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CELESTIAL INFRARED CALIBRATION SOURCES IN THE 8-14 MICROMETER REGION: VENUS AND JUPITER

Thomas E. Cecil, et al

Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

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Thomas E. Cecil Lloyd M. Logan
John W. Salisbury Graham R. Hunt

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13. ABSTRACT

Venus and Jupiter are often used as long wavelength infrared (LWIR) calibration sources. We have reviewed the literature on radiometric and spectrometric measurements of these two planets and adopted reasonable brightness temperatures and spectral dependencies for their thermal radiation. Using these data, we have calculated irradiance coefficients that can be used to determine the irradiance reaching the earth from these planets at any time. A crucial factor in the utility of these planets as calibration sources is the constancy with which they radiate in the infrared. We conclude that Jupiter may be a variable source. Venus, on the other hand, appears to be generally quite constant, but brief temporal variations may take place.

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Celestial Infrared Calibration Sources in the 8–14 Micrometer Region: Venus and Jupiter

1. INTRODUCTION

Celestial LWIR calibration sources are required for both civilian and military purposes. Stellar sources do not provide the optimum temperature for some purposes, so planetary sources are used instead. In this report we review pertinent data on the brightness temperatures of the planets Venus, and Jupiter, adopt reasonable temperatures and spectral dependencies of their thermal emission, and calculate irradiance coefficients which can be used to determine the irradiance reaching the earth from these planets at any time.

2. VENUS

In examining the potential usefulness of Venus as a calibration source, we must determine the extent to which the irradiance from this planet is known, and the extent to which it is variable.

Although high resolution spectroscopic measurements in the visible and near-infrared permit the rotational temperatures of certain constituents in the Cytherian

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atmosphere to be accurately determined[1], it is not possible to calculate LWIR irradiance from Venus because knowledge of the structure and composition of the Cytherian atmosphere is not yet sufficiently detailed. One very generalized calculation of irradiance from simple energy balance considerations utilized visible albedo measurements and assumed gray body behavior[2]. Venus does not, however, display gray body behavior in the 8-14 µm region, and the energy balance problem is complicated by greenhouse and other poorly understood effects, making the usefulness of such a calculation extremely limited.

Being unable to calculate irradiance from Venus, as we have from Mars[3], we must depend upon LWIR observational data. While such data have been collected from Venus over a period of about 50 years, they are very limited in quantity and variable in quality. With the exception of the Mariner 2 flyby experiment, all observations have been made with ground-based telescopes, utilizing a variety of detectors and instrumentation. The results of modern measurements are summarized in Table 1, which illustrates the range of different temperatures determined by different investigators. The usefulness of Venus as a calibration source will be determined by the significance of these differences, so each measurement will be discussed in some detail.

Pettit[4] reported in 1961 on a series of brightness temperature measurements that he had made with S. B. Nicholson during the period 1922-1955. These measurements were made with a vacuum thermocouple and yield a maximum brightness temperature of 240°K. Pettit states no error, but his detector was relatively insensitive, and his primitive filtering made calibration difficult. Considering these difficulties, a great deal of weight cannot be placed upon the measured brightness temperature. Perhaps more important, Pettit and Nicholson discovered that the unilluminated portion of the Cytherian disk was no cooler than the illuminated portion. This was the first indication of the long thermal time constant of the Cytherian atmosphere, that is an important factor in making Venus a good calibration source.

Sinton and Strong[5] made an extensive series of measurements of Cytherian

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1. Young, A. T. (1973) Are the clouds of venus sulfuric acid?, Icarus **18**:564-582.
2. Ramsey, R. C. (1962) Spectral irradiance from stars and planets, above the atmosphere, from 0.1 to 100.0 microns, Appl. Opt. **1**:465-471.
3. Logan, L. M., Balsamo, S. R., and Hunt, G. R. (1973) Absolute measurements and computed values for martian irradiance between 10.5 and 12.5 µm, Icarus **18**:451-458.
4. Pettit, E. (1961) Planetary temperature measurements, Chapter 10 in The Solar System, Vol. III, Planets and Satellites, The University of Chicago Press.
5. Sinton, W. M., and Strong, J. (1960) Radiometric observations of venus, Ap. J. **131**:470-490.

Table 1. Brightness Temperature Measurements of Venus

Investigators	Approximate λ Range	Brightness Max	Temperature Disk	Remarks
Pettit, 1961	8 - 13 μm	240°K	----	Detector size large. No stated error.
Sinton & Strong 1960	8.2-12.4 μm	234°K	226°K	No stated error. Disk temp calculated.
Sinton, 1963	7.3-10.3 & 10.4-13.4 μm	----	235°K $\pm$ 7	Statistical error (one standard deviation).
Chase et al 1963	7.8-8.9 & 10.0-10.7μm	245°K $\pm$ 10	----	Questionable calibration.
Westphal et al 1965	8 - 14 μm	205-227°K	----	No stated error. Emphasized relative measurements.
Gillett et al 1968	7.5-13.8μm	----	~213°K	Temperature estimated by us from spectrum. No stated error.
Hanel et al 1968	8 - 13 μm	----	~250°K	From a single observation. No stated error.
Moroz et al 1969	10.0-11.7 μm	$223°K^{+12}_{-3}$	$210°K^{+15}_{-5}$	Questionable calibration. Error includes systematic error.

brightness temperature using smaller more sensitive thermocouple detectors, and considerably more sophisticated ancillary equipment and techniques. In addition to measuring brightness temperature, they obtained infrared spectra which showed that Venus does not radiate as a gray body (see Figure 1). Examination of Sinton and Strong radiometric data shows that, although individual measurements during a given night might vary by as much as 10°K, averages for each night vary by less than $\pm$ 2°K, and variations in average disk temperature over a period of two years cover a range of only 3°K. Their value for the maximum brightness temperature on the disk is 234°K, while their average disk temperature is 226°K. These measurements show a high degree of consistency, but the authors do not discuss systematic errors and, consequently, it is difficult to evaluate the magnitude of such errors.

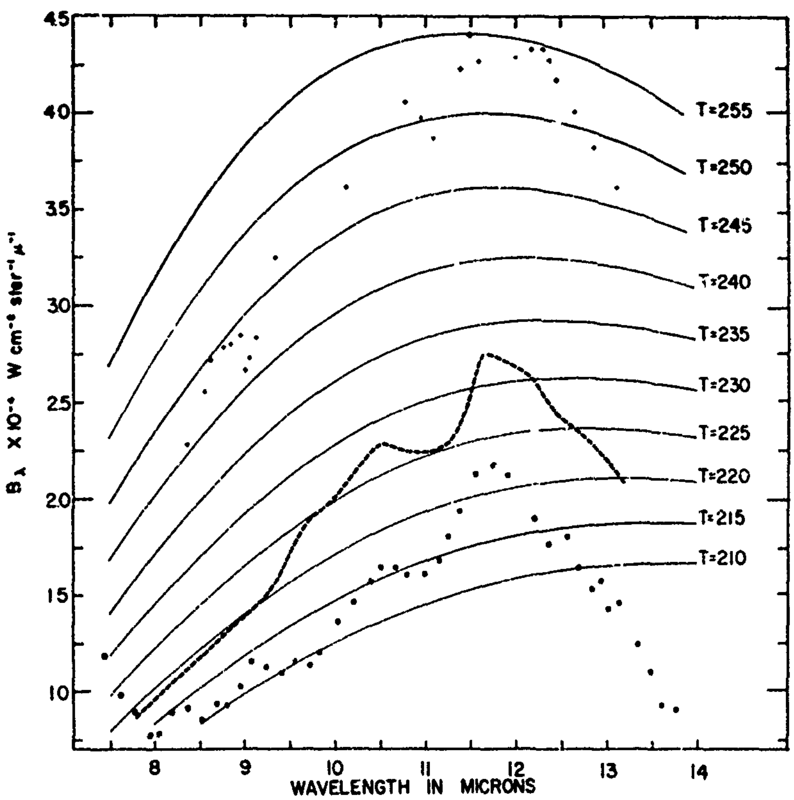

Figure 1. Spectral Irradiance of Venus as Recorded by Three Different Experimenters. Hanel et al, 1968 (crosses); Gillett et al, 1968 (squares); and Sinton and Strong, 1960 (dashed curve). Blackbody curves are shown for comparison.

A possible indication of the magnitude of systematic errors in such ground-based radiometric measurements of Venus is provided by subsequent observations by Sinton[6]. Using a different telescope and a different observing site from those used by Sinton and Strong[5], he obtained an average disk temperature 9°K higher, with a standard deviation of 7°K for observations on any one day.

Chase et al[7] reported on a radiometer experiment aboard Mariner 2. Measurements in two narrow bandpasses within the 8 to 14 μm region showed good agreement with each other, and indicated a maximum temperature of 245°K.

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6. Sinton, W. M. (1963) Infrared observations of Venus in Physics of Planets, Memoires de la Societe Royal des Sciences de Liege, VII:300-310.
7. Chase, S. C., Kaplan, L. D., and Neugebauer, G. (1963) The mariner 2 infrared radiometer experiment, J. of Geophys. Res. 68:6157-6170.

Unfortunately, the absolute calibration for this experiment was not satisfactory, and the stated error (± 10°K) is large.

Westphal et al[8] were the first experimenters to use a cryogenically cooled detector to measure the brightness temperature of Venus. They specialized in mapping the brightness temperature distribution over the disk with a differential accuracy of about 1/3°K. With this sensitivity, small asymmetries and local anomalies were common on the maps, indicating a complex temporal variation in the radiation from the Cytherian atmosphere. However, these anomalies constitute only relatively minor distortions to a very simple planetary brightness temperature envelope, and should have very little effect on the average disk temperature. More pertinent to our problem is the observed variation in maximum temperature between 205°K and 227°K, which lies 7°K to 29°K below that recorded by Sinton and Strong[5]. Westphal et al[8] point out that the importance of their observations is in the two-dimensional picture of the infrared radiation rather than the absolute value of the central temperature. Indeed, their quoted temperatures contain no correction for an unknown telescope transmission loss; they simply point out that the expected systematic error could account for the disparity between their measurements and those of Sinton and Strong[5]. Thus, Westphal et al[8] were not primarily interested in absolute temperature measurements and their approach to the calibration problem reflects this interest. Their correction for atmospheric transmission was directed towards accurate differential measurements, and despite the large variation in peak temperature observed by them, they conclude that the question of absolute brightness temperature of Venus and possible variations in that quantity will be in doubt until extra-atmospheric fluxes in this wavelength region are known for some standard object.

Gillett et al[9], like Sinton and Strong, obtained an emission spectrum of Venus (see Figure 1). The spectrum shows generally the same features as does the Sinton and Strong spectrum, but the indicated brightness temperature is approximately 10°K lower. Gillett et al[9] quote no error for their measurement, nor is there any indication of the number of observations made or the scatter in them. They are unable to explain the disparity between their result and those of Sinton and Strong.

Hanel et al[10] also obtained an infrared spectrum of Venus, which again follows

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8. Westphal, J.A., Wildey, R.L., and Murray, B.C. (1965) The 8-14 micron appearance of venus before the 1964 conjunction, Ap. J. **142**:799-802.

9. Gillett, F.C., Low, F.J., and Stein, W.A. (1968) Absolute spectrum of venus from 2.8 to 14 microns, J. Atmos. Sci. **25**:594:595.

10. Hanel, R., Forman, M., Stambach, G., and Meilleur, T. (1968) Preliminary results of venus observations between 8 and 13 microns, J. Atmos. Sci. **25**:586-593.

the general shape of Sinton and Strong's. However, their indicated brightness temperature is considerably higher. A subsequent unpublished work by the Hanel group has revised this figure downward to the neighborhood of the Sinton and Strong result[11]. The fact that the same group utilizing careful calibration procedures can obtain such disparate results at different times indicates either a large temporal fluctuation in Cytherian irradiance, or more likely just how difficult a measurement of absolute irradiance is when attempted with a ground-based telescope.

The last published measurement of Cytherian irradiance was made by Moroz et al[12]. They had calibration problems and, when efforts to experimentally determine the transparency of the atmosphere failed, a correction was made assuming an atmospheric model with 50 percent humidity. The temperature quoted is lower than that of Sinton and Strong, however, they encountered difficulty in correcting for atmospheric transmission, and so the quoted error is relatively large.

In summary, of all of the measurements listed in Table 1, the largest number of observations over the longest time period were carried out by Sinton and Strong. Their results are internally highly consistent, and are also compatible with the latest unpublished results of the Hanel group. We therefore adopt their average brightness temperature of 226°K for Venus, and calculate the irradiance at several wavelengths utilizing their measured spectral distribution. The question of short term temporal variations in brightness temperature must be left unanswered. Given the inherent difficulties of performing absolute irradiance measurements, the variations in the measured temperatures listed in Table 1 cannot be cited as strong evidence for time variability. The only reliable source of such information is the reproducibility of measurements made by the same workers using the same equipment over extended periods of time, and only the work of Sinton and Strong[5] and Sinton[6] provide such data. There, the only indication of gross variability appears in one of Sinton's series of 27 radiometric observations, and this one differs by more than three standard deviations from the mean. Sinton concludes that Venus generally has a constant effective radiating temperature, but suggests that it may occasionally undergo a substantial temporal variation.

If we assume that radiance from Venus does not vary with time, the irradiance

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11. Virgil Kunde, personal communication.

12. Moroz, V.I., Davydov, V.D., Zhegulev, V.S. (1969) Photometric and spectroscopic observations of planets in the 8-14 μ range, Soviet Astron - AJ. 13:101-109.

equation which describes the energy reaching earth from Venus is

$$H_\lambda = \frac{W_\lambda(T)\,(4\pi r^2)}{4\pi D^2} \tag{1}$$

where

H_λ = the spectral irradiance at wavelength λ, in $W\ cm^{-2}\ \mu^{-1}$,

T = the average disk brightness temperature of Venus for the wavelength under consideration,

$W_\lambda(T)$ = the Planck blackbody function for T, λ,

that is,

$$W_\lambda(T) = \frac{c_1}{\lambda^5}\ \frac{1}{e^{c2/\lambda T}-1} ,$$

where c_1, c_2 are the first and second radiation constants whose values

$$c_1 = (3.7415 \pm .0003) \times 10^4\ W\ cm^{-2}\ \mu^{-1} ,$$

$$c_2 = (1.43879 \pm .00019) \times 10^4\ \mu\ ^\circ K ,$$

were recommended in July 1963, by the Committee on Fundamental Constants of the National Academy of Sciences National Research Council,

and

D = the distance from the earth to Venus,

r = the mean radius of Venus. The value used (r = 6115 km) was the one measured by Dollfus.

Equation 1 can be expressed in terms of an irradiance coefficient H_λ^o at each wavelength

where

$$H_\lambda = H_\lambda^o / D^2 \tag{2}$$

Then, the irradiance can be computed for any arbitrary time by dividing the irradiance coefficient by the square of the earth-Venus distance in astronomical units as listed by the ephemeris for that time. Computed values of the irradiance coefficients are given in Table 2.

Table 2. Venus Irradiance Coefficients*

8 μm	5.14×10^{-13}
9 μm	7.35×10^{-13}
10 μm	1.060×10^{-12}
11 μm	1.192×10^{-12}
12 μm	1.407×10^{-12}
13 μm	1.170×10^{-12}
14 μm	7.09×10^{-13}

* To obtain irradiance reaching earth in W $cm^{-2}\mu^{-1}$ divide irradiance coefficient by the square of the distance between earth and Venus in astronomical units.

These irradiance coefficients are completely dependent on our brightness temperature choice of 226°K. Unfortunately, there is little information available to use in assessing the correctness of this value. Most authors avoid the issue and quote only the reproducibility of the measurement, making no mention of the likely magnitude of systematic error in their experimental procedure. Moroz et al [12] alone attempted to do this, but their quoted error is large. Thus, we are unable to evaluate the importance of the spread in the tabulated brightness temperatures. A variation of approximately ± 10°K from our chosen value of 226°K corresponds to a ± 40 percent variation in irradiance. Quoting such an error in the irradiance coefficients is probably unduly pessimistic, especially as the Sinton and Strong result appears to be substantiated by the very recent data obtained by Hanel et al[10, 11]. Hopefully, the results of the complete reduction of this new data and our own balloon-borne measurements, scheduled for November 1973, will resolve this issue.

3. JUPITER

Jupiter is an unusual source of non-stellar infrared celestial background energy, because it radiates approximately 2.7 times more power than it receives from the sun (Aumann et al[13]). It also departs significantly from gray body behavior (Gillett et al[14]). The sole previous calculation of irradiance by Ramsey[2] took place before modern measurements of spectral dependence and brightness temperature were available. Consequently, Ramsey's calculations do not incorporate the considerable contribution to the irradiance from the internal energy source within the planet. An attempt is made here to correct this deficiency by using measured brightness temperatures.

Several independent measurements of Jupiter's brightness temperature have been made. In the 8 to 14 μm range, Murray et al[15] found the temperature of the center of the disk to be 128.5 ± 2°K while Moroz et al[12] quoted 128^{+5}_{-3} °K (± 2°K corresponds to approximately ± 20 percent in flux). Gillett et al[14] made a series of measurements over a six month period of the spectrum between 2.8 and 14 μm with a spectral resolution of 2 percent. They found that the shape of the spectral curve (Figure 2) in the 8 to 14 μm region remained relatively constant, however, there were significant changes in the measured brightness temperature requiring normalization factors that varied between 0.56 and 1.25 in order to substantiate a temperature of 125°K. There was no correlation between the normalization required and orbital position. Because of changing experimental conditions during the period of their observations, the authors were unable to determine whether their results provided evidence for temporal variation in the 8 to 14 μm region.

As is the case of the Venus measurements, there is, in general, a problem in differentiating between temporal variations in brightness temperature and statistical measurement errors. Hence, the question of time variability in the 8 to 14 μm brightness temperature remains unresolved. The fact that Jupiter has a large internal source of thermal energy suggests to us that temporal variability is likely. Lacking proof that this is the case, we assume no variability beyond that which may be contained in the statistical variation in the brightness temperature measurements of Murray et al[15].

On this basis, we have computed irradiance-values using the average disk brightness temperature (125°K) observed by Murray et al[15]. The wavelength

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13. Aumann, H.H., Gillespie, C.M., Jr., and Low, F.J. (1969) The internal powers and effective temperatures of jupiter and saturn, Ap. J. 157:L69-L72.
14. Gillett, F.C., Low, F.J., and Stein, W.A. (1969) The 2.8-14 micron spectrum of jupiter, Ap. J. 157:925-934.
15. Murray, B.C., Wildey, R.L., and Westphal, J.A. (1964) Observations of jupiter and the galilean satellites at 10 microns, Ap. J. 139:986-993.

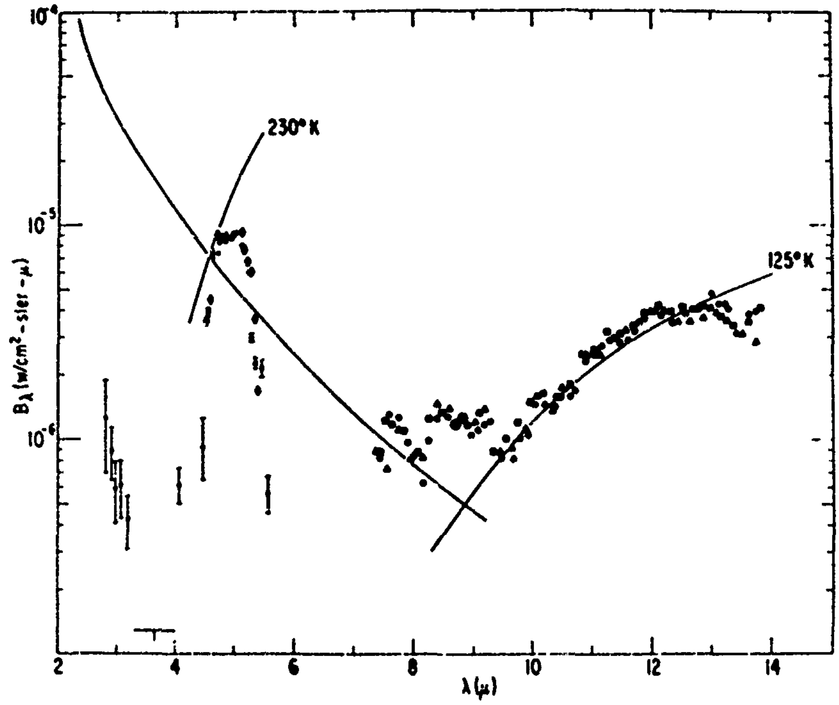

Figure 2. Monochromatic Surface Br ghtness of Jupiter From 2.8 to 14 μm. Symbols represent data taken at different times. Blackbody curves and a curve for absorption-free scattered sunlight are shown for comparison. (From Gillett et al, 1969).

dependence of the emission in the 8 to 14 μm region was taken from the spectrum recorded by Gillett et al[14] (see Figure 2). Specifically, blackbody behavior with a 125°K temperature was assumed between 9.5 and 13 μm. At 8, 9 and 14 μ, the departure from blackbody behavior necessitated the use of equivalent brightness temperatures of 139°K, 133°K and 115°K, respectively. The irradiance coefficients computed assuming a radius of 68.7×10^3 km[16] are shown in Table 3. Judging from the quoted error of Murray et al[15], these irradiance coefficients may be in error by ± 20 percent.

In view of the possible time variability of Jupiter's emission, it should be used as a calibration standard with care until more accurate measurements can be made. Initial measurements are planned for 1973 using the AFCRL balloon-borne telescope system, but an extended series of flights will be necessary in order to determine the range of any time variability.

Table 3. Jupiter Irradiance Coefficients*

8 μm	5.78×10^{-13}
9 μm	3.73×10^{-13}
10 μm	7.91×10^{-13}
11 μm	1.40×10^{-12}
12 μm	2.16×10^{-12}
13 μm	3.03×10^{-12}
14 μm	1.94×10^{-12}

* Irradiance calculation performed as described in Table II.

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2. Ramsey, R.C. (1962) Spectral irradiance from stars and planets, above the atmosphere, from 0.1 to 100.0 microns, Appl. Opt. 1:465-471.
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13. Aumann, H.H., Gillespie, C.M., Jr., and Low, F.J. (1969) The internal powers and effective temperatures of jupiter and saturn, Ap. J. 157:L69-L72.

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14. Gillet, F.C., Low, F.J., and Stein, W.A. (1969) The 2.8-14 micron spectrum of jupiter, Ap. J. 157:925-934.

15. Murray, B.C., Wildey, R.L., and Westphal, J.A. (1964) Observations of jupiter and the galilean satellites at 10 microns, Ap. J. 139:986-993.