stars are one hundred times fainter than 0 magnitude stars and that most stellar temperatures lie between the limits 30,000° K and 2,500° K. Stellar classifications are assigned by the spectral characteristics observed in the visual region from class O for the extremely hot or "early" stars through B, A, F, G, K, and finally to M for the cool, red, or "late" stars.

4.0 SUMMARY AND CONCLUSIONS

In summary, it is again emphasized that the measurements presented in this report were obtained during an almost "crash" program with a versatile but not ideal radiometer. Scans of the night sky were obtained in three spectral regions: 1.3–3.0 μ with a PbS detector, 3.0–4.0 μ with a Te detector, and 8.0–13.0 μ with a Ge:Hg detector as required in the Statement of Work. Eighteen per cent of the sky was scanned in the near IR with every fifth scan repeated in the intermediate and every tenth scan repeated in the far IR.

In the near infrared many of the expected bright sources were indeed detected which have been measured on previous programs, although all of the sources predicted in another study on extrapolation of the supposed blackbody characteristics of stars were not found. Conversely, several strong sources of near IR magnitude –1.0 were detected which were not included on the extrapolated list, having arisen from stars of visual magnitude below 7.0. The temperature of these sources must be significantly below 2000 K.

Irradiance values associated with several early stars of visual magnitude below 5.0 may be indicative of the presence of cool companions. The true number of such cool stars is still unknown, but it can be demonstrated that the near IR, as covered by the PbS detector, is the ideal spectral region in which to search for such objects. Due to the superior detectivity of available detectors for this region, objects hotter than 550 K can be best detected here.

It has been tentatively established that the combined irradiance due to the assemblage of dim stars is greater in the near IR than that due to the few bright stars. Indications of diffuse clusters of cool stars or gas have been qualitatively obtained, although the space filter used with the instrument discriminated against detection of such sources. The average irradiance experienced in the 1.3–3.0 μ region is of the order 4×10^{-15} w/cm^2 for each square degree of the celestial sphere and may be significantly greater if diffuse assemblages of stars exist in large numbers.

The NEPD obtained with large fields of view in the intermediate and far infrared did not allow detection of a significant number of sources, so that an upper limit can be placed on celestial sphere irradiance from these regions. It must be lower than 5×10^{-13} w/cm^2 for all but a few individual stars, and collectively lower than 10^{-16} if a relationship similar to that obtained in the near infrared is observed, relating bright single sources to the average ensemble of IR stars. These estimates would be reduced by one order of magnitude in the 8–13 μ region, although only one star has been detected (not on this program) in the far IR This makes the assignment of background irradiance values extremely tentative at these wavelengths.

It can be concluded from the near IR measurements that presently assigned temperatures of the late classification stars and especially the irregular and long period variables are probably too high; the irradiance produced by these sources is frequently underestimated. Stars of the same late spectral classification are observed to have a wider spread of infrared indices than $\pm$ 1 as tentatively assigned by Walker for earlier types.

5.0 METHOD USED TO SCAN THE IR STELLAR BACKGROUND

5.1 Radiometer Description

The radiometer used to obtain the measurements during this program has been previously described[1,2], and only a brief summary will be given here. The instrument employs a 50.8 cm aperture f/2.5 spherical primary mirror with a Newtonian folding mirror directing the focused radiation to the detector mounting on the side of the radiometer tube. The physical arrangement is pictured in Figure 1, which is a rear view of the radiometer mounted on

FIGURE 1 INFRARED RADIOMETER, 50.8 CM APERTURE

its concrete pedestal and equatorial mount to the rear of the laboratories in San Fernando, California. The radiometer tube is wrapped with insulating blankets of glass wool which were found to be effective in reducing wind induced temperature variations which caused the background level to shift.

The instantaneous field of view of the radiometer depended upon the detector size and any post focal plane image compression used. For the IR stellar background program, three interchangeable detectors were used. A 2 x 2 mm lead sulfide detector* cooled to 195° K by solid dry ice plugs was equipped with a fused silica field lens and gold plated cone channel condenser to provide an effective speed of f/1.0. The instantaneous field of view was 1/4° x 1/4° with a radial spoke space filter in the focal plane providing four chopper blades and four spaces within the field frame at all times. The resulting space filtering of 1,167 waves/radian was provided primarily for the initial purpose of the radiometer, that of tracking orbiting satellites. The PbS detector was equipped with an interference filter which rejected all wavelengths shorter than 1.30 μ, with the long wavelength cutoff measured in the laboratory at approximately 3.2 μ. However, the strong water vapor absorption in the atmosphere centered at 2.7 μ influenced the longer wavelength cutoff characteristics due to the variable and unknown influence of the wings of the absorption band near 3 μ.

For intermediate wavelengths, an InSb detector** had been previously used, and was initially installed for the 3–4 μ scans to be performed during the present study. However, due to the availability of a Te*** detector with much higher detectivity in the desired 3–4 μ region, the InSb detector was replaced by Te when it became available. This detector was equipped with a Ge field lens so that its 2 x 2 mm size provided an instantaneous field 1/4° x 1/4° with an effective speed of f/1.2. A 3.0 μ cuton interference filter limited the spectral response to the 3–4 μ band.

For the 8–13 μ region a Ge detector doped with Hg was used**** and is shown mounted on the radiometer in Figure 1. The detector was in a demountable dewar equipped with an Irtran II window. An 8–13 μ bandpass interference filter was used to limit the spectral response to the desired atmospheric window region. Since experiments showed that focal plane chopping with the Ge detector introduced very large instrument signals, the space filter was removed when

---

* Eastman–Kodak Type N.

** Texas Instruments Type M–2000.

*** Minneapolis–Honeywell No. 226.

**** Texas Instruments No. 1479–20.

using the detector with signal modulation provided only by the scanning mirror. An instantaneous field of view of 0.1° x 0.1° at f/2.5 was obtained.

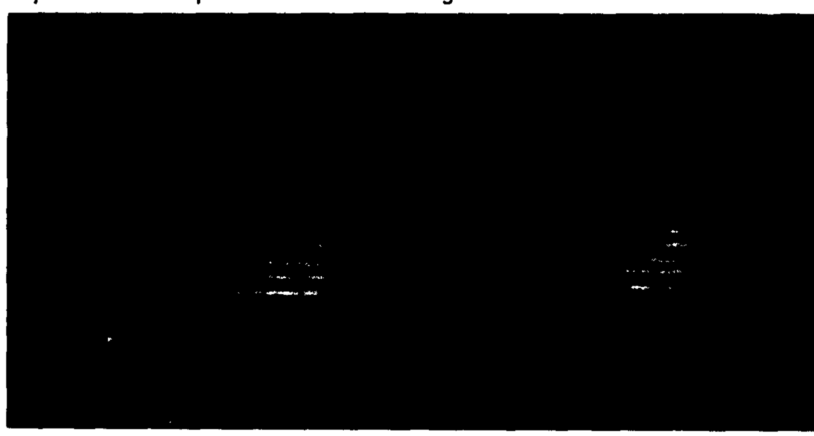
Operation of the Ge detector was convenient in that one filling of the outer dewar with liquid nitrogen and of the inner dewar with liquid helium to provide a 4° K operating temperature lasted for four hours. The detector was filled in the laboratory and then mounted against prefocused stops on the instrument for use. A liquid helium transfer line supplied by the Linde Company proved simple to use; the filling operation is depicted in Figure 2 below.

FIGURE 2 FILLING THE Ge:Hg DETECTOR WITH LIQUID HELIUM

5.2 Experimental Procedure

The nodding Newtonian mirror scanned the nominal 1/4° x 1/4° instantaneous field of view through ± 2.5°, so that a frame 1/4° x 5° was scanned. By positioning this frame so that the 5° dimension was parallel with a celestial meridian, the earth's rotation provided for the scan in right ascension with the nodding mirror providing the 5° scan in declination. Thus, a 5° wide strip of celestial sphere was scanned as the night progressed. The speed of the scanning mirror was controllable so that ten scans of a given point in the sky were provided during the time the earth rotated $1/4^\circ$. Thus, ten scans per minute could be provided at the celestial equator with the possibility of employing somewhat slower scan rates at higher declinations or of stepping the radiometer a small amount in right ascension to speed the scanning procedure at the end of each ten scan interval.

Ten scans per minute were chosen as the rate to be used during the program, since previously developed circuitry provided for a 10 line display on a memory oscilloscope*. As the nodding mirror moved from one declination limit



(a) (b)

FIGURE 3 MEMORY OSCILLOSCOPE DISPLAY IN THE ABSENCE (a) AND PRESENCE (b) OF A STAR SIGNAL

stop to the other, the amplified signal from the detector was displayed along the X-axis of the oscilloscope. On the next scan the oscilloscope display was stepped vertically to provide a new pattern traced directly below the previous scan. After ten such scans, occupying one minute of time, the memory oscilloscope was erased and a new set of scans presented. This technique was

---

* Hughes Aircraft Company, Model 104.

used previously to detect orbiting satellites[1]. A typical display in the absence of any source is given in Figure 3a. The failure of the scans to align completely along the edge is due to an out-of-adjustment condition on the microswitches which served to trip the stepping counter, a strictly mechanical problem which was frequently encountered and corrected during the program. Had a strong infrared star been present in the scanned field, the signals from the star would lie in a vertical line since the X displacement corresponds with declination, while the time occupied to trace the entire pattern was one minute from top to bottom of the display, corresponding to one minute in right ascension (at the celestial equator), just equal to the dimensions of the field of view.

In Figure 3b the star α Aur is scanned. Although this is a strong source, it will be seen that some of the signals on any one given line are not exceptionally larger than random noise signals also presented. However, the ordered vertical pattern presented by repeated scans across the star is easily detectable by the human observer so that signals significantly below the noise level on any one given scan can be detected by repeated correlated presentations of the radiometer signals.

The memory oscilloscope was the key detection device utilized during the study. At all times during the scan measurement, at least one observer was monitoring the oscilloscope watching for patterns which showed vertical alignment from scan to scan. Simultaneously, the output of the radiometer was recorded on a two-channel paper strip recorder with the format displayed in Figure 4.

The top noisy trace is a direct recording of the amplified PbS current. The second triangular wave represents the output from a potentiometer attached to the scanning mirror, thus indicating the position of the instantaneous radiometer field of view as a function of time. At the bottom of the trace, second markings indicate the passage of time. It will be noted that a rather strong signal was detected near the middle of the nodding mirror scan before 2239 hours and that the Memoscope operator depressed the marker button to place an additional pip on the timing channel when he detected the signal on the scope. Although redundant information in case of such a strong target, this marker pip was useful in locating weaker targets from the strip chart record. During this particular night the radiometer was scanning from 45.0–50.0 degrees declination so that the occurrence of the strong target near the center of the nodding position indicates a declination of 47.5 degrees for the source. A second marker pip of longer duration was recorded when the star ν Her was observed to transit through the radiometer field with the boresighted M–17 spotting scope at 2239 hours. This transit information allows

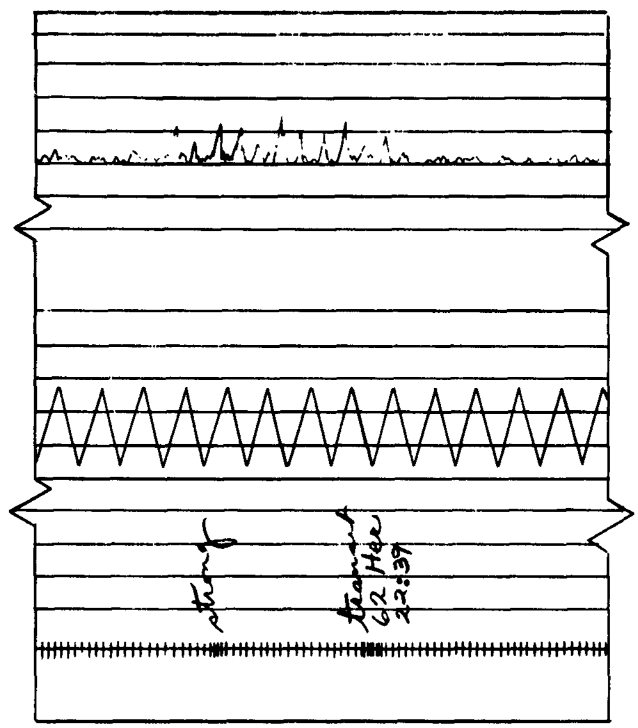


FIGURE 4 SAMPLE OF PAPER TAPE RECORDING FORMAT USED DURING THE PROGRAM

relating the local time to sidereal time and locates the strong source as the variable X Her, an M6 variable star.

By measuring the height of the scan signals from the strip recorder, it was possible—by relating with scans across stars of known IR magnitude—to determine roughly the magnitude of the source. However, due to the brief time that the stars are within the field of view, a more accurate determination of magnitude necessitates many rescans with the nodding mirror stationary to provide for longer integration times. This was done for a limited number of sources.

As stated earlier, the Memoscope was the key detection device during the entire project. While consideration was given to the photography of the tube face, it was determined that this time-consuming process was of no particular value since, even then, the detection method is qualitative, and reliable measurements would require rechecks o. each source detected. Rough estimates of the magnitude of these sources were indicated by the Memoscope operator by writing directly on the paper tape at the time of detection. A source such as X Her was defined as "strong" since displayed scans from each line overlapped onto the next line, being always stronger than the noise pulses and showing on all ten lines of the display. Somewhat weaker sources which might not show on every line of the scope display, and yet which yielded four or more pulses considerably larger than any of the random noise spikes, were termed "definite." Sources which showed from seven to ten lines on the display, but which produced pulses not significantly greater than the noise, on the average, were termed "probable." And in those instances where small signals showed correlation on from three to six lines, detection was termed "possible" for the lowest reliability of a true source detection.

It was desired to map as many sources as possible and, if feasible, to construct isoradiance diagrams of the night sky for infrared sources. The NEPD of the radiometer was not sufficient to allow producing isoradiance maps, but the requirement of working close to the signal-to-noise (S/N) limit near 1.0 necessarily led to many more "possible" sources than are indeed present. An estimate of the reliability of "possible" detections was obtained by two methods. For several 5° strips, the entire area of the sky was rescanned on subsequent evenings, and the number of "possible" sources appearing on both tapes which correlated in time to within one minute of right ascension and in declination to within 1° were counted and related to the total number of possible sources. This led consistently to between twenty and thirty per cent of the possible sources repeating in position. Another method was to carefully scan those areas of possible sources with the nodding mirror stationary and longer integration times used to provide a lower NEPD. This technique showed that twenty per cent of the possibles were indeed true sources, and this lower value than the rescan reliability method is to be expected, since the radiometer field of view of only 1/4° made exact pointing of the radiometer with the stationary folding mirror more difficult than in rescanning. In addition, some of the sources detected were termed "diffuse" in that they did not show the sharp rise and decay characteristic of a point source, but occupied several degrees in width. Some were found to occur in the same position from night to night, indicating perhaps an unresolved assembly of infrared stars. The space filtering used in the radiometer, of course, discriminated against detection of such diffuse assemblages so that no accurate contours of these sources were obtained. More will be said in Section 5 on the characteristics of such diffuse areas.

5.3 Radiometer Calibration

The radiometer was calibrated using essentially the distant small source method.[3] A collimator placed the source optically at an infinite distance. The exact method used has been described previously[1]; a carefully measured pinhole aperture in a polished brass plate served as an artificial star in front of a commercial blackbody source*, and the exit aperture of the collimator was made coincident with the entrance aperture of the radiometer. For the PbS detector, the blackbody source was operated at 700° K to obtain sufficient S/N at the shorter wavelengths, but for the intermediate and far IR detectors, the source was used at 500° K. The spectral response characteristics of each of the detector–filter combinations was measured on a Perkin–Elmer 112–U spectrometer using a globar source. Dependence was placed upon the blackness of the thermocouple detector for reference (KBr window on the thermocouple). The relative response curves so obtained are given in Figure 5 on Page 16.

---

* Barnes Engineering Model RS–3A.

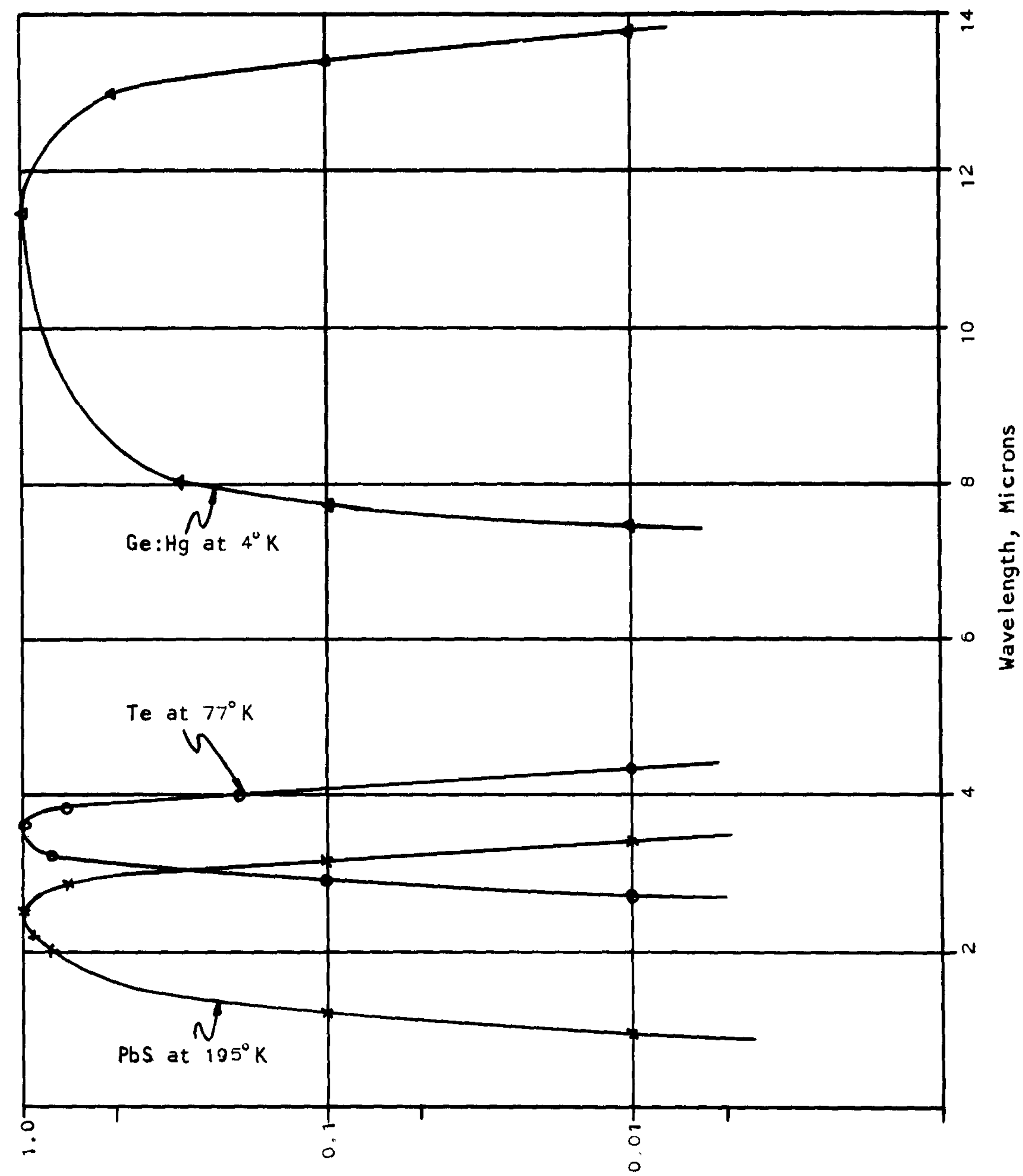


FIGURE 5 RELATIVE SPECTRAL RESPONSE CURVES FOR THE THREE DETECTORS USED

The spectral power responsivity R_{P_λ} of the radiometer is defined as

$$R_{P_\lambda}(\lambda) = \lim_{\Delta\lambda \to 0} \left[\frac{(\Delta V/\Delta\lambda)}{(\Delta P/\Delta\lambda)} \right] = \frac{V_\lambda}{P_\lambda} \qquad (1)$$

where V is the radiometer output, measured as millimeters deflection on the recorder, and P the incident power in watts. P_λ is determined by assuming ideal blackbody characteristics for the calibration source. Since measurements were made over a spectral band where both the detector responsivity and source characteristics are expected to vary, the band normalized responsivity is given by

$$R_P = \frac{V}{P} = \frac{\int_{\lambda_1}^{\lambda_2} V_\lambda(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} P_\lambda(\lambda)\, d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} R_{P_\lambda}(\lambda) P_\lambda(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} P_\lambda\, d\lambda} . \qquad (2)$$

This calibration technique then allows the assignment of an effective irradiance in the various spectral bands which should be independent of the detector–filter characteristics so long as the source radiant characteristics do not vary widely in the band. Using this technique, the NEPD—normalized to the peak of the radiometer spectral responsivity in each of the spectral bands with a one second electrical bandwidth—was determined as shown in Table I.

Calibration of the radiometer with the collimated blackbody "artificial star" was a tedious time–consuming procedure, and was repeated only occasionally during the measurement program. However, on each night several standard stars

Spectral Band	1–3 μ PbS	3–4 μ Te	8–13 μ Ge:Hg
NEPD, watts/cm^2	9.0×10^{-15}	5.1×10^{-13}	2.9×10^{-13}

TABLE I   NOISE EQUIVALENT POWER DENSITY OF THE RADIOMETER

were scanned with the radiometer before beginning the search program as a check on both the instrument and atmospheric conditions. An appreciation for the constancy of the instrument response and the observing site conditions was indicated by the mean deflection of 8.0 mm obtained for α Lyr with a standard deviation of 0.93 mm as obtained from twenty-one night recordings. No sufficiently intense stellar sources were found to monitor the performance of the intermediate and far IR detectors, as will be discussed further in Section 6.

5.4   Region of the Sky Scanned

Nearly twenty per cent of the celestial sphere was scanned with the PbS detector as shown on the equal area sky projection map in Figure 6. Ten per cent of the area scanned was rescanned to check the reliability of results and to show the influence of the atmosphere.

Using the Te detector the region from 15–20 and 40–45 degrees declination was scanned as well as spot checks of bright near IR sources and a three hour scan along the center of the galactic plane. With the Ge detector the strip from 40–45 degrees was scanned from 13–20 hours; a two hour scan along the galactic plane was also performed, as well as spot checks of 10 of the strong near IR sources. No signals were detected for the intermediate or far IR scans except from Venus and Mars with the Ge detector.

5.5   Experimental Limitations

It was pointed out in the introduction that the radiometer used, while capable of performing a rapid search for point sources in the near IR, was not

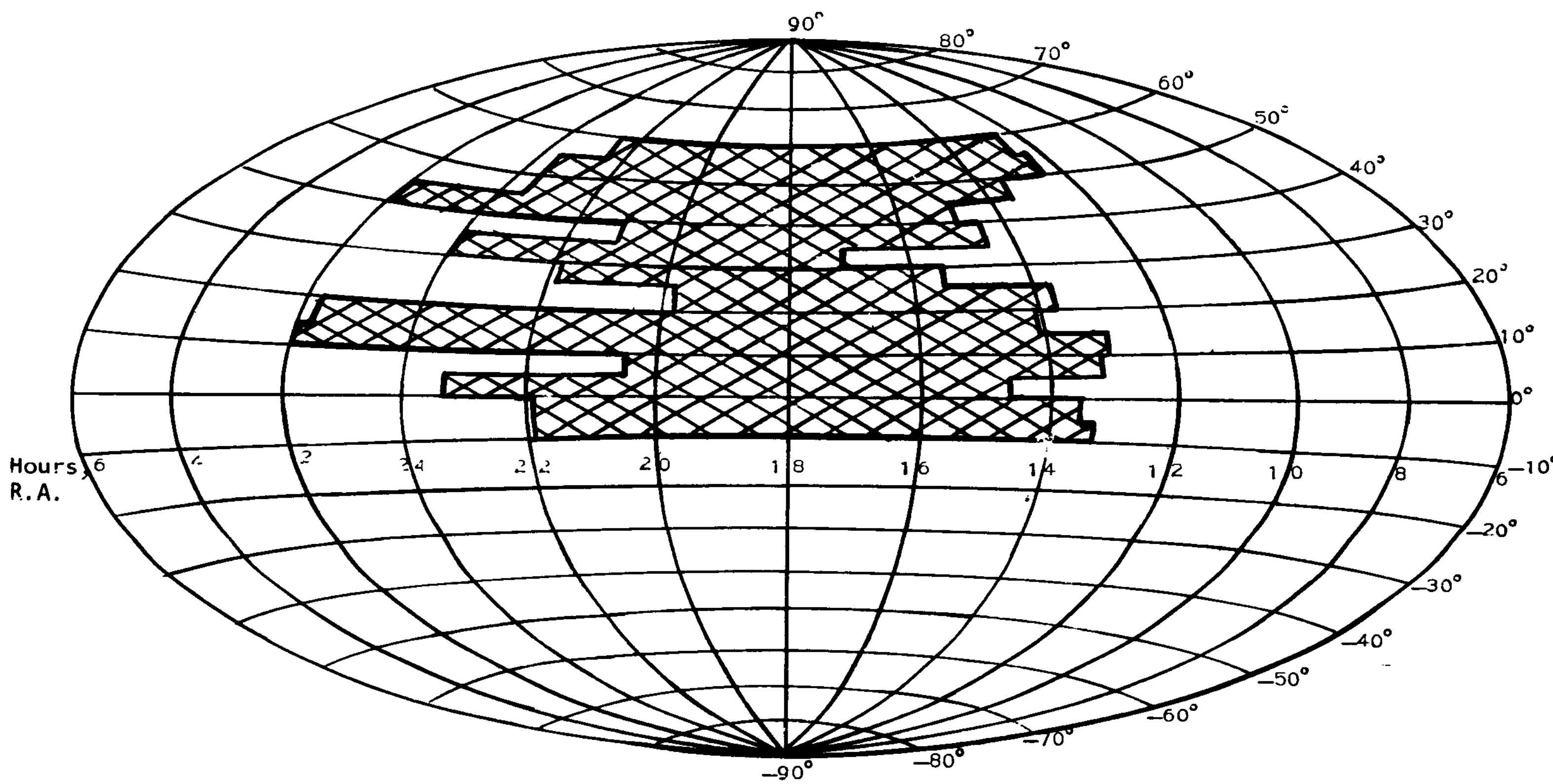


FIGURE 6 AREA OF SKY SCANNED IN 1.3–3.0 μ REGION

the best instrument which could be designed to map the stellar background. It was an inexpensive instrument, and it was in existence. The large instantaneous field of view 1/4° x 1/4° required space filtering to avoid excessive noise due to variations in atmospheric transmission and thermal emission as well as airglow emission. With the space filtering capacity removed by placing a stationary "space chopper" in the focal plane, so that complete sky modulation was obtained in the near IR, the airglow irradiance was found to be on the order 5×10^{-13} watts/cm^2 for the unfiltered PbS detector. Since the NEPD of the instrument was two orders of magnitude lower than this irradiance value, the space filtering of 1167 waves/radian improved background discrimination by these two orders of magnitude. This was usually accomplished; however, on certain nights the OH airglow emission was evidently much greater than usual, especially during the twilight hours when large background gradients and fluctuations within the five degree fan scanned were noted. These gradients were not so steep as to interfere with source detection on the Memoscope, but almost eliminate the chance of confirming the presence of weak sources on the paper chart record. A typical Sandborn record from such a noisy twilight scan is presented in Figure 7 which shows the relatively uniform gradient across the field with slow variations from one scan to the next. The background is enhanced by some vignetting at the edge of the scan frame. The effect obviously does not interfere with the detection of a strong source, such as α Her, which was detected near the upper limits of the scan frame on this evening.

Airglow fluctuation noise was apparent only with the PbS detector. The Te detector operating in the 3–4 μ region was the least influenced of all of the spectral regions by the presence of the earth's atmosphere, although windy evenings with the resultant turbulent mixing of warm and cool air parcels near the earth's surface did contribute to background fluctuations several times the still air NEPD of the instrument. (This effect was especially marked during one evening when heated air from a nearby forest fire alternately drifted within the field and was blown away.)

In the 8–13 μ region the greatest trouble with atmospheric effects was experienced. Indeed, insects flying close to the entrance aperture of the instrument led to many large spurious signals which took some time to identify and recognize. Cigarette smoking within fifty feet of the instrument led to

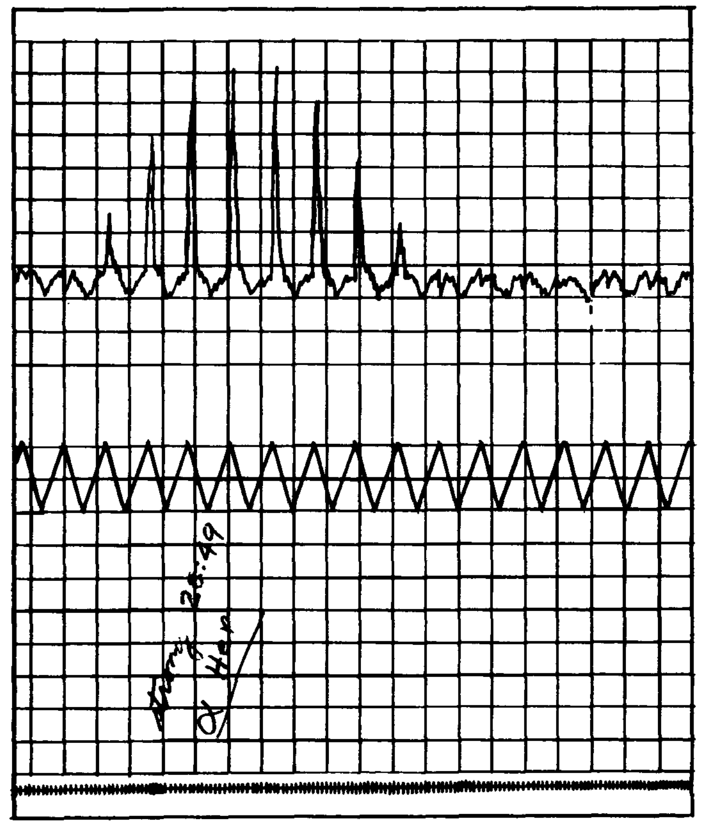


FIGURE 7 TRACE OBTAINED WITH FLUCTUATING AIRGLOW BACKGROUND

rising thermal columns which contributed to atmospheric noise as did the passage of freight trains one quarter mile away when the radiometer pointed at large zenith angles.

The slight mechanical shock of the scanning mirror reversing its direction of scan led to microphonic noise from the detector due to the cantilevered construction of the double dewar container. Thus, only the central areas of the five degree scanned region reached the ultimate NEPD of the instrument with the mechanical reverberations making the edges of scan useless.

In all of the spectral regions, visually detectable clouds led to attenuation of the signals as determined by measurement of strong sources in the near IR or an increase in background level in the 3–4 and 8–13 μ regions. During early August, a marine air layer only several hundred feet thick moved into the observing site between 0200 and 0400 hours, leading at first to an increase in noise level and then an abrupt attenuation of previously measured sources. The influx of this moist air was detectable with a humidigraph which was run continuously during the course of observations. But the presence of tenuous high clouds—which were shown to be equally detrimental to the experimental results—could not always be reliably monitored. This showed especially in rescans of some of the sky areas on one night when thin high clouds were suspected to be present, although visually only a slight haze was noticed; previously detected strong sources were not found under these conditions.

The observing site at San Fernando, California, was quite satisfactory for weather conditions and atmospheric transmission characteristics, and the convenience of operating close to the laboratory with accessible test instruments and prompt delivery of supplies made operation more convenient than on a remote mountain site. During the six weeks of extended observation, only one night was completely canceled out due to cloud cover with the previously mentioned marine layer influx limiting ten nights observation to five hours each. It should be noted that locating an infrared observatory above the atmosphere would eliminate all of the previous troublesome effects—unknown atmospheric transmission, airglow emissions, atmospheric turbulence and emission variations, and certainly insects.

The radiometer was positioned in declination by referring to a bright star positioned near the center of the desired declination scan. The radiometer was then slewed in right ascension to reach the position where a search would begin although it was never positioned more than several hours on either side of the local meridian to obtain the minimum possible atmospheric transmission path. WWV time signals were noted so that the passage of sources could be located to within one minute accuracy in right ascension. Source location in declination was somewhat less certain, as can be appreciated from the twenty instantaneous fields in each declination scan. Due to the time constant of the filter selected to display the weak targets with highest detectability on the oscilloscope tube, mechanical play in the scan and reversal switch, and noise in the recording frequently comparable with the sources detected, declination probable errors of approximately one degree are to be expected. Whenever charted stars as displayed in the Becvar Atlas[4] were located within one minute in right ascension and one degree in declination, they were assumed to have contributed to the detected source.

It was found that a time constant of 0.4 seconds led to the most readily detectable signals from small sources on the oscilloscope presentation. Thus, the deflection did not reach the level which was obtained with the stationary scanning mirror and this same electronic bandwidth. It was, therefore, difficult to obtain accurate irradiance measurements simultaneously with the detection scan experiment: calibration checks with the stationary and scanning mirror indicated that all stars brighter than zero magnitude in the near IR should have been detected with a high degree of reliability for clear skys. Limitations of detection between magnitude 2.0 and 3.0 were obtained for "possible" detections. These figures will be further documented in Section 6 where the results of the experiment are discussed.

6.0 RESULTS OF THE MEASUREMENT PROGRAM

6.1 PbS Scans, 1.3–3.0 μ

The area of the celestial sphere scanned with the PbS detector is shown in Figure 6, representing 18% of the sky. As explained in Section 5, when the Memoscope observer detected a target, the position was noted and the target strength classification as possible, probable, definite, or strong, was written onto the paper tape. The positions and strengths of these source detections were then tabulated and compared with positions of known stars and the results plotted on star maps using the following key to indicate the classification of the target:

+	possible	⊕	probable
□	definite	☆	strong

When the star charts used[4] indicated that the source was associated with a known star, a dot was placed in the center of the coded symbol. To aid in orienting the map, some of the brighter stars are indicated as solid black dots on the maps, given in Figures 8 through 12. Many of the solid dots representing the brighter stars to aid in orienting the maps have been numbered according to their appearance in the constellations in order of right ascension. The numbers are thus a further aid in unambiguously defining the position of the infrared sources detected. As an example of the use of these numbers, the star Arcturus with a right ascension 14 hours, 13 minutes and a declination of 19.5° is the sixteenth numbered star in the constellation Bootes as well as being the brightest star, or α, in the constellation. Thus, it is also known as 16 α Boo. Known variable stars are indicated by capital letters, the first variable to be discovered in a constellation having been given the letter R with subsequent variables identified by one or two capital letters. Several of these are indicated on the maps since the long period variables are frequently cool stars with infrared magnitudes much brighter than those found in the visual region. Isophotes of the Milky Way are also included for reference. Those areas where a general rise in background signal was

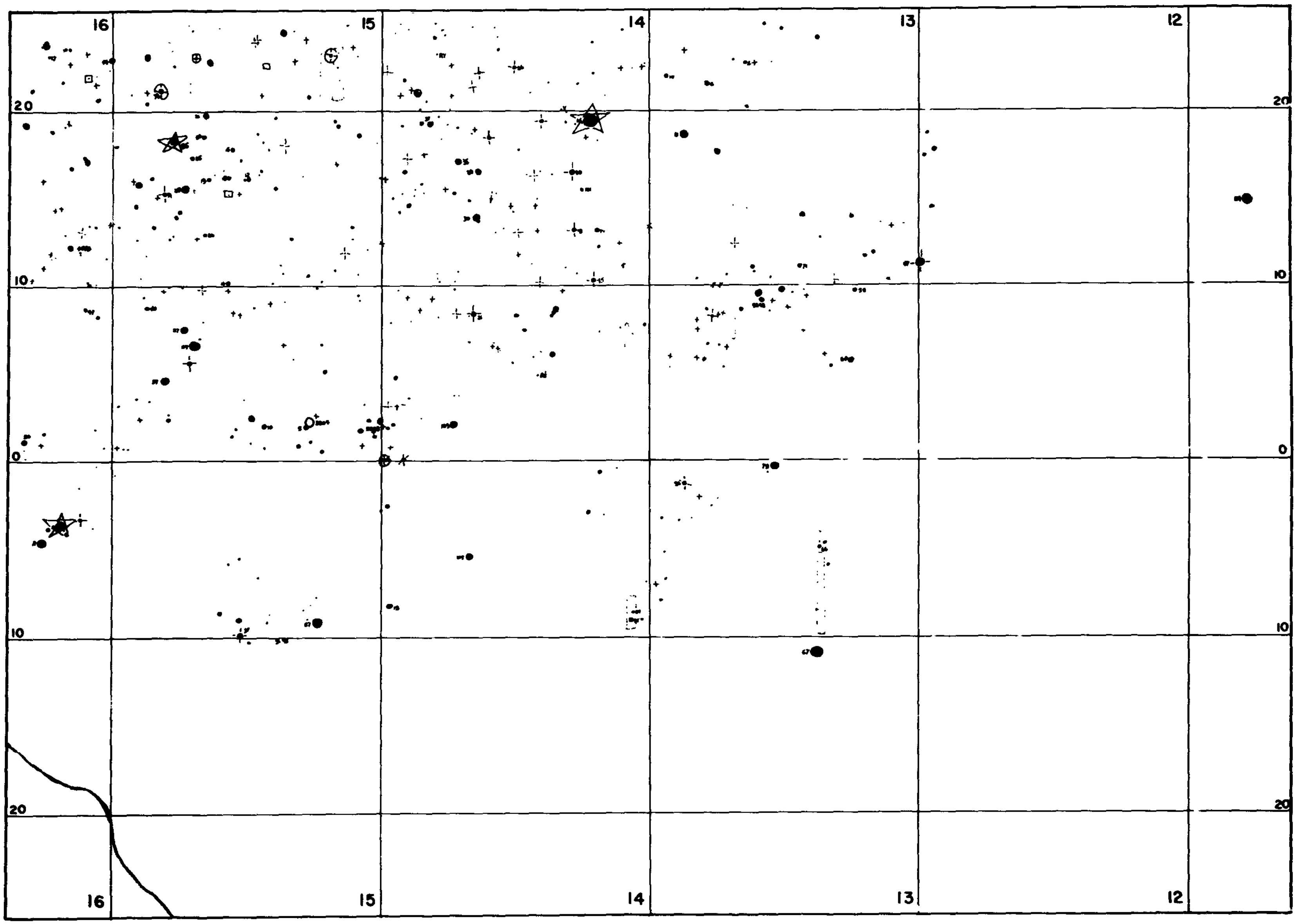


FIGURE 8 1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1300 TO 1600 HOURS, –10° TO 25° DECLINATION

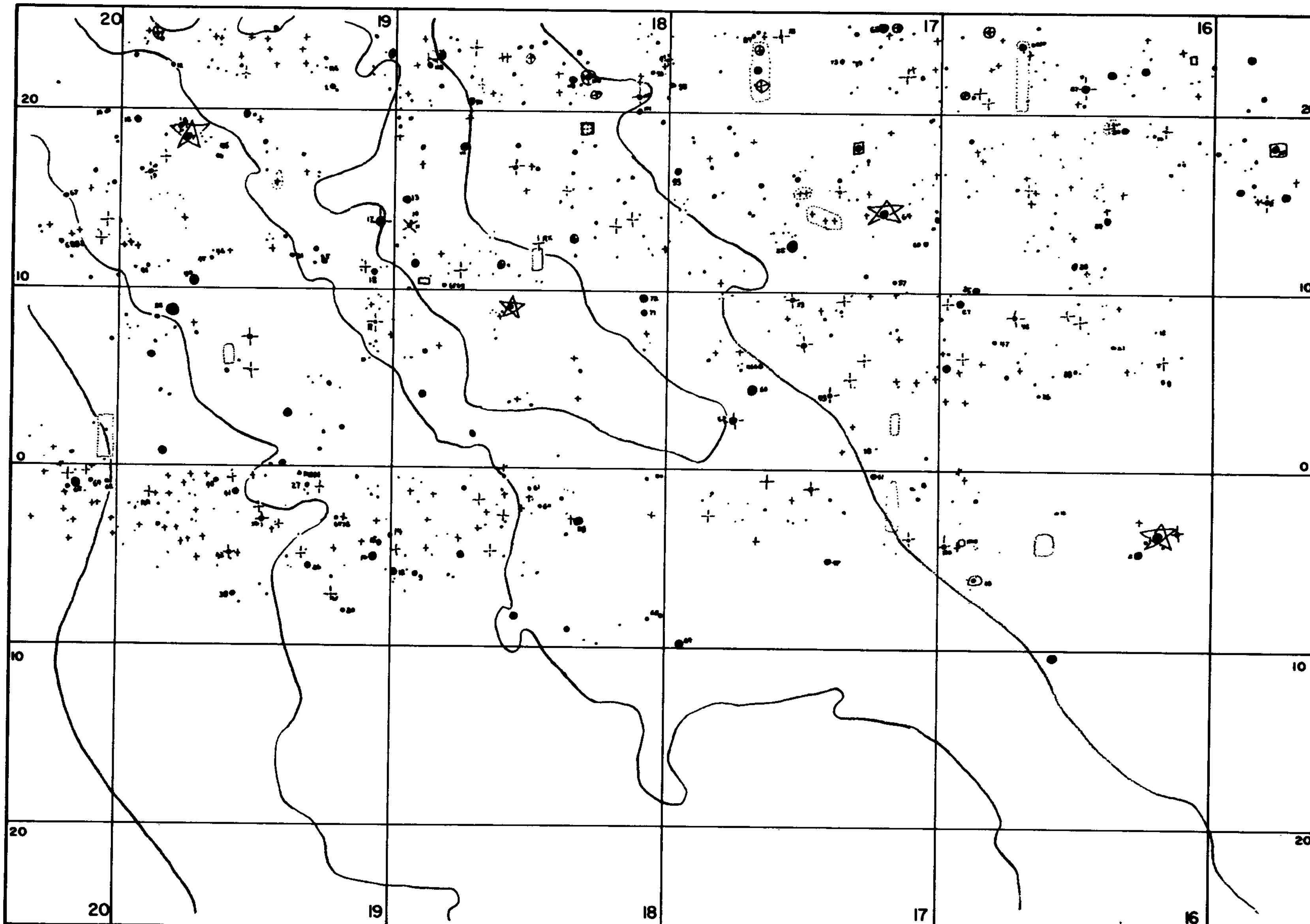


FIGURE 9 1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1600 TO 2000 HOURS, –10° TO 25° DECLINATION

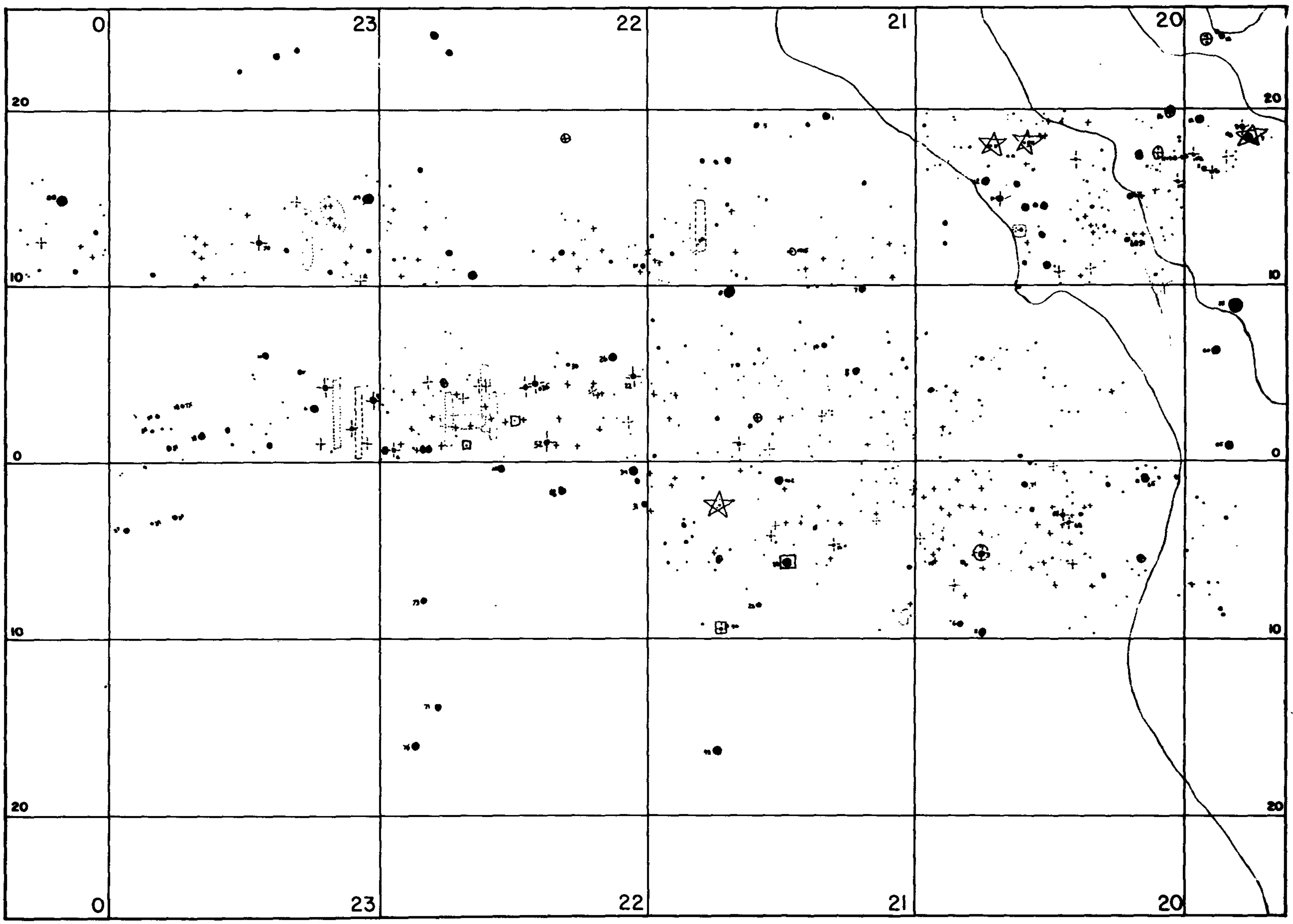


FIGURE 10 1.3–3.0 μ INFRARED SOURCES DETECTED FROM 2000 TO 2400 HOURS, −10° TO 20° DECLINATION

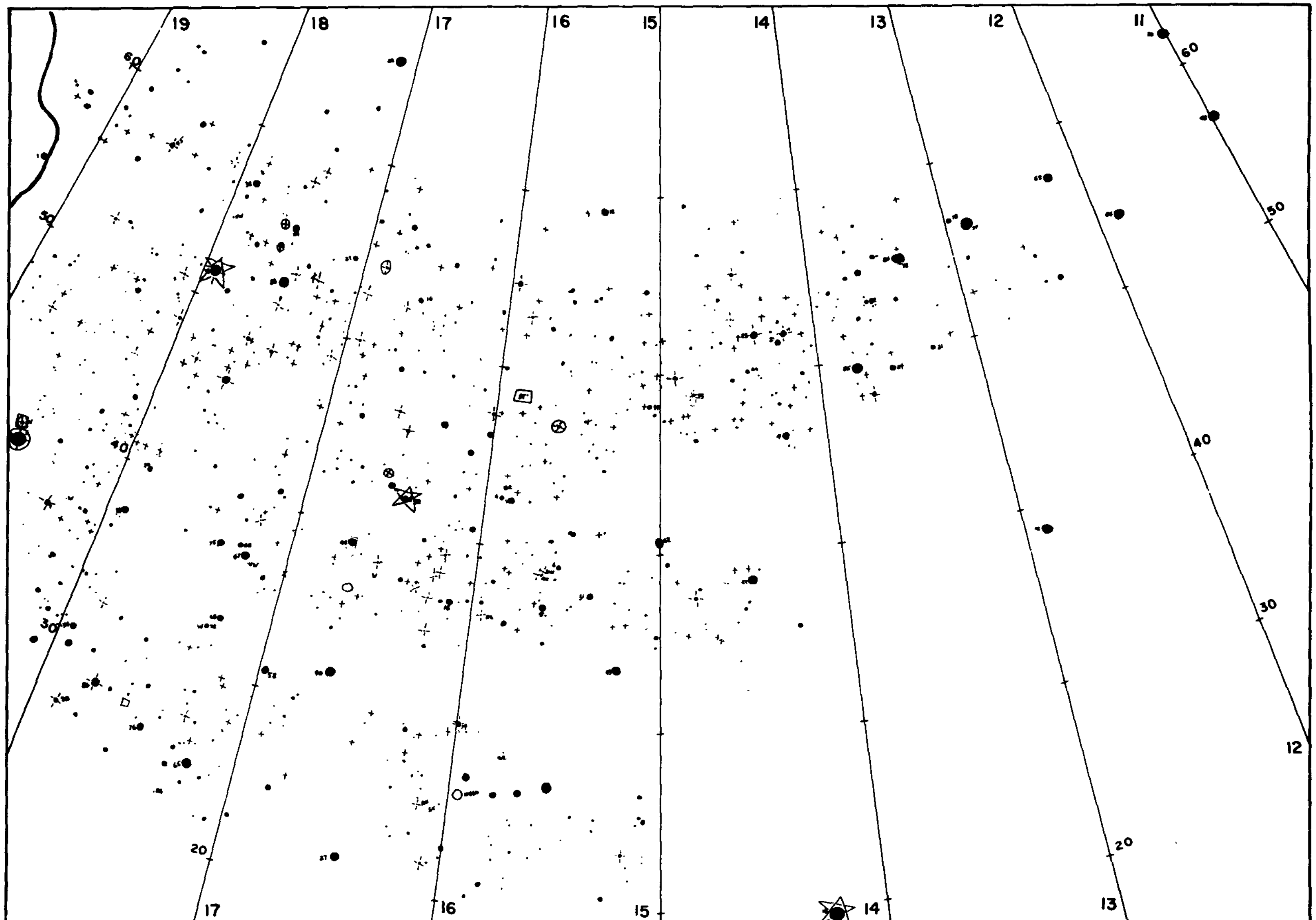


FIGURE 11 1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1300 TO 1800 HOURS, 20° TO 60° DECLINATION

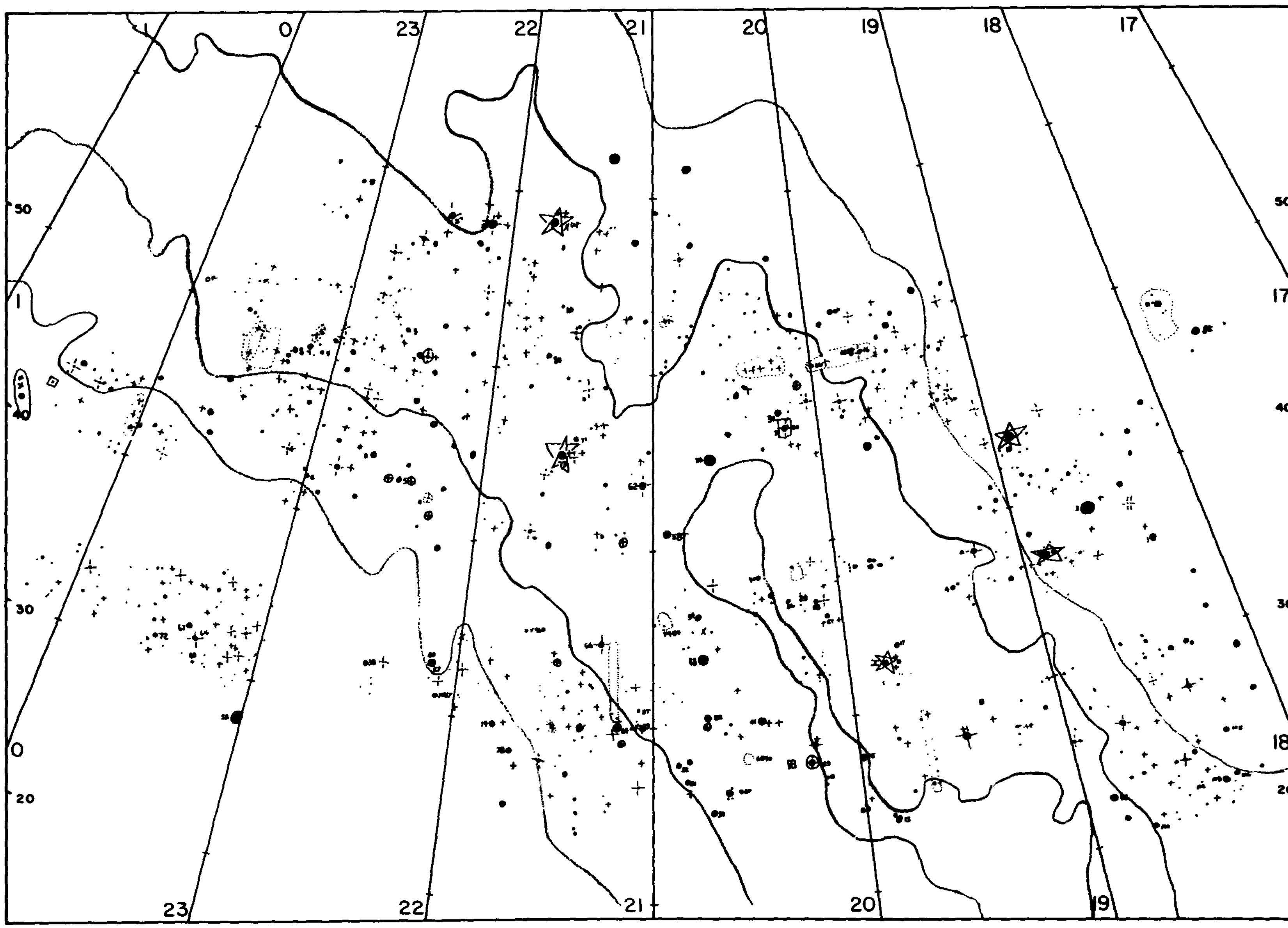


FIGURE 12 1.3–3.0 μ INFRARED SOURCES DETECTED FROM 1800 TO 2400 HOURS, 20° TO 60° DECLINATION experienced, not characteristic of a typical point source, are outlined with a dotted pattern.

All of the sources detected on the Memoscope are indicated on the maps, although only 20–30% of the possible sources repeat when areas are rescanned or spot checks made with the stationary scanning mirror, as explained earlier. Since time limitations did not permit rescanning all of the area, all of the possibles have been included, although the number would undoubtedly be reduced on more careful rescanning. The probable sources, indicated by the circle and cross, have a higher reliability with rescans and spot checks indicating that 60–70% of these targets correspond to real sources producing an irradiance significantly above the NEPD of the instrument.

The definite sources indicated by the square enclosure must approach 90% in reliability as indicated by rescans, and there is no doubt of the existence of the strong sources. These produced irradiances at least one order of magnitude above the NEPD of the scanning radiometer.

An examination of the maps given in Figures 8–12 shows certain areas where much clustering of possible sources occurs. An example is the region between 2200 and 2315 hours from 0° to 5° declination. Examination of the paper tape for this scan shows a gradual increase in airglow noise during the morning twilight period when the record was obtained, casting some doubt on the existence of these sources. The recorded gradients are so steep on the tape that small point sources are almost hidden in the background. As mentioned previously this effect was not so noticeable on the Memoscope, but it is possible that a rescan of this area might produce entirely different results. However, the clustering observed between 2300 and 2400 hours from 30° to 35° declination was measured on a rather quiet morning with the tape indicating correlation for many of the possible patterns obtained. This clustering may, therefore, be real.

Of higher positional accuracy than the indications on the map are the lists of strong, definite, and probable sources given in Tables II and III. Several small mistakes were noted on the maps after return from the printers, especially the omission of the strong source X Her which is indicated as only a possible on the maps. In Table II all of the definite and strong sources

TABLE II

COMPARISON OF EK – ITTFL ∼0 MAG SOURCES

R.A.	Dec.	(max.) m_V	Star	EK m_x (predicted)	ITT m_{Si} (meas.)	Class	Notes
0025	17.6	4.6	TVPsc	–0.2		gM3	possible
0034	42.5	5.4	GC 726			gK5	
0044	15.2	5.6	57Psc	0.5		gM4	possible
0201	42.1	2.3	γ And	–1.1		gK3	strong
1329	–6.0	4.8	74Vir	0.1	2.4	gM3	no detection
1330	–6.9	6.0	S Vir	–0.4	1.4	gM7e	" "
1339	–8.5	5.2	82Vir	0.8	2.2	gM2	" "
1339	54.9	4.8	83UMa	0.4	0.8	gM2	" "
1413	19.5	0.2	α Boo	–2.5		gK0	strong
1524	59.1	3.5	12 ι Dra	0.1		gK3	no detection
1534	15.2	7.5	τ^4 Ser		–0.5	M6	definite
1542	6.6	2.8	α Ser	–0.4	1.5	gK2	possible
1546	18.2	4.2	κ Ser		1.2	gM1	strong
1549	48.6	7.0	ST Her		1.6	M7	definite–strong (IR variable ?)
1553	43.3	5.5	2 Her	0.8	1.6	sgM3	possible
1557	26.1	(2.0)	T Cr B	–2.7		Q+gM3	no detection
1601	47.5	6.3	X Her		–1.2	M6	strong
1605	21.9	6.3	GC 21678			K0	definite
1612	–3.5	3.0	δ Oph	–0.9		gM0	strong
1616	59.9	5.6	+60° 1665	0.5		gM4	no detection
1627	42.0	5.0	30g Her	–1.0		gM6	strong
1637	49.0	5.1	42 Her	+0.7	+0.9	gM2	possible
1650	15.0	5.9	S Her	0.3		gM5e	no detection
1701	14.2	5.1	14° 3179	+1.3		gM3	no detection
1712	14.5	3.5	α Her	–2.1		gM5	strong
1713	36.9	3.4	π Her	–0.2	1.0	gK5	possible
1718	18.1	5.2	GC 23426			gM2	definite
1724	4.2	4.4	49σ Oph			gK1	definite
1735	27.5	6.6	GC 23872			Ma	definite
1741	4.6	2.9	β Oph	0.0		gK1	no detection
1754	37.3	4.0	θ Her	0.7		cK1	no detection
1755	51.5	2.4	γ Dra	–1.2	–1.2	gK5	strong
1810	31.4	5.0	104 Her	0.3		gM3	no detection
1816	17.5	7.3	IQ Her			M6	definite (on two tapes)
1820	49.1	5.1	49° 2782	0.7		gM2	possible
1832	–8.3	4.1	α Sct	0.6		gK5	no detection

TABLE II (continued)

COMPARISON OF EK – ITTFL ∼0 MAG SOURCES

R.A.	Dec.	(max.) m_v	Star	EK m_x (predicted)	ITT m_{Si} (meas.)	Class	Notes
1836	8.8	5.9	X Oph	–0.1		gM6e	strong
1836	39.6	6.1	XY Lyr		0.0	cM8	definite
1853	43.8	4.0	R Lyr	–1.6	–2.0	gM5	strong
1853	36.8	4.5	12 δ^2 Lyr	–0.6		gM4	strong
1904	8.2	5.1	R Aql	–1.3		gM7e	definite
1912	–7.1	7.2	W Aql			Se	definite
1927	24.5	4.6	α Vul	0.4	0.9	gM1	probable
1944	10.5	2.8	γ Aql	–0.7		gK4	no detection
1945	18.4	3.8	δ Sge	–0.6	–0.1	gM2	strong
1949	32.7	2.3	χ Cyg	–4.1		gM7e	strong
1956	19.3	3.7	γ Sgr	–0.2		gM0	no detection
1958	17.4	5.6	13 Sge	0.5		gM4	no detection
2012	46.6	4.0	31 Cyg	1.5	0.7	cK1	possible
2014	47.6	4.2	32 Cyg	0.2		cK5	definite
2019	27.5						definite (noisy tape)
2025	–3.0						definite (noisy tape)
2035	18.1	6.2	EUDel		–0.5	M7	strong
2043	17.9	5.6	U Del	–0.4	+0.1	M6e	strong
2044	33.8	2.6	ε Cyg	–0.1	0.8	gK0	no detection
2045	–5.2	4.6	3 Aqr	–0.1		gM3	probable
2129	–5.8	3.1	β Aqr			cG0	definite
2134	45.2	5.0	W Cyg	–0.1	–1.6	gM4e	strong
2142	58.5	3.6	μ Cep	–0.9		cM2e	strong
2144	–2.5	7.2	GC 30482		–1.0	M7	strong
2144	–9.5	6.2	47 Cap			gM3	definite
2209	58.0	3.6	ζ Cep	–0.4		cK5	probable
2231	2.4	7.5					definite
2240	0.8						definite
2304	1–3						definite (noisy)
2315	48.8	5.0	8 And	0.6			no detection
2350	18.9	5.2	φ Peg	0.5			no detection

TABLE III

LIST OF "PROBABLE" STELLAR SOURCES IN SURVEY

R.A.	Dec.	Star	m_v	Class	Notes
1330	9.8	GC18291	7.9	F8	
36	9.7				
1453	21.1	20091	6.9	K0	m_{Si} = 1.6
59	0.0	20212	5.9	gM2	m_{Si} = 1.7
1511	23.2	20474	6.3	A0	
22	24.5				
29	2.5	20868	7.6	A0	
31	47.0	21044	5.8	dF1n	
38	22.8	[redacted]	[illegible]		
43	23.0	21171	7.4	F2	
48	21.1	21311	4.9	K5	
52	23.1				
1615	24.0	21887	6.6	K0	
23	22.0				
34	43.2				
50	24.8	22708	5.2	gK1	
53	18.5	22816	5.6	gK5	on two tapes
54	53.5	22852	6.7	Ma	
55	21.2				
57	5.5				
1702	11.0				
10	25.0				
18	2.5	23404	6.9	Mb	
18	18.1	23426	5.2	gM2	
31	54.5				m_{Si} = 1.0
35	24.5	23901	5.7	A0	
36	24.5				
36	54.0				
39	18.0	24009	5.6	F5	on two tapes
39	21.6				
40	21.5				
40	47.0				
41	22.5				
41	23.6				
1816	21.0				
18	22.0	25033	5.0	gM0	correlates on tape
21	12.8				m_{Si} = 2.0
1 31	23.0				
35	38.5	α Lyr	0.1	A0	
36	11.2				
43	24.0				

TABLE III (continued)

LIST OF "PROBABLE" STELLAR SOURCES IN SURVEY

R.A.	Dec.	Star	m_v	Class	Notes
1851	22.5				noisy tape
52	43.8				
53	10.5	25937	6.8	K0	m_{Si} = 2.0
56	11.5				
58	−4.5	26122	7.1	K2	
58	30.5				
1901	23.2				noisy tape
03	31.5				
04	8.0	R Aql	6.2	gM7e	
10	−3.0				
28	−3.0	26936	5.2	gM1	
54	24.2				
55	−3.5	27659	7.1	K5	
2000	35.7	27760	6.4	K0	
03	20.0	η Sge	5.3	sgK1	m_{Si} = 1.3
05	48.8				
06	0.0	27930	6.0	gK1	
09	−5.5				
10	17.5				
14	27.5	28152	4.7	gK2	m_{Si} = 1.9
31	14.7				
37	26.1				could not confirm
43	30.0	28942	4.3	gG7	m_{Si} = 1.6
45	−6.2	28979	4.6	gM3	
2109	29.0				m_{Si} = 1.9
10	40.5				m_{Si} = 1.7
21	30.0				
28	4.5				
29	33.5				m_{Si} = 1.9
35	2.5				
44	−5.5				
2216	41.2				
18	18.5				
18	42.5				
23	42.8				
26	45.0	31393	6.8	K5	on two tapes
31	42.0				
34	1.0				noisy tape
34	3.5				" "
45	4.5				" "
49	0.8				" "
51	0.8				" "
59	1.0				" "
2307	31.5				
15	32.5				
2404	32.0				

are listed as well as those stars predicted to be of near infrared magnitudes near 0.0 or brighter in a blackbody extrapolation survey performed by Eastman Kodak and Ohio State University.[5]

In the area scanned, 46 stars listed in the EK–OSU table of predicted strong sources were covered. The initial evening scan on 26 July 1962 was set to cover three of these sources: 74 Vir, S Vir, 82 Vir. None of these sources was detected! This particular evening was somewhat hazy, and the zenith angle exceeded 45°, but similar zenith angles for other known bright sources did not attenuate more than one magnitude so that the failure to detect S Vir was especially disturbing. Later measurements with the stationary scanning mirror of these three sources gave the values indicated in Table II. The predicted magnitudes were, in all cases, too bright by from 1.4 to 2.3 stellar magnitudes.

The EK–OSU magnitude predictions were for the spectral region 2.0–2.4 μ which they referred to as the x–band, thus, the heading of the predicted magnitude column with m_x. Magnitudes in this more narrow infrared region will correspond almost exactly with the m_{Si} measured during this program so that direct comparisons are valid. Time did not permit stationary mirror measurements of all sources detected during the scanning mode of operation, so that many of the stars were not measured for an m_{Si} value. It was attempted to measure those which showed a surprisingly large or small irradiance based on predicted IR magnitudes. This explains the many gaps found in the column headed ITT m_{Si}.

Of the 46 stars on the EK–OSU list, 19 were not detected during the course of the scan program, although later spot checks of several of these stars showed that they should have been classed at least as possibles or probables. Explanation for this failure to detect the sources must lie in obscuration of the stars by tenuous clouds which could not be detected visibly, by star transit through the scanned field of view during the time the dry ice plug was being replenished (later checks showed this might have been the case for three or four of the stars, this operation requiring some thirty seconds and resulting in somewhat degraded performance due to temporary warming for fifteen additional seconds), or a defocused condition due to failure of the nodding mirror to accurately follow the cams during the scanning motion. This latter mechanical problem was recognized early in the study and every effort made to keep an adequate grease film on the cams which are necessary to insure retention of the curved focal plane on the detector during the nodding motion.

Twenty-one stars not found on the EK-OSU list are listed in Table II corresponding to strong or definite detections. An outstanding example of the difficulties in extrapolating from visual observations to predict near IR magnitudes is shown by the 7.2 magnitude M7 star at 2144 hours, minus 2.5° listed in Boss's general catalog as 30482. This star was found to be a strong source of PbS magnitude −1.0 where, following the usual procedure, Class A0 stars are defined as having the same magnitude in any spectral region. Thus, this star has a PbS index defined as $m_{Si} - m_V$ (as measured effectively with a silicon filter on PbS) of 8.2. A. J. Deutsch, who has studied the characteristics of such cool, red stars, estimated in a private discussion that from the visual spectrum characteristics, that is the presence of molecular absorption details in the spectrum, that the temperature of this source would be judged to be 2400° K. This makes it one of the cooler stars known, serving as a standard model for an M7 star. If the star were indeed a blackbody at 2400° K, a PbS index of 4.3 would be expected. And since the true value is 3.9 times this high, the star is 36 times too bright in the near IR. The observed index corresponds to an effective temperature of approximately 1700° K.

Two other interesting sources which were detected as strong or definite-to-strong were κ Ser and ST Her which were both later measured to be of m_{Si} = 1.6 which should not have given such a positive detection. The scanned records indicate that these two sources were indeed strong sources on the night measured, although several months later they were evidently less bright, indicating the possibility of infrared variable stars. The star X Her was measured to be a $m_{Si} = -1.2$, but this M6 variable was not included on the EK-OSU list. The danger of extrapolating from visual properties to even the near IR is further documented by the inclusion of T CrB which is a Class Q+gM3 with a maximum visual magnitude of 2.0. The EK-OSU prediction of -2.7 magnitude in the near IR was evidently based on the assumption that the gM3 star was a variable of second visual magnitude where, in reality, the Q nova has reached this magnitude only twice during recorded history! This star could not be detected with the stationary scanning mirror.

Another indication of the danger of extrapolation of the infrared properties of stars from visual magnitudes and stellar types is shown in the failure to detect ε Cyg, a g KO star of visual magnitude $m_V = 2.6$. This star is predicted by EK-OSU to have a PbS magnitude of -0.1, and a similar magnitude is predicted for W Cyg, a g M4e star of $m_V = 5.0$. The latter star was found to be a strong source. Later measurements of both of these stars gave a $m_{Si} = 0.84$ for ε Cyg and -0.94 for W Cyg, nearly two magnitudes different for stars predicted to be identical.

The unknown characteristics of the cool star atmospheres and especially the variable stars, which are known to be less influenced in their magnitudes in the near infrared than in the visual, makes extrapolation even more dangerous for these types. A good example is given by the two variables EU Del and U Del which were both detected as strong sources, although later measurements showed the former to be $m_{Si} = -0.5$ compared to 0.1 for the latter. Only the latter appears on the EK-OSU list, although the former star is actually 0.6 magnitudes brighter.

An examination of Table II indicates that all of the strong sources have been identified with known stars and most of the definite sources. Such is not the case with the list of probable sources given in Table III. Those stars which could be identified in the Becvar Catalog and in the Boss General Catalog are listed. Identity was assumed when the cataloged star was positioned within the co-ordinate accuracy previously described. Even so, only 34% of the detections are identified. In some instances spot-checks were made on the magnitudes of stars which could not be found in the catalogs and positive confirmation of the existence of these sources obtained. An example is the source at 1731 hours, 54.5° which is of $m_{Si} = 1.0$.

Most of the identified classifications for the probable sources are for late stars, as was the case with the strong and definite detections. However, a significant number of earlier stars are also present, and the measured $m_{Si} = 1.6$ for the KO star 20091 of $m_v = 6.9$ leads to a PbS index of 5.3 for this star. The theoretical values of the index for KO stars calculated for the identical detector used in this study by Walker[6], is 2.8, so that this star evidently has anomalously bright infrared characteristics. The possibility of a cool companion star cannot be overlooked. Similarly, the occurrence of the F5 star 24009 on two tapes indicates an m_{Si} on the order 1.5, leading to a PbS index of 4.0 where the theoretical value should be 1.0. Even though the reliability of the probable detections is from 60 to 70%, the not uncommon occurrence of early stars or stars below the 8th visual magnitude indicates that there are a significant number of objects with anomalous infrared characteristics which could influence the near and probably the far infrared backgrounds of search detection sets operating in the NEPD range 10^{-14} to 10^{-15} watts/cm^2.

Table IV lists those possible stellar sources which correlated on two scans of the same region of the sky or were confirmed by spot checks. All of the more than 900 possible sources will not be listed except as included on the maps, due to the low reliability of true detection for these objects which produced irradiance values near the NEPD of the scanning radiometer. Those sources that do appear in Table IV surprisingly contain no M class stars; all of the sources which correlate closely in position with known stars lead to anomalously large PbS indices, if indeed these stars are responsible for the signals. Parallax information was not readily available for these stars to see if they might be close-by objects wherein the excess infrared could be associated with a reasonably sized cool companion.

By comparing the near IR magnitudes as measured during this program, or on previous programs described in the Appendix, with the strength classifications it is possible to assign magnitudes which correspond closely with the four detection classes used. Strong sources correspond to stars of $m_{Si} = 0.0$ or brighter; several instances where the measured irradiance was less than expected seem to have been due to variable infrared characteristics. Definite

TABLE IV

LIST OF "POSSIBLE" STELLAR SOURCES ON TWO TAPES OR CONFIRMED

R.A.	Dec.	Star	m_v	Class	Notes
1701	12.5				$m_{Si} \sim 2.5$
16	15.0				
50	17.0	24302	6.6	F5	
1809	10.5				
44	16.5	25723	8.3	G0	
59	17.0				
1917	17.0	26637	6.9	F5	
31	18.0				
2008	16.0	28012	7.3	K0	
23	19.5	28431	6.4	K0	

sources are of $m_{Si} = 0.5$ or brighter. Probable sources lie in the range $m_{Si} = 1.0$ to 2.0, and possible sources lie in the range 1.0 to 3.0. Some overlap in these magnitude ranges is to be expected due to variable observing conditions, the attention of the observer through the twenty minute observation periods assigned as a maximum for one observer at a time, and instrument malfunctions. Using the magnitude to irradiance scale suggested by Walker[6], it is then possible to obtain the relationship shown in Figure 13, where the irradiance values outside the atmosphere for the three spectral regions examined during this study are related to stellar magnitudes in each of these three regions. Thus, in the PbS region from 1.3–3.0 μ, a 0.0 magnitude A0 class star would produce an irradiance near 1.0×10^{-13} watts/cm^2. The graph clearly shows the rather unfortunate choice of A0 stars for establishing the absolute scale, since comparable irradiance values in the various spectral regions correspond to an increasing scale of stellar magnitude brightness for the longer wavelengths.

The average atmospheric transmittance encountered during this study was probably from 0.5–0.7 in the near IR and somewhat higher in the other two bands. The detection of stars below $m_{Si} = 2$ indicates the radiometer was obtaining an NEPD in the 10^{-15} w/cm^2 range in the near IR which correlates closely with the results of the collimated calibration tests.

A total of eighteen strong sources were observed in the 18% of the celestial sphere scanned. If the average magnitude of these sources is taken to be −1.0, which is perhaps somewhat too bright, it is found that the average irradiance from 1 square degree of sky from such strong sources will be $H_{-1} = 1.1 \times 10^{-15}$ w/cm^2. If now the distribution of the possible sources is examined and point counts made per square degree area, it is found that an expectation of somewhat over 0.10 is obtained for one possible source per square degree and 0.015 for two possible sources per square degree. (Much smaller probabilities are obtained for three sources per square degree, and in no instances are four sources found, except for one square degree in the Milky Way region.) No significant difference is found within and without the Milky Way for possible source distribution. If the average magnitude of the possible source is assigned as +2.0—which is probably somewhat less bright than that obtained for these sources, and only 20% of the possible detections are assumed to be reliable—the irradiance from each square degree scanned

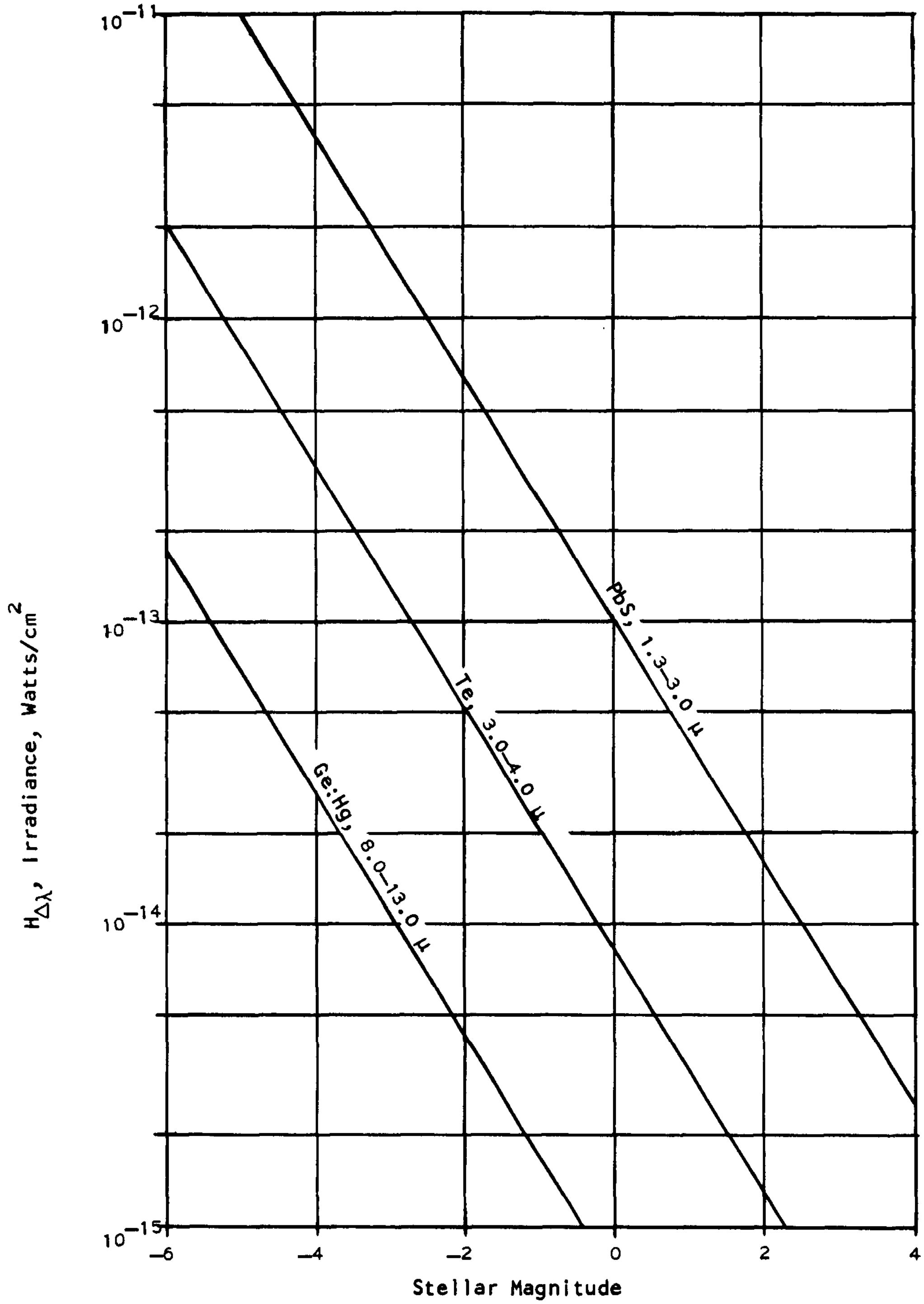


FIGURE 13 IRRADIANCE TO INFRARED MAGNITUDE RELATION FOR THE THREE SPECTRAL REGIONS

due to these sources is found to be $H_2 = 3.2 \times 10^{-15}$ w/cm^2, or three times that due to the strong sources! This indication that total irradiance is greater from the larger number of less bright stars is in line with similar conclusions reached by Walker and Ramsey, as discussed in Appendix A. Although such a trend could not continue indefinitely due to the finite size of the galaxy, a more severe background problem may exist due to unresolved clusters of cool stars producing an entirely splotchy infrared background for equipment with an NEPD in the 10^{-15} w/cm^2 region.

Perhaps the diffuse radiance regions marked on the map with the dotted outlines, which were observed on the Memoscope to extend over greater angular dimensions than the instantaneous field of view, can be explained by the presence of such clusters. Neglecting the one morning when extremely noisy airglow fluctuations were encountered, it is seen that these diffuse areas do cluster in the Milky Way where large numbers of visual clusters are also found.

The detection of diffuse targets, especially in the regions near the Milky Way, suggested that a scan of the nearest galaxy M31, where the nucleus is unobscured by galactic plane dust, might be interesting. Repeated scans of this object were inconclusive with some indications of a slight decrease in noise during scans past the nucleus, but an increase in noise immediately before and after the nucleus drifted through the center of the field. These qualitative assessments thus indicate that the galaxy was essentially undetectable, at least with the space filtering used in the radiometer, but the distance to this galaxy of 10^6 light years would make the expected irradiance much less than that due to nearby clusters. Stebbins and Whitford[7] have shown that the transmittance of interstellar space may be quite high in the near IR, so that dust in our own galaxy may not be as detrimental to local cluster detection as in the visual region.

6.2 <u>Te Scans, 3.0–4.0 μ</u>

The NEPD of the Te detector equipped radiometer was 5×10^{-13} w/cm^2 which should have provided for S/N = 1 for a −2.0 magnitude infrared star. This is close to the predicted magnitude for α Boo which was scanned several times with a possible but unreliable detection. Similarly, α Her may have been just detectable. Scans in the region 15–20° declination and 40–45° from 13 to 20 hours failed to reveal any other sources, nor did a three hour scan along the center of the galactic plane reveal diffuse areas as detected with PbS. It must be remembered that the 1167 wave/radian space filter was used with this detector also, so that it can be stated that no point source irradiance values much greater than 5×10^{-13} w/cm^2 in this spectral region are to be expected on the basis of the small area scanned. Several of the brighter stars, and especially α Ori, would have been readily detectable with this radiometer configuration, but accidental damage to the detector on another experiment prevented confirmation of these predictions.

6.3 Ge:Hg Scans, 8.0–13.0 μ

The space filter was not used with this detector, so that both point sources and diffuse areas would have been mapped had they been detected. Actually, only the planets Venus and Mars were detected with the NEPD of 3×10^{-13} w/cm^2. Even α Ori could not be detected, and measurements by Murray[8] indicate that 2×10^{-14} w/cm^2 is to be expected in this wavelength region, which is a factor ten below the NEPD of the instrument. Failure to detect this source is, therefore, explained. And it is only possible to again state that no brighter source was observed in a scan of the strip from 40 to 45° in declination from 13 to 20 hours, nor in a two hour scan in the galactic plane in the direction of the nucleus.

7.0 RECOMMENDATIONS

The Stellar Irradiance Measurement Program produced several positive results, such as the mapping of unexpected bright infrared sources. The limited time and NEPD of the instrument served to provide tantalizing information on other aspects of the infrared background in space, such as the possible existence of extremely cool stars and clusters of infrared stars. More specifically, this information might be tantalizing for the astrophysicist but frustrating for the designer of infrared systems for operation in space. The study has at least produced a somewhat more complete picture of the infrared background that indicates much is still unknown about infrared clutter due to cosmic sources. In many instances in the past, extremely clever optical systems have been designed to detect certain targets; but these techniques have failed in operation, due to the lack of understanding of the background conditions in which such devices must operate. If a repetition of this history is to be avoided for space-borne infrared devices, it is recommended that the following steps be undertaken:

A. A more comprehensive scan of the entire sky in the near infrared should be repeated a sufficient number of times to provide positive detection for all sources producing an irradiance greater than 10^{-16} w/cm^2.

B. Spot-check interesting or anomalous areas or stars in the intermediate and far infrared.

C. Conduct space-borne measurements of the spectral characteristics of these sources.

The reasoning behind these recommendations follows. An infrared search device in space will use a large field of view to quickly scan for targets; detector arrays will probably be used with no requirement for "astronomical" angular resolution. In the near IR, linear arrays of PbS with individually high D* values are already available, and the incorporation of Peltier cooling devices in a simple radiometer would allow reaching an NEPD of 10^{-16} watts/cm^2 or below. Since arrays are not yet so readily obtainable in the intermediate and far IR, only spot-checks might be necessary in these regions, since extrapolation over a very short wavelength region in the infrared would be involved as contrasted to the large extrapolation from the region of atomic to molecular spectra involved in past studies. Since the superior D* of PbS makes it the best detector to use for sources hotter than 550° K, the gross map can still best be obtained with this simple to operate detector. Limited area scans in the intermediate and far IR would serve to confirm the accuracy of this technique in a limited period of time, perhaps somewhat more than one year.

Spectral studies from a space-borne platform would enable measuring the emission characteristics of infrared sources without the troublesome intervening atmosphere. This would provide a much clearer understanding of these sources, perhaps leading to a spectral discrimination technique to reduce the background clutter for military optical systems.

Besides the necessary knowledge for infrared systems design, scientific prestige would be gained for the United States in the discovery of new data about the physical universe and the possible detection of objects in space much closer than the nearest known star. For the above reasons, it is strongly recommended that the Air Force consider sponsoring such a measurement program.

APPENDIX A

—STATUS OF INFRARED ASTRONOMY—

Discussions of infrared and astronomy must certainly go hand in hand, since Sir William Herschel discovered the infrared spectrum during an astronomical experiment.[9] Investigations of the infrared solar spectrum continued during the nineteenth century using thermometer, thermocouple, thermopile, and evaporagraph detectors.[10] Coblentz[11] was apparently the first to measure stars other than the sun with a vacuum thermocouple; crude determinations of spectral distribution were made by means of water-cell filters. More elaborate filters were used in a later investigation by Coblentz,[12] and the accuracy of his radiometric measurements was confirmed in studies by Pettit and Nicholson,[13] who measured many late stars of Class M3 and cooler and found an indication of departure from blackbody radiation characteristics based on colorometric temperature estimates.

Dispersive spectroradiometric measurements were first performed by Abbott,[14] but the data was rather poorly resolved and too noisy to provide for investigations of departure from blackbody radiation characteristics. Radiometric measurements were also made by Emberson,[15] who measured none of the later class stars and thus did not confirm the departure from blackbody radiation characteristics detected by Pettit and Nicholson. It should be noted that all of these earlier efforts involved radiometric measurements of the brighter early stars and of known stars with later spectral classifications or late class variables.

The next significant advancement in infrared astronomy came in the development of the silver-cesium oxide-cesium photoemitter surface (S-1). This detector was used by Stebbins and Whitford[16] to establish a six-color photometry system for the stars, expanding greatly the previous photoemissive measurements. The law of space reddening could be more completely determined with the S-1 detector, and a series of scans across the plane of the galaxy indicated the galactic center by its excess infrared radiation.[7]

Infrared quantum detectors useful past the photoemissive cut-off became available after the end of World War II. Kuiper[17,18] was evidently first in applying the PbS detector for astronomical studies in 1946, recording the spectra of several stars and planets from .75–3 μ. Molecular absorption bands in M stars were resolved. Whitford[19] used a PbS detector to extend the law of interstellar reddening but does not seem to have continued his search for the galactic nucleus at wavelengths beyond 1 μ, as mentioned in his paper; Whitford measured only O and B class stars with PbS.

During the past twelve years, measurements have been made of selected stars by Fellgett,[20] Lunel,[21] Hall,[22] and by the Eastman Kodak–Ohio state team.[5] Recent measurements by Johnson[23] with an InSb photo–voltaic detector through 4.1 μ indicate that late type dwarf stars deviate from blackbody radiation predictions based on the six color photometry in the visual and near IR with a large excess of radiation around 1.0 μ.

These studies have recently been summarized and analyzed by Walker,[6] who emphasizes potential Air Force interest in the status of infrared astronomy. Walker's summary confirms the earlier conclusions by Hall[22] that the theoretical infrared stellar magnitudes calculated by extrapolating the blackbody radiation characteristics of the star provides reliable approximations for early stars from Class O through G, but that increasing scatter from these theoretical predictions must be expected for the later K and M class stars where departures from the theoretical curves by 1 to 2 stellar magnitudes are to be expected.

The lack of complete infrared irradiance measurements for many stars has required the derivation of models to predict such values based on spectral classification and luminosity types derived from visual region observations. Such models and extrapolations have been performed by Kuiper,[24] Larmore,[25] in the Eastman Kodak–Ohio State Study,[5] Zachor,[26] and by Ramsey.[27] Johnson's measurements show bolometric corrections proposed by Kuiper as early as 1938 are indeed quite accurate to wavelengths of 4 microns for giant stars but underestimate the infrared irradiance due to dwarfs, due to the previously mentioned excess near 1.0 μ. Extrapolations to the 10 μ region as performed by EK–OSU (their z magnitude region) have not yet been confirmed by measurements by this group, although Murray[8] has succeeded in obtaining the first measurement of 10 μ radiation from an object outside of the solar system when the irradiance of α Ori was found to be 3.92×10^{-15} w/cm^2 μ, a measurement which does not suggest a significant revision for this star based on an extrapolation of

3100° K blackbody characteristics. As a super giant of Class 1 luminosity, α Ori seems to be more well behaved than the dwarfs, based on the measurements of Johnson. Clearly, more measurements are needed in this spectral region to confirm the radiation characteristics of the stellar background.

Some insight into the reasons for departure from blackbody characteristics is given in the near IR stellar spectra obtained with PbS detectors by Kuiper[17] and Sinten[28], who show that the presence of molecular absorption bands in stars of identical spectral classification may differ considerably with CO at 1.6 μ having been identified in α Ori but apparently not present in β Peg. P. W. Merrill[29] suggested some time ago that since the atmospheric temperatures of M class stars—and especially the long period variables—are below the boiling point of refractory substances, such as carbon, that particulate clouds may form in the atmosphere of such stars which might be more effective in scattering or absorbing visual light then infrared. Possible absorption and scattering by particulate matter in the stellar atmospheres is further complicated by molecular band absorption of titanium-oxide in the M stars, zirconium-oxide in S stars, and carbon compounds in N stars[30].

We may conclude this section by noting that existing measurements of known stars indicate that infrared magnitudes may be calculated with a fair degree of precision from empirically modified blackbody effective temperature assignments with a probable error of a factor of 2, as discussed by Walker[6] for wavelengths to 4 μ. Completely insufficient data is available for longer wavelengths for any predictions, but the one measurement by Murray[8] shows that for one star the probable error of 2 is probably experienced.

From the results of the present mapping investigation, the effect of unresolved clusters of cool stars, as they contribute to the infrared background, should be considered. Both Ramsey[27] and Walker[6] have discussed this problem and show that the number of stars detectable for decreasing NEPD increases by more than ten for each decade of performance improvements. Thus, the overall contribution of the fainter stars increases, at least to PbS irradiance values of 10^{-14} w/cm^2. This conclusion is not contradicted by the present study. Of course, this increase does not continue without bounds, due to the finite dimensions of the galaxy. However, a radiance map of the infrared background should be obtained with a radiometer capable of mapping diffuse and unresolved areas as well as specific stars to irradiance values below the NEPD planned for any military system. Otherwise, due to the uncertain transmission characteristics of the dust and gases in the galaxy, it is not possible to predict at this time the influence of such sources.

LIST OF REFERENCES

1 F. F. Hall, C. V. Stanley, and T. P. Dixon, "Research on the Detection of Infrared Emission from Satellite Vehicles," Scientific Report No. 1, AF19(604)-4971, AFCRL-215, December 1960 (AD 257170).

2 F. F. Hall, Jr. and C. V. Stanley, Applied Optics 1, 97 (1962).

3 F. E. Nicodemus and G. J. Zissis, "Methods of Radiometric Calibration," University of Michigan Report 4613-20-R, October 1962.

4 Antonin Becvar, Atlas of the Heavens, Catalog of the Heavens, Sky Publishing Corporation, Harvard, 1958.

5 Reports have been issued on Contracts DA-30-069-ORD-2803 and -3516, "Space Background Study" by W. H. Haynie, P. E. Barnhart, et al., Eastman Kodak Company Reports EK/ARD ED-442,575,692,735,874 dated July 1960 through July 1962.

6 R. G. Walker, "Infrared Celestial Backgrounds," Air Force Surveys in Geophysics No. 149, AFCRL-62-807, July 1962.

7 J. Stebbins and A. E. Whitford, Astrophys. J. 106, 235 (1947).

8 B. C. Murray and R. L. Wildey, "Stellar and Planetary Observations at 10 Microns." Note submitted for publication to the Astrophysical Journal, September 21, 1962.

9 Sir William Herschel, Phil. Trans. Roy. Soc. 90, 284 (1800).

10 R. A. Smith, F. E. Jones, R. P. Chasmar, The Detection and Measurement of Infra-Red Radiation, Clarendon Press, Oxford, 1957.

11 W. Coblentz, Lick Obs. Bul. 8, 104 (1915).

12 W. Coblentz, Scientific Papers, U. S. Bur. Stan. 17, 725 (438), (1922) and Astrophys. J. 55, 20 (1922).

13 E. Pettit and S. B. Nicholson, Astrophys. J. 68, 279 (1928), and Astro. Phys. J. 78, 320 (1933).

14 C. G. Abbott, Astrophys. J. 60, 87 (1924).

15 R. M. Emberson, Astrophys. J. 94, 427 (1941).

16 J. Stebbins and A. E. Whitford, Astrophys. J. 98, 20 (1943).

17 G. P. Kuiper, W. Wilson, R. J. Cashman, Astrophys. J. 106, 243 (1947).

18 G. P. Kuiper, Astrophys. J. 106, 251 (1947).

19 A. E. Whitford, Astrophys. J. 107, 102 (1948), A. E. Whitford, Astronom. J. 63, 201 (1958).

20 P. B. Fellgett, Mon. Not. Roy. Astron. Soc. 111, 537 (1951).

21 M. Lunel, Ann. D'Astrophysique 23, 1 (1960).

22 F. F. Hall, Jr., Proc. IRIS 6 (1), 137 (January 1961).

23 H. L. Johnson, Astrophys. J. 135, 69 (1962).

24 G. P. Kuiper, Astrophys. J. 88, 429 (1938).

25 L. Larmore, "Infrared Radiation From Celestial Bodies," Project RAND, Research Memorandum RM-793-1 (1952) (Unclassified).

26 A. Zachor, Mass. Inst. Tech., Naval Supersonic Laboratory A-R413 (1959) (Unclassified).

27 R. C. Ramsey, Appl. Opt. 1, 465 (1961).

28 W. M. Sinten, Appl. Opt. 1, 105 (1962).

29 L. Goldberg and L. H. Aller, Atoms, Stars, and Nebula, Blakiston, Philadelphia, 1943, p. 149.

30 L. Campbell and L. Jacchia, The Story of Variable Stars, Blakiston Company., Philadelphia, 1941.