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ONE-MILLIMETER BRIGHTNESS TEMPERATURES OF THE PLANETS

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ABSTRACT

New values for the 1 mm brightness temperatures of Mercury, Venus, Jupiter, Saturn, Uranus and Neptune have been determined using Mars as the absolute photometric standard.

I. INTRODUCTION

The temperatures of the planets at millimeter wavelengths are of interest both in defining the characteristics of the planets and because the planets often serve as calibration sources for astronomical observations. The most recently published measurements of planetary brightness temperatures in this spectral range are those of Loewenstein et al. (1977b) in the submillimter (λ = 410 μm) and those of Rather, Ulich, and Ade (1974) and Courtin et al. (1977) at 1.4 mm.

In this paper we present the results of a determination of the relative brightness at a wavelength of 1 mm of Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune. These relative measurements have been converted to absolute temperatures by the use of a thermal model for Mars. The thermal model has been checked by observations of Mars and Jupiter at two different epochs.

II. OBSERVATIONS AND RESULTS

The observations were made at the prime focus of the 5 m Hale telescope, using as the detector a liquid helium cooled composite bolometer. The beam full width at half intensity was 55", and scans of the planets showed the beam profile to be roughly Gaussian. Further details concerning the apparatus are provided by Elias et al. (1978).

Two different spectral bandpasses were used for the planetary measurements. Many of the data on the brighter planets were taken using a metal mesh interference filter centered at 1.0 mm with $\Delta\lambda/\lambda$ = 0.3.

When the filter was not used the spectral response was determined by absorption by water vapor in the earth's atmosphere and by diffraction; typically this produced a bandpass extending from 700 μm to 1.5 mm with an effective wavelength close to 1.0 mm (Elias *et al*. 1978).

A. Measurements in 1976 February

Most of the data presented here were taken during 1976 February, at which time all of the planets were at large enough angles from the Sun to be observed. The observing program was set up so that pairs of planets were measured at the same time and at the same air mass, so that it was possible to determine the relative 1 mm fluxes of the planets by applying only minimal atmospheric corrections.

For each air mass coincidence, the data consist of 3 to 6 measurements of the signal from each of a pair of planets at times within one hour of the air mass coincidence. A least-square fit of a function of the form $s(a) = s(a_o)e^{-k(a-a_o)}$ was made to the data for each planet and the parameters $s(a_o)$ and k were determined. Here $s(a)$ is the signal measured at air mass a, while a_o is the air mass of the coincidence. The ratio of the values of $s(a_o)$ for the two planets was taken as an estimate of the flux ratio; these ratios, the angular sizes of the planetary disks, and the air mass at coincidence for each set of data are given in Table 1. For Jupiter, Saturn, Uranus, and Neptune, the sizes given are the mean of the semi-major and semi-minor axes. All angular sizes were taken from the *American Ephemeris and Nautical Almanac*, except for Uranus and Neptune. For Uranus the

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mean disk radius is based on an equatorial radius of 25650 km and an oblateness of 0.02 as discussed by Gulkis, Janssen and Olsen (1977). For Neptune an equatorial radius of 24753 km and an oblateness of 0.026 (Freeman and Lynga 1970) were used.

On the basis of extensive measurements with this equipment, it is felt that systematic uncertainties limit the accuracy of each determination of a flux ratio to 5% of the mean. Therefore, an error is listed for the flux ratio in Table 1 only if the statistical uncertainty exceeds 5%.

B. Measurements of Mars and Jupiter in 1975

In 1975 May and June, Jupiter and Mars were in conjunction, and the flux ratio of Jupiter to Mars was measured on three days. On each day, several pairs of measurements were made at different airmasses. Since the planets were always in airmass coincidence, the data have been analyzed by computing a ratio for each pair of measurements and then computing an average ratio for each day. The results of these determinations are included in Table 1.

C. Determination of the Temperature of Venus

The disposition of the planets in 1976 February was such that Venus and Mercury rose after the other planets had set. Three measurements of Venus relative to Saturn and one of Venus relative to Jupiter were, however, obtained prior to 1976 Feburary; these data are also included in Table 1. In each case, the measurements were made at or close to an airmass coincidence, and the data were analyzed in a manner similar to that described above. It is assumed, on the basis of microwave observations, (Muhleman, private communication) that the

1 mm temperature of Venus is essentially independent of the phase of the planet.

III. ANALYSIS

A. Overview

The determination of the planetary temperatures from the data presented in Table 1 proceeded as follows. Mars served as the primary standard for the determination of the temperature of Jupiter; two measurements were made at times when the predicted temperatures of Mars differed by 20%, thus providing a check on the calibration. The temperature of Saturn was then derived (a) by an independent comparison with Mars, and (b) by using Jupiter as a secondary standard. Saturn was subsequently used as a secondary standard for the determination of the temperature of Uranus; finally, Neptune was measured relative to Uranus. The temperature of Venus was obtained from measurements of Venus relative to both Jupiter and Saturn. The temperature of Venus was then used as a reference to evaluate the temperature of Mercury.

B. Absolute Calibration

The mean ratios derived from the data presented in Table 1 were converted to absolute fluxes by using the thermal model of Kieffer *et al*. (1973) to compute the 1 mm flux from Mars, which was used as the primary photometric standard. This model, based on Mariner 9 results, gives the surface temperature as a function of the local time and latitude on Mars. It assumes a thermally homogeneous planet with a thermal inertia of 0.0065 cal cm^{-2} $s^{-1/2}$ K^{-1}, an albedo of 0.25 and an emissivity of 1.00 at 10 μm where the Mariner measurements were made. Recent data obtained from the Viking infrared thermal mapper are generally consistent with this model (Kieffer et al. 1977); local variations in the thermal properties of the surface should not introduce an uncertainty in the overall disk temperature of more than ± 5 K (Kieffer, private communication).

The emission at 1 mm was calculated from the surface temperatures of the thermal model assuming the emissivity at 1 mm to be 0.93 and that the intensity varies as $(\cos z)^{1.1}$; z is the angle between the local vertical and the observer. The choice of emissivity, which corresponds to a dielectric constant of 3.2, falls within the range deduced for the lunar surface (Gary, private communication). The calculated Martian disk temperature is directly proportional to the assumed emissivity; an uncertainty of ± 5% is probably a reasonable estimate of this uncertainty. The angular dependence of the emission at 1 mm is also uncertain; the dependence used is valid for 10 μm (Neugebauer et al. 1971). If the emission were assumed to go as cos z, the disk temperatures would be raised by ~ 10 K. No account was taken of the emission from layers beneath the surface of Mars. The electrical skin depth at a wavelength of 1 mm is on the order of 3 mm; the thermal model calculations indicate that at this depth temperatures are about 3 K colder than at the surface.

The Martian disk temperatures derived from the model vary with time due both to the eccentricity of the Martian orbit and to variations of the Sun-Mars-Earth angle. In particular, the model gave a value of 227 K for the disk-averaged 1 mm brightness temperature of Mars in 1976 February and 1975 May/June. This calibration procedure is similar to that described by Wright (1976).

C. Temperature Determination

The flux ratios have been used to compute brightness temperatures under the assumption that each planet is uniformly bright over the solid angle of its disk. This assumption neglects effects such as limb darkening and emission from Saturn's rings, which are discussed below.

The ratio of the measured fluxes is related to the planetary temperatures by:

$$\frac{\text{Flux(Planet 1)}}{\text{Flux(Planet 2)}} = \frac{C_1 B(1\ \text{mm}, T_1)\Omega_1}{C_2 B(1\ \text{mm}, T_2)\Omega_2} \qquad (1)$$

where T_i is the disk brightness temperature of planet i, $B(1\ \text{mm},\ T_i)$ is the Planck function, Ω_i is the disk solid angle for planet i, and C_i is a correction factor, less than unity, due to resolution of the disk by the telescope beam. For 1976 February, C_i was 0.88 for Jupiter and greater than 0.96 for the other planets. The ratio of surface brightnesses, $B(1\ \text{mm},\ T_1)/B(1\ \text{mm},\ T_2)$, as derived from the measured flux ratio is given in Table 1; from this ratio the temperature of one of the planets can be obtained if the temperature of the other is known. The data of Table 1 shows that within the uncertainties the flux ratios measured with the filter were the same as those measured without the filter. Hence all observations were grouped together for analysis and referred to an effective wavelength of 1.0 mm. The mean ratios $< B(1\ \mathrm{mm}, T_1)/B(1\ \mathrm{mm}, T_2) >$ and the resultant planetary temperatures are summarized in Table 2.

In computing temperatures in this way it is assumed that each planetary spectrum can be approximated by a single blackbody curve, and that both spectra have the same shape over the band pass of the experiment. These assumptions are supported by the agreement of the broad and narrow band flux ratios and by the fact that even for the lowest temperature (~ 80 K) encountered in this study a blackbody curve does not deviate by more than 5% from a Rayleigh-Jeans slope over the band pass. In order to obtain the temperatures of Venus and Mercury it was also necessary to assume that the temperatures of Saturn, Jupiter and Venus remained constant between 1974 April and 1976 February.

IV. RESULTS AND DISCUSSION

The final results for the mean planetary disk temperatures are given in Table 3. The uncertainties quoted in Table 3 largely reflect the possible systematic uncertainties; the statistical uncertainties are dominant only for determination of the temperatures of Neptune and Uranus. There is an additional systematic uncertainty of ~ 10% in all the temperatures due to the uncertainties in the Martian thermal model and its application to millimeter wavelengths.

Confidence in the results of this work can be derived from the agreement between the independent determinations of the temperatures of Jupiter, Saturn, and Venus. In particular, it can be seen from

Table 2 that independent determinations of the Jupiter and Saturn temperatures are internally self-consistent within $< 5\%$ and that measurements at times when the thermal model predicts extreme values for the temperature of Mars give consistent results for the temperature of Jupiter. Similarly, the separate determinations of the temperature of Venus by measurements relative to both Saturn and Jupiter give values which are in very good agreement.

Comparison of the present results with those of Loewenstein _et al_. (1977b) suggests that for Venus, Jupiter, and Uranus the brightness temperatures are higher at 1 mm than at 410 μm, this would be expected if the planetary atmospheric opacity is decreasing with increasing wavelength over this interval. The present results for Jupiter and Uranus are consistent with the brightness temperatures measured at 1.4 mm by Courtin _et al_. (1977), but significantly lower temperatures are obtained in the present experiment for both Saturn and Neptune.

The results given in Table 3 differ slightly from the preliminary values quoted by Elias _et al_. (1978) and used by them for the determination of the 1 mm fluxes of a number of extragalactic objects. The present values are to be preferred and will be used subsequently for calibration. Neither the numerical results nor the scientific conclusion of the earlier paper are affected significantly by the change in calibration.

V. COMMENTS ON INDIVIDUAL PLANETS

A. Mercury

The present result refers to 1976 February, at which epoch 0.60 of the planetary disk was illuminated. Studies of the thermal properties of Mercury have shown that the thermal inertia of the surface is on the order of 0.002 cal cm^{-2} $s^{-1/2}$ K^{-1} (Murdock and Ney 1970; Chase et al. 1974). For this value of the inertia and an albedo of 0.07, thermal model calculations predict a millimeter disk temperature of 313 K for 1976 February; the 1 mm emission characteristics of the surface were assumed to be the same as used in deriving the Martian disk temperatures. The agreement of the predicted temperature with the result given in Table 3 is probably fortuitous in view of the variations of the thermal properties with location on Mercury reported by Chase *et al.* and of uncertainties in the application of the model to 1 mm wavelength.

B. Jupiter

Since Jupiter is partially resolved by the beam of this experiment, the measured temperature of 168 K may, because of the effects of limb darkening, be slightly higher than the effective disk temperature which would be measured with a large beam. A limb-darkened model by Gulkis, Klein, and Olsen (1977) predicts a central disk temperature of 173 K and a mean disk temperature of 164 K for Jupiter at 1 mm. If this model is convolved with the beam of the present experiment, taking the angular size of Jupiter as of 1976 February, the predicted flux is within a few percent of what is actually measured.

and Muhleman, private communication). It is seen from Tables 3 and 4 that if this holds at 1 mm the flux from the ring system is very small at this wavelength.

D. Uranus

The brightness temperature of Uranus, 87 ± 7 K, is in good agreement with the predictions of the cool Palluconi model for Uranus discussed by Gulkis, Janssen, and Olsen (1977).

E. Neptune

The present results show that at 1 mm the brightness temperature of Neptune (96 ± 10 K) is very close to that of Uranus. These two planets also have similar temperatures in the far infrared (Loewenstein, Harper, and Moseley, 1977a; Fazio et al. 1976), but differ dramatically in their near infrared properties (Gillett and Rieke, 1977). The temperature measured at 1 mm is significantly less than that (153 ± 30 K) measured by Courtin et al. (1977) at 1.4 mm.

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TABLE 1

LOG OF OBSERVATIONS

PLANET 1	PLANET 2	DATE UT	AIR MASS	FILTER*	MEAN SEMIDIAMETER Planet 1 (")	MEAN SEMIDIAMETER Planet 2 (")	FLUX (PLANET 1) / FLUX (PLANET 2)†	B(1)/B(2)**,†
Jupiter	Mars	1975 May 27	1.2	B	17.14	3.01	23.2	0.81
	(T = 227 K)	1975 Jun 24	1.2	B	18.36	3.31	20.1	0.74
		1975 Jun 24	1.2	N	18.36	3.31	18.4	0.68
		1975 Jun 25	1.2	B	18.40	3.32	19.5	0.72
Jupiter	Mars	1976 Feb 17	1.2	B	17.40	4.79	10.5	0.89
	(T = 191 K)	1976 Feb 17	1.2	N	17.40	4.79	9.3	0.79
		1976 Feb 19	1.2	B	17.32	4.70	10.6	0.88
		1976 Feb 19	1.2	N	17.32	4.70	10.6	0.88
Saturn	Mars	1976 Feb 18	1.1	B	9.61	4.74	3.00	0.75
	(T = 191 K)	1976 Feb 18	1.1	N	9.61	4.74	3.16	0.79
		1976 Feb 19	1.1	B	9.60	4.70	3.12	0.77
		1976 Feb 19	1.1	N	9.60	4.70	2.97	0.73
		1976 Feb 20	1.1	B	9.59	4.65	2.91	0.71
		1976 Feb 20	1.1	N	9.59	4.65	3.38	0.82
Jupiter	Saturn	1976 Feb 18	1.5	B	17.36	9.61	3.49	1.17
		1976 Feb 18	1.5	N	17.36	9.61	3.52	1.18
		1976 Feb 19	1.5	B	17.32	9.60	3.53	1.18
		1976 Feb 19	1.5	N	17.32	9.60	3.67	1.23
Saturn	Uranus	1976 Feb 18	1.8	B	9.61	1.93	34 ± 6	1.45 ± 0.3
		1976 Feb 19	1.8	B	9.60	1.93	38 ± 4	1.6 ± 0.2
		1976 Feb 20	1.8	B	9.59	1.93	47 ± 4	2.0 ± 0.2
		1976 Feb 20	1.8	N	9.59	1.93	41 ± 13	1.7 ± 0.6
Uranus	Neptune	1976 Feb 19	1.8	B	1.93	1.11	3.1 ± 1.2	1.0 ± 0.4
		1976 Feb 20	1.8	B	1.93	1.11	2.8 ± 0.4	0.9 ± 0.1
Venus	Saturn	1975 Dec 17	1.6	B	8.56	9.55	1.55	1.93
		1976 Jan 18	2.2	B	7.04	9.76	1.06	2.04
		1976 Jan 18	2.2	N	7.04	9.76	0.98	1.88
Jupiter	Venus	1974 Apr 4	1.4	B	16.49	12.35	1.01	0.60
Venus	Mercury	1976 Feb 18	4.2	B	6.12	3.33	2.6 ± 0.2	0.77 ± 0.07
		1976 Feb 19	4.2	B	6.09	3.29	3.29	0.96
		1976 Feb 19	4.2	N	6.09	3.29	2.8 ± 0.8	0.8 ± 0.2
		1976 Feb 20	4.2	B	6.07	3.25	2.72	0.78
		1976 Feb 20	4.2	N	6.07	3.25	3.1 ± 0.8	0.9 ± 0.2

* B = broad band 0.7 - 1.5 mm (see text).
N = narrow band 0.8 - 1.1 mm.

† If no error is quoted, the statistical uncertainty is less than 5% which is taken as the systematic uncertainty in the measurements.

** The ratio of the surface brightness of Planet 1 to that of Planet 2. See text.

TABLE 2

SUMMARY OF OBSERVATIONS

PLANET 1	PLANET 2	$\frac{B(1)}{B(2)}$[+]	PLANET[†]	DERIVED TEMPERATURE (K)
Jupiter	Mars[*]	0.74	Jupiter	170
Jupiter	Mars[**]	0.86		166
Saturn	Mars[**]	0.76	Saturn	148
Jupiter	Saturn	1.19		142
Saturn	Uranus	1.74 ± 0.15	Uranus	87 ± 7
Uranus	Neptune	0.91 ± 0.10	Neptune	96 ± 10
Jupiter	Venus	0.60	Venus	275
Venus	Saturn	1.95		277
Venus	Mercury	0.86	Mercury	320

[†] Planet whose temperature is to be determined.

[*] T = 227 K

[**] T = 191 K

[+] The ratio of the surface brightness of Planet 1 to that of Planet 2. See text. An error is quoted only when the statistical uncertainty exceeds 5%.

TABLE 3

FINAL TEMPERATURES

PLANET	(K)
Mercury*	320 ± 16
Venus	276 ± 14
Saturn	145 ± 7
Jupiter	168 ± 8
Uranus	87 ± 7
Neptune	96 ± 10

* Temperature determined in 1976 February when 0.60 of the disk was illuminated.

TABLE 4

SATURN DISK TEMPERATURE FOR
DIFFERENT VALUES OF RING EMISSIVITY

DISK BRIGHTNESS TEMPERATURE	1 mm EMISSIVITY OF RINGS
160	0.00
147	0.15
139	0.25
133	0.33
118	0.50

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