THE ASTROPHYSICAL JOURNAL, 210:250–253, 1976 November 15

RECALIBRATION OF THE FAR-INFRARED BRIGHTNESS TEMPERATURES OF THE PLANETS

EDWARD L. WRIGHT*

Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory

Received 1976 February 16; revised 1976 May 3

ABSTRACT

The far-infrared planetary brightness temperatures of Armstrong, Harper, and Low are recalibrated to allow for the varying temperature of Mars, using the thermal model of Neugebauer *et al.* The revised 30–300 μ brightness temperatures are: Jupiter, 127 ± 3 K; Saturn, 85 ± 2 K; and Venus, 240 ± 8 K. The Jupiter value agrees with the *Pioneer 10* and *Pioneer 11* radiometer experiment. A table of Mars brightness temperatures until 1978 October is given.

Subject headings: infrared: spectra — planets: atmospheres

I. INTRODUCTION

Aumann, Gillespie, and Low (1969, hereafter AGL) performed an absolute calibration of Mars, and obtained an effective temperature of 234 ± 7 K. Armstrong, Harper, and Low (1972, hereafter AHL) then used 235 K for the brightness temperature of Mars to calibrate their measurements of planetary brightness temperatures. However, Mars is in an elliptical orbit, and its distance from the Sun varies by almost 20 percent. Furthermore, the phase of Mars viewed from Earth can vary through ±45°. This corresponds to sub-Earth points with Martian solar times ranging from 9 A.M. to 3 P.M. The distance from the Sun and the apparent phase can each change the brightness temperature of Mars by over 20 K, so the total range of brightness temperatures is 45 K.

To predict the brightness temperature of Mars, I need a model of the thermal behavior of the surface. Such a model is provided by Neugebauer *et al.* (1971). This model has parameters adjusted to fit the 10 μ and 20 μ radiometer observations from *Mariner 6* and *Mariner 7*. Becklin *et al.* (1973) used this model to refine the stellar 10 μ and 20 μ calibrations, while Sutton, Becklin, and Neugebauer (1974) used the model to calibrate 34 μ observations. The model predicts brightness temperatures ranging from 202 K to 246 K at 65 μ. In this paper I will use the Neugebauer *et al.* model to recalibrate the AHL planetary brightness temperatures, and give a convenient table to aid the calibration of other far-infrared experiments.

II. THE THERMAL MODEL

The parameters necessary to describe a homogeneous surface interacting with radiation are the thermal conductivity K, the specific heat c, the density ρ, the bolometric Bond albedo A, and the emissivity ϵ. K, ρ, and c affect the surface temperature only through the combination $I = (K\rho c)^{1/2}$. Neugebauer *et al.* use the values $I = 0.006$ cal cm^{-2} s$^{-1/2}$ K^{-1}, $A = 0.29$, and $\epsilon = 0.90 (\cos\theta)^{0.10}$, where θ is the angle between the line of sight and the surface normal. In addition, a constant heat input from the atmosphere of 0.01 times the local noon insolation is assumed. For a given Martian latitude, the insolation is determined from the Mars-Sun distance and the Martian declination of the Sun, D_S. Given the periodic insolation, I have used the method of Jaeger (1953) to find the daily variation of the surface temperature. Where Jaeger used 20 longitudes, I have used 32. The calculation is repeated for six different Martian latitudes, chosen to allow six-point Gaussian integration over latitude. Finally, the flux at the Earth is computed for various wavelengths, and converted to whole disk brightness temperatures. Four geometric parameters must be taken from the ephemeris: the Mars-Sun distance; the Martian declinations of the Sun and Earth, D_S and D_E; and the difference in Martian right ascensions between the Earth and the Sun, $A_E - A_S$.

I have investigated the effect of the finite latitude and longitude steps by running models with a finer integration mesh, and I found that the computed values were altered by less than 1 K. So the computations accurately reflect the model, but the model is clearly an oversimplification of the true Martian situation. Variations in albedo and topography will change the temperature distribution, and introduce daily modulation of the Martian flux. Traub (1975, private communication) has computed the transmission of the Martian atmosphere to a surface at 6 mb pressure, and finds 85–95 percent mean transmission in the 30–300 μ region. But the absorbed parts of the Martian spectrum would be blocked by terrestrial water vapor lines for observations made from airplanes, such as AHL, so I have ignored the atmospheric absorption.

The polar caps of Mars obviously do not follow the thermal model. The largest perturbation of the total infrared flux from Mars occurs when the visible cap starts its rapid retreat. At this time the thermal model predicts a temperature well above the actual temperature of the cap, while the visible area of the cap is still large. If one uses 150 K as the polar cap temperature,

---

[*] Junior Fellow, Harvard University Society of Fellows.

TABLE 1

BRIGHTNESS TEMPERATURE OF MARS, $T_{♂}$(K)

Date	10 μ	20 μ	34 μ	65 μ	100 μ	150μ
1968 Dec. 2......	243	235	229	223	219	217
1971 Feb. 15.....	246	236	229	223	219	217
1971 Sept. 15.....	256	245	237	229	226	223
1971 Oct. 15......	252	238	230	222	219	216
1972 Mar. 15.....	237	227	220	213	210	207

and the observed extent compiled by Murray and Malin (1973), the maximum perturbation is less than 5 percent of the infrared flux at any wavelength. I have not included this correction in the model calculations.

In Table 1 I give brightness temperatures versus wavelength for the dates of the AHL and AGL observations. The effective temperature of the model for 1968 December 2 is 240 K, in agreement with the observed 234 ± 7 K. Thus the *Mariner 6* and *Mariner 7* calibration and the AGL calibration are consistent.

A further check is given by comparison with the model and observation of Logan, Balsamo, and Hunt (1973). For 1971 April 4, they calculate 259 K for the 10.5–12.5 μ brightness temperature, using the values $I = 0.00545$, albedo = 0.10, and emissivity = 0.85. If these parameters are adopted my computer program gives 258.75 K for the predicted brightness temperature at 11.5 μ. Thus the computer codes agree very well. Using a balloon-borne telescope at 32 km altitude, Logan *et al.* made an absolute determination of 254 ± 4 K as the Martian brightness temperature, while the Neugebauer *et al.* model used in this paper predicts 247 K.

Finally, on 1974 May 14 I observed Mars at 10.6–12.6 μ using the KPNO 1.3 m telescope and the MIT big-beam infrared photometer. Using the stellar calibration of Gehrz, Hackwell, and Jones (1974), I obtained an 11.6 μ flux of $(43.5 \pm 4) \times 10^3$ Jy, or a brightness temperature of 230 ± 4 K. The model predicts 230 K, giving perfect agreement.

Thus the Neugebauer *et al.* model gives good agreement with four independent calibrations of Mars at 10–20 μ. Furthermore, the *Mariner 9* results taken after the dust storm confirm the *Mariner 6* and *Mariner 7* model (Kieffer *et al.* 1973). From the scatter in the observed minus predicted brightness temperatures for the four calibrations, the uncertainty in the predicted whole disk 10–20 μ brightness temperature is ±3 K (1 σ of the mean), which could be caused by variations of ±0.03 in the albedo. Unfortunately the far-infrared emissivity, which has very little effect on the 10–20 μ flux, is not well determined. The infrared spectrometer on *Mariner 9* showed an almost constant emissivity, but only for $\lambda < 50\ \mu$ (Curran *et al.* 1973). For $\lambda > 50\ \mu$, the flux could be between 0 to 1.1 times the predicted flux, even if the model surface temperatures are correct. However, emissivity variations larger than +5 percent or −10 percent are unlikely. Allowing a ±5 percent uncertainty in the far-infrared emissivity implies a ±10 K uncertainty in the far-infrared temperatures given by the model.

Dyck and Simon (1975) calibrated 33 μ measurements using a Martian brightness temperature of 218 K on 1974 February 14/15. This temperature is given by a model with $A = 0.29$, $I = 0.006$, and $\epsilon = 1.0$. The lower emissivity used in this paper gives a 33 μ brightness temperature of 214 K, or a 4 percent lower flux. The 27 percent flux increase proposed by Hagen, Simon, and Dyck (1975) requires a 33 μ brightness temperature of 243 K, which is not consistent with any reasonable thermal model of Mars. Extreme emissivity variations are necessary to reconcile the Hagen *et al.* 33 μ flux scale with the *Mariner* thermal model of Mars: for example, $\epsilon(10\ \mu) = 0.55$, $\epsilon(20\ \mu) = 0.72$, and $\epsilon(33\ \mu) = 1.0$ will give the same 10 and 20 μ fluxes as the *Mariner* model, and also give the Hagen *et al.* 33 μ flux. But the Hagen *et al.* recalibration is based on unpublished data, so I have no basis for comparing their observations with the Martian thermal model.

(*Note added 1976 July 7.*—The radiometric emissivity used in calculating the model surface temperatures for this paper was 0.9/1.1, while the self-consistent value is 0.9/1.05. As a result, the brightness temperatures are 2 or 3 K higher than the Neugebauer *et al.* model, but the comparison with the observations of Logan *et al.*, AGL, and this paper is not affected.)

III. RECALIBRATION OF THE AHL WIDEBAND TEMPERATURES

AHL give two types of data. The first data are ratios of planetary surface brightnesses in two broad far-infrared filters: 30–300 μ and 45–300 μ. These have been converted to brightness temperatures by solving the following equation for T_p:

$$\frac{\int W_\nu B_\nu(T_p)d\nu}{\int W_\nu B_\nu(235)d\nu} = \frac{S_p/\Omega_p}{S_{♂}/\Omega_{♂}},$$

where S_p and $S_{♂}$ are the observed signals from a planet and Mars, Ω_p and $\Omega_{♂}$ are the respective solid angles, and W_ν is the wide-band filter transmission curve. To recalibrate the derived T_p, I replace the 235 K above by the $T_{♂}$ computed from the model. The calibrated T_p' is given by

$$\frac{\int W_\nu B_\nu(T_p')d\nu}{\int W_\nu B_\nu(T_p)d\nu} = \frac{\int W_\nu B_\nu(T_{♂})d\nu}{\int W_\nu B_\nu(235)d\nu} = F.$$

The correction factor F depends only on the date of observation, and is tabulated in Table 2 for the AHL observation dates. I have taken the middle of the month for all observations made in a given month. The recalibrated T_p' is given for all the AHL data in Table 3, which is a revision of AHL's Table 1. The average temperatures are weighted means, but the uncertainties include a ±5 percent uncertainty in the Martian flux. The uncertainties in Tables 4 and 5 are treated similarly.

The Saturn temperatures are given for the area of the disk plus rings. The AGL effective temperature of

Saturn was given for the area of the disk alone. For the disk plus rings, the AGL result is $T_e = 90 \pm 4$ K.

TABLE 2

Flux Correction Factor F

Date	30–300 μ	45–300 μ
1971 Feb. 15........	0.9374	0.9193
1971 Sept. 15........	0.9974	0.9640
1971 Oct. 15.........	0.9415	0.9190
1972 Mar. 15........	0.8601	0.8565

IV. RECALIBRATION OF THE MEDIUM-BAND TEMPERATURES

The AHL medium-band temperatures were not determined by directly observing the signal ratio between a planet and Mars in a narrow filter. Instead, the ratio of medium-band to wide-band signal was measured for each planet, then compared with the similar ratio for Mars. Medium-band brightness temperatures, T_n, were then calculated from the double ratio

$$\frac{\int N_\nu B_\nu(T_n)d\nu \int W_\nu B_\nu(235)d\nu}{\int W_\nu B_\nu(T_p)d\nu \int N_\nu B_\nu(235)d\nu} = \left(\frac{S_n}{S_w}\right)_p \left(\frac{S_w}{S_n}\right)_{\male},$$

where N_ν is the medium-band filter transmission curve, and S_n and S_w are the signals in the medium and wide filters. To obtain a recalibrated medium-band temperature, T_n', I replace T_p by the recalibrated T_p', and 235 K by $T_{\male}$ for the date of the medium-band observations: 1972 March. It happens, however, that the color temperature of Mars in 1972 March was very close to 235 K, even though the brightness temperature was much less. In fact, the correction factor given by

$$G = \frac{\int W_\nu B_\nu(235)d\nu \int N_\nu B_\nu(T_{\male})d\nu}{\int N_\nu B_\nu(235)d\nu \int W_\nu B_\nu(T_{\male})d\nu}$$

ranges from 0.998 for the 30–45 μ filter to 1.006 for the 125–300 μ filter of AHL. Thus the major effect comes from replacing T_p by T_p'. The recalibrated medium-band brightness temperatures are given in Table 4, which is a revision of AHL's Table 2.

TABLE 3

Recalibrated Wide-Band Brightness Temperatures, T_p'(K)

Planet	Date	30–300 μ	45–300 μ
Jupiter........	1971 Feb.	133 ± 3	...
	1971 Sept.	132 ± 2	130 ± 3
	1972 Mar.	126 ± 1	130 ± 4
	Average	127 ± 3	130 ± 4
Saturn........	1971 Feb.	77 ± 4	...
	1971 Oct.	87 ± 1	94 ± 3
	1972 Mar.	...	86 ± 1
		86 ± 1	86 ± 1
		82 ± 1	85 ± 1
	Average	85 ± 2	86 ± 2
Venus........	1971 Feb.	245 ± 1	...
	1972 Mar.	235 ± 1	240 ± 5
	Average	240 ± 8	240 ± 9

TABLE 4

Recalibrated Medium-Band Brightness Temperatures, T_n'(K)

Planet	30–45 μ	45–80 μ	65–110 μ	125–300 μ
Jupiter.....	131 ± 2	142 ± 6	144 ± 8	138*
Saturn.....	87 ± 4	90 ± 2	92 ± 5	86 ± 4
Venus.....	247 ± 7	256 ± 8	267 ± 20	256 ± 45

* This is a recalibration of AHL's *assumed* value of 150 K.

V. RECONCILIATION OF THE MEDIUM-BAND AND WIDE-BAND TEMPERATURES

In AHL, every medium-band temperature for every planet is higher than the weighted mean wide-band temperature for that planet. This indicates that there is a systematic error in the medium-band temperatures, even though the double ratio technique should eliminate such a bias. I have computed reconciled medium-band temperatures by requiring that the flux ratios between the medium-band filters be preserved for each planet, while the overall flux scale is shifted down to agree with the wide-band temperatures. That is, I find T_n'' such that

$$\frac{\int N_\nu B_\nu(T_n'')d\nu}{\int N_\nu B_\nu(T_n')d\nu} = K$$

where, for a given planet, the correction factor K is the same for all four medium-band filters, and

$$\int W_\nu B_\nu(T_n'')d\nu = \int W_\nu B_\nu(T_p')d\nu .$$

Since T_n'' is a function of ν, I do the integrals by linearly interpolating T versus ν between the filter centers. The resulting reconciled medium-band temperatures are given in Table 5. This is only one of many possible ways of reconciling the AHL data, so the values in Table 5 are only indicative of possible far-infrared planetary spectra. In particular, the 125–300 μ temperatures are based on the AHL assumption of 150 K for Jupiter. When this assumption is propagated through the analysis in this paper, it gives an unreasonably low value. If I use the Jovian model of Orton (1975) to give a 125–300 μ temperature of 133 K for Jupiter in Table 5, then the 125–300 μ temperature

TABLE 5

Reconciled Medium-Band Brightness Temperatures, T_n''(K)

Planet	30–45 μ	45–80 μ	65–110 μ	125–300 μ
Jupiter.....	124 ± 2	133 ± 6	133 ± 8	121*
Saturn.....	84 ± 4	85 ± 2	89 ± 5	79 ± 4
Venus.....	238 ± 7	238 ± 8	259 ± 20	240 ± 45

* Based on AHL's *assumed* value of 150 K.

1976ApJ...210..250W

TABLE 6

Calculated Brightness Temperature of Mars, $T_{♂}$(K)

Julian Day (2,440,000.5+)	10 μ	20 μ	34 μ	65 μ	100 μ	150 μ	250 μ	350 μ
2760........	249	241	234	227	224	221	219	218
2800........	237	226	219	212	208	206	204	203
2840........	229	218	210	203	200	197	195	194
2880........	229	217	210	203	199	196	194	193
2920........	231	221	213	206	203	200	198	197
2960........	235	225	218	212	208	206	203	202
3000........	240	230	224	217	213	211	208	207
3040........	244	235	229	222	219	216	214	213
3080........	249	241	234	227	224	221	219	218
3120........	254	246	239	232	229	226	224	223
3160........	260	251	245	238	234	232	229	228
3200........	265	257	250	243	240	237	235	234
3240........	269	260	253	246	242	240	238	237
3280........	269	259	253	245	242	239	237	236
3320........	265	255	248	241	237	234	232	231
3360........	258	248	241	233	229	227	224	223
3400........	252	242	235	228	224	221	219	218
3440........	248	239	232	225	222	219	217	216
3480........	246	238	232	225	222	219	217	216
3520........	245	237	231	224	220	218	216	215
3560........	235	225	218	211	208	205	203	202
3600........	230	219	211	204	200	198	195	194
3640........	230	219	212	205	202	199	197	196
3680........	234	223	216	209	206	203	201	200
3720........	238	228	221	214	211	208	206	205
3760........	243	234	227	220	217	214	212	211
3800........	249	240	233	226	222	220	218	217

of Saturn becomes 86 K, and that of Venus becomes 268 K.

VI. TABLE OF MODEL BRIGHTNESS TEMPERATURES

The Martian thermal model depends on four geometric parameters, but all of these are easily predicted. For the convenience of other far-infrared experimenters, Table 6 gives the predicted brightness temperature of Mars every 40 days from 1975 December 14 to 1978 October 19. The temperature changes most rapidly at opposition as the sub-Earth point moves rapidly from the afternoon to the morning side of Mars. The thermal model does not apply to dust storm conditions, so the temperatures should not be used during a large dust storm.

VII. DISCUSSION

Jupiter has been observed by *Pioneer 10* and *Pioneer 11*, and Ingersoll *et al.* (1975) used the infrared radiometer data to derive an effective temperature of 125 ± 3 K. The close agreement between this value and the recalibrated AHL 30–300 μ value is very encouraging. The predicted Martian brightness temperatures should help to establish a consistent set of far-infrared flux standards, which is necessary for the understanding of the thermal emission of the outer planets and galactic H II regions.

For Saturn, the recalibrated 30–300 μ temperature of 85 ± 2 K is close to the effective temperature. Using the AGL albedo of $A = 0.45(+0.12, -0.06)$, I find that Saturn radiates $1.44(+0.44, -0.20)$ times as much energy as it receives from the Sun, but this conclusion depends critically on the assumption of equal ring and disk brightnesses. Rieke (1975) has measured the brightness of the disk and rings between 12 and 34 μ, and finds significant differences between the *A* and *B* rings. Rieke's measurement of a 33.5 μ total disk-plus-rings brightness temperature of 88 ± 2 K is consistent with both the original AHL 30–45 μ value and the recalibrated and reconciled values. By subtracting an extrapolation of his observed ring brightness from the original AHL data, Rieke obtains a large internal heat source for Saturn. But this procedure subtracts two large numbers to get a small result; and by revising the AHL total fluxes downward, my recalibration causes a large reduction in Saturn's internal heat source. If Rieke's extrapolation of the ring brightness is correct, then the total flux is consistent with a vanishing internal heat source. However, Rieke's measured disk brightnesses indicate that Saturn radiates 0.8 ± 0.2 of the absorbed solar flux in the band $10\,\mu < \lambda < 40\,\mu$, so some internal heat source is very likely.

REFERENCES

Armstrong, K., Harper, D. A. Jr., and Low, F. J. 1972, *Ap. J.* (*Letters*), **178**, L89.

Aumann, H. H., Gillespie, C. M. Jr., and Low, F. J. 1969, *Ap. J.* (*Letters*), **157**, L69.

Becklin, E. E., Hansen, O., Kieffer, H., and Neugebauer, G. 1973, *A.J.*, **78**, 1063.

Curran, R. J., Conrath, B. J., Hanel, R. A., Kunde, V. G., and Pearl, J. C. 1973, *Science*, **182**, 381.

Dyck, H. M., and Simon, T. 1975, *Ap. J.*, **195**, 689.

Gehrz, R. D., Hackwell, J. A., and Jones, T. W. 1974, *Ap. J.*, **191**, 675.

Hagen, W., Simon, T., and Dyck, H. M. 1975, *Ap. J.* (*Letters*), **201**, L81.

Ingersoll, A. P., Münch, G., Neugebauer, G., Diner, D. J., Orton, G. S., Schupler, B., Schroeder, M., Chase, S. C., Ruiz, R. D., and Trafton, L. M. 1975, *Science*, **188**, 472.

Jaeger, J. C. 1953, *Proc. Cambridge Phil. Soc.*, **49**, 355.

Kieffer, H. H., Chase, S. C. Jr., Miner, E., Münch, G., and Neugebauer, G. 1973, *J. Geophys. Res.*, **78**, 4291.

Logan, L. M., Balsamo, S. R., and Hunt, G. R. 1973, *Icarus*, **18**, 451.

Murray, B. C., and Malin, M. C. 1973, *Science*, **182**, 437.

Neugebauer, G., Münch, G., Kieffer, H., Chase, S. C. Jr., and Miner, E. 1971, *A.J.*, **76**, 719.

Orton, G. S. 1975, *Icarus*, **26**, 125.

Rieke, G. H. 1975, *Icarus*, **26**, 37.

Sutton, E., Becklin, E. E., and Neugebauer, G. 1974, *Ap. J.* (*Letters*), **190**, L69.

Edward L. Wright: Physics Department, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139