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VARIATIONS IN THE INFRARED BRIGHTNESS TEMPERATURE OF SATURN'S RINGS

The rings of Saturn were first detected in the thermal infrared by Allen and Murdock (1971). They determined $T_B = 83 \pm 3$ K at 12 μm in late 1969. Before that time the rings were thought to be very cold due to their apparently high albedos. Low had set an upper limit of $T_B = 60$ K at 20 μm in 1965 (Low, 1966). Six years later, Murphy, Cruikshank, and Morrison (1972) reported still higher temperatures at 11 μm and 20 μm, and they suggested that the ring temperature may be varying with the Saturnocentric declination of the Sun, B'. This hypothesis was apparently confirmed by Murphy in 1972, when he measured the 20 μm brightness temperatures of the A, B, and C rings, finding $T_B = 94 \pm 2$ K for the B ring (Murphy, 1973). Additional data were provided by the independent observations of Morrison (1974), who found $T_B = 96 \pm 3$ K at 20 μm and $T_B = 90 \pm 3$ K at 11 μm.

Thus, it appears that the brightness temperature of the rings does vary with time. Before the observed temperatures may be compared with any model predictions, some adjustments must be made. When the adjustments have been made, the evidence for variations in T_B with B' are less pronounced but still apparently real. The observed variations appear to contradict the hypothesis that the rings consist of a multilayer assemblage of particles which are small compared to the thickness of the rings.

SUMMARY OF BRIGHTNESS TEMPERATURES AND ADJUSTMENTS TO THE DATA

The first attempt to measure the infrared brightness temperature was made by Low in 1964. He found $T_B < 80$ K at 10 μm at a time when $B' \sim +9°$ (Low, 1965). This upper limit, seemingly of little consequence at that time, severely constrains any model since it lies in a critical range of B' not covered by more recent data. The measurement was made at a time when Saturn was 9.8 A.U. from the Sun.

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To compare to the 1972 data when Saturn was 9.0 A.U. from the Sun, we increase the observed upper limit by the factor $(9.8/9.0)^{1/2} = 1.04$.

Next, we adjust for the difference between the brightness temperature of the entire ansa and that for the B ring alone. Murphy (1973) found $T_B = 89 \pm 3$ K for the A ring and $T_B = 94 \pm 2$ K for the B ring. From these data we estimate a +2 K correction is needed to relate Low's measurement of the ansa to the later measurements of the B ring alone. We note that the difference in the brightness temperatures of the ring components may be a function of the volume density of the rings and of the Sun's declination B', and the 2 K correction may be valid only near $B' = 26°$ as when Murphy's measurements were made. The original observational upper limit to the brightness temperature is listed in table I, and the adjusted B ring brightness temperature is listed in table II and plotted in figure 1.

In 1965 Low set an upper limit to the brightness temperature at 20 μm of

TABLE 1.—*Infrared brightness temperatures of Saturn's rings.*

Observation year	Observers	λ, μm	Position	T, °K
1964	Low	10	Ansa	< 80
1965	Low	20	Ansa	< 60
1969	Allen & Murdock	12	Ansa	83 ± 3
1971	Murphy et al.	20	Peak at ansa	89 ± 3
1972	Murphy	20	B ring at ansa	94 ± 2
1972	Murphy	20	A ring at ansa	89 ± 3
1973	Morrison	11	B ring at ansa	90 ± 3 [1]
1973	Morrison	20	B ring at ansa	96 ± 3 [1]
1973	Nolt et al.	35	Ansa	90–95

[1] Temperature Difference $T_{20} - T_{11}$ accurate to ±2° K.

TABLE II.—*Adjusted B-ring brightness temperatures.*

Observation year	Observers	λ, μm	T, °K
1964	Low	10	85
1965	Low	20	64
1969	Allen & Murdock	12	86 ± 3
1971	Murphy et al.	20	90 ± 3
1972	Murphy	20	94 ± 2
1973	Morrison	11	90 ± 3
1973	Morrison	20	96 ± 3
1973	Nolt et al.	35	92–97

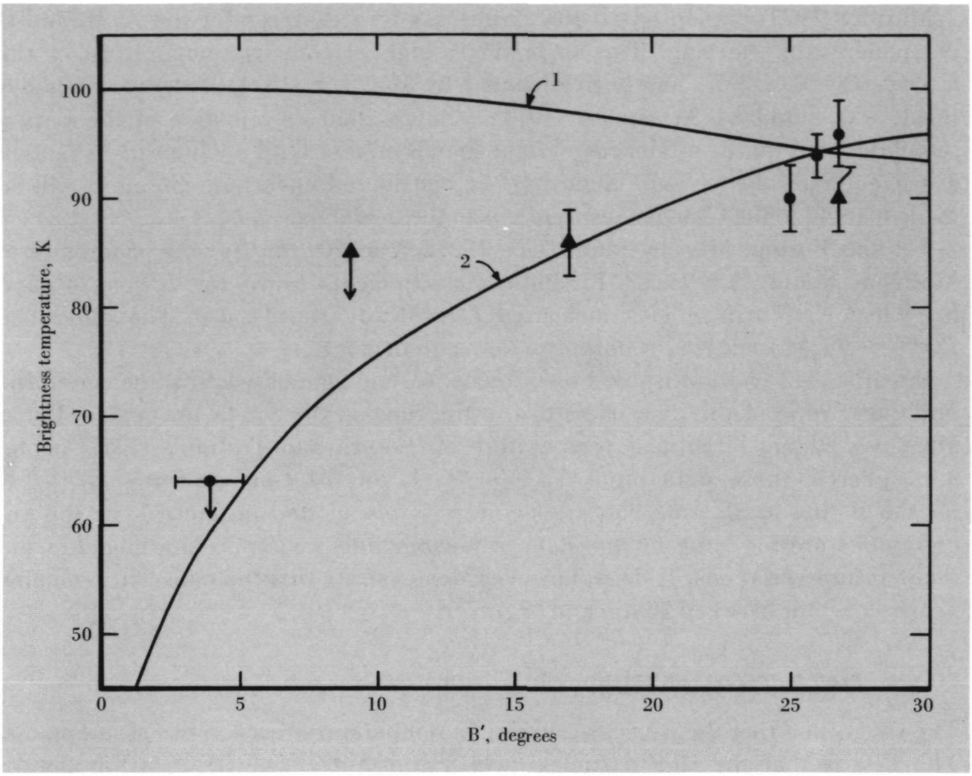

FIGURE 1.—*Adjusted B ring brightness temperature measurements vs Saturnocentric declination of the Sun B′. Triangles refer to ~ 10 μm and circles to 20 μm values listed in table II. The solid curves refer to brightness temperature models discussed in the text.*

$T_B < 60$ K (Low, 1966). Saturn was 9.7 A.U. from the Sun, and the Saturnocentric declination of the Sun B' was ~5°. The adjusted B ring temperature is $T_B <$ 64 K. The horizontal error bar in figure 1 indicates that the exact value of B' is not available.

Allen and Murdock's 1969 measurements of $T_B = 83 \pm 3$ K (Allen and Murdock, 1971) were made when $B' \sim -17°$ and when $R = 9.2$. The adjusted B ring temperature at 12 μm is $T_B = 86 \pm 3$ K.

In 1971 Murphy et al. (1972) measured the relative fluxes of Mars, Saturn, and Saturn's rings with high spatial resolution at 11 μm and 20 μm. They quoted brightness temperatures of the rings relative to the disk which, in turn, was calibrated by observations of Mars earlier in the night. We reevaluated the data and used Murphy's (1973) model-dependent brightness temperature of Saturn as the calibration. We found $T_B = 89 \pm 3$ K for the B ring at 20 μm while the 11 μm data were found to have been incorrectly analyzed. No meaningful 11 μm temperature may be derived, but it is clear that the rings are ≥ 5 K cooler at 11 μm than they are at 20 μm. For these measurements $B' \sim -25°$ and $R = 9.1$ A.U. The adjusted B ring brightness temperature is 90 ± 3 K.

Murphy (1973) presented 20 μm brightness temperatures for the A, B, and C components of the ring. The surprisingly high brightness temperature of the C ring, $T_B = 89 \pm 3$ K, has been disputed by Morrison (1974), although a similar result was found by Armstrong (1971). Confirmation or rejection of the C ring temperature requires a telescope larger than 3 m, and until such an investigation has been made the measurement must be considered uncertain. No effort will be made to include the C ring measurements in the modeling.

For the B ring, Murphy found $T_B = 94 \pm 2$ K at 20 μm. Several months later Morrison found $T_B = 96 \pm 3$ K. Both measurements were for $B' \sim -26°$ and $R = 9.0$ A.U. Morrison also measured $T_B = 90 \pm 3$ K at 11 μm. The difference $T_B(20) - T_B(11) = 6$ K is accurate to better than ± 2 K.

In early 1973 Nolt, Murphy, Ford, Radostitz, and Donnelly (1973) measured the brightness ratio of the disk of Saturn to the rings in the 30–43 μm region. Using Murphy's 20 μm brightness temperature for Saturn and Trafton's (1967) model atmospheres, these data imply $T_B \sim 90$–95 K for the ring ansa or ~ 92–97 K for the B ring at 35 μm. This temperature is not plotted in figure 1, as the uncertainties are too large for the data to meaningfully constrain any model of the temperature variations. It does, however, demonstrate that the emissivity remains nearly constant between 20 μm and 35 μm.

DATA EVALUATION

The suggestion that the rings are varying in temperature rests on two assumptions. The first is that the ring particles have a constant emissivity as a function of wavelength. The second assumption is that the upper limits of Low (1965, 1966) are valid.

The first assumption is clearly incorrect. Morrison's (1974) measurements show that the relative emissivities are $\epsilon_{11}/\epsilon_{20} \sim 0.4$, a surprisingly low value. The ratio $\epsilon_{20}/\epsilon_{35} \sim 1$, when combined with the ratio of 11 μm and 20 μm, suggests that the particle radii might be on the order of 25 μm. Yet other data clearly suggest $r \sim 1$ cm is more nearly typical (Pollack, Summers, and Baldwin, 1974; Morrison, 1974). It is also unlikely that the sharp drop in emissivity can be caused by restrahlen features in the particle spectra (Murphy, Logan, Salisbury, and Hunt, 1974). Any fully successful model must explain the emissivity ratios.

When the 11 μm and 20 μm data are examined separately, we see that evidence for variation in the B ring temperature at 11 μm is almost nonexistent, while the 20 μm variation is evidenced primarily by the upper limit set by Low (1966). Thus we see the importance of this one measurement, and the need for further information on the observation is emphasized. (The temperature is obtained from Aumann, Gillispie, and Low (1969), which references an abstract in 1966 that provides no details.)

It is important to note, however, that the classical ring model favored by Pollack et al. (1974) and others is inconsistent with the data, even if Low's 1965 point is invalid. The brightness temperature of a multilayered model must necessarily increase as $|B'|$ decreases. The observed brightness temperature will be

$$T_B = T_{particle}(1 - e^{-\tau \sec B'})^{1/4} \qquad (1)$$

We have calculated the variation of T_B with B' following equation (1), using $\tau = 0.7$ (Kemp and Murphy, 1973), and plotted it as curve 1 in figure 1. The data were arbitrarily passed through the point ($T_B = 94.5$ K, $B' = 26°$) by setting the particle temperature equal to 100 K. We have not allowed for the drop in the particle temperature as we penetrate more deeply into the ring; the effect of a decreasing temperature with depth would be to straighten out the curve, resulting in little or no temperature variation with B'. At the same time, a temperature gradient in the ring would cause the apparent 11 μm brightness temperature to be *greater* than the 20 μm brightness temperature. This latter effect is caused by the more rapid decrease in flux with temperature at 11 μm than at 20 μm, with consequent greater weight being given to the hotter particles at 11 μm. The temperature difference is estimated to be between 1 K and 3 K in the opposite sense from the observed temperature difference. That is, if $T_B(20) = 96°$, then $T_B(11)$ should be 98 K, not 90 K as was observed. The difference in flux from 98 K to 90 K at 11 μm is more than a factor of 3.

A much more satisfactory fit to the data is obtained with a model that is somewhat unrealistic physically. In curve 2 of figure 1 we show the variation in brightness temperature of a monolayer assemblage of flat particles with the large surfaces lying in the ring plane. Each ring particle then receives less sunlight per unit area as the angle B' decreases and the temperature of a particle decreases according to

$$T_{particle} = T_{max}(\sin B')^{1/4} \qquad (2)$$

and

$$T_B = T_{particle}(1 - e^{\tau'})^{1/4} \qquad (3)$$

where τ' is the optical thickness, which does not vary with B' for a monolayer of particles that are thin compared to their width and breadth.

Curve 2 is seen to be in good agreement with all of the data including Low's (1965, 1966) upper limits and allowing for $\epsilon_{11}/\epsilon_{20} \sim 0.4$ (or alternatively $T_{20} - T_{11} = 6 \pm 2$ K) through some as yet unknown mechanism.

A closely packed monolayer of spherical particles would behave similarly to curve 2 but with a slower decline in T with decreasing B'. The very low value, $T_B < 64$ K, can still be explained since the Saturnocentric declination of the Earth B was greater than B' at the time of Low's observation. Thus he may have been measuring much of the shadowed portions of the ring particles, which may be very cold for sufficiently large particles.

CONCLUSIONS

The infrared brightness temperature variations place important constraints on models of Saturn's rings. After adjusting for the decreased Sun-Saturn distance and adjusting all measurements to B ring values only, we see that the temperature variations are not as large as was originally thought. If Low's upper limit of $T < 60°$

(Low, 1966) is valid, then the particles must lie in a monolayer and have flattened surfaces lying in the ring plane, or possibly be spheres nearly in contact with one another. The "classical" multilayered agglomerate of small particles cannot produce the observed variations. If Low's (1966) upper limit is incorrect, the classical model is still inadequate but may be ultimately reconcilable with the data. The difference between the 11 μm and 20 μm brightness temperatures must be explained by any satisfactory model.

DISCUSSION[1]

William Irvine I attempted to do a very quick computation of the effect of thermal emission from particles in the upper layer of a multilayer model on the particles lower down. If you treat the ring particle as having a grey opacity, then you can do a simple transfer problem and you find that the source function goes down essentially linearly with optical depth, which means that the temperature decreases very slightly, going as the fourth root as you go down through the layers. Also, if you neglect the Low (1966) measurement, there is very little tilt effect.

Robert Murphy That's right, you can almost argue that there is no tilt effect if you are willing to discount Low's original measurement.

Irvine Far be it for me to do that.

Murphy But it is a possibility.

Hugh Kieffer In my presentation I neglected to mention that we had a problem in dealing with the apparent brightness temperature and the bolometric albedo for the rings. We introduced a concept that has been helpful in this, and that is the concept of a radiative anisotropy index, q (i.e., the extent to which the thermal radiation is peaked in the solar direction or Earth direction (we have ignored the phase angle)). The problem is that if you use an albedo on the order of 0.6, you end with anisotropy on the order of 2, and that means that the radiation in the solar direction is on the order of twice the mean radiation in all directions. I don't really know what this means just yet in terms of the allowable particle size, rotation rates, and thermal inertias, but it is going to be constraining to some extent certainly. It tends to make it very difficult to have small, highly conductive particles, because they simply cannot generate such high anisotropy in their thermal emission.

Irvine Let me see if I understand that. You require that kind of anisotropy in order to match the brightness temperatures.

Kieffer Yes, in order to make the infrared brightness temperature measurements compatible with the insolation, which is known. The thermal measurements are higher than one would predict for the amount of energy we expect to be absorbed by the rings.

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[1] Editors' note: At the workshop Murphy presented a multilayer model with a steep temperature drop inward from the illuminated face due to shadowing. Following discussion, a portion of which is included above, this model was deleted from the revised text on physical grounds.

You have to throw in the shadowing factors and the relative geometry as well. They do not differ greatly, depending on the detailed placement models you use. We looked at a hexagonal monolayer, where the spacing is hexagonally symmetric. The monolayer ended with the particles being spaced about 2 radii apart. And we also looked at the case of small particles uniformly distributed—in other words, perfectly uniform spacing of the particles in the ring and opacities on the order of 1. The amount of shadowing and the solid angle of the remainder of the ring as seen by any given particle are not strong functions of the detailed geometry that is used.

I think there is some evidence for an incompatibility between the reported visual albedo of the ring particles and their bolometric albedo based on the thermal radiation measurements.

James Pollack What value of bolometric albedo do you require in order to have an anisotropic value of 1?

Kieffer A bolometric albedo of about 0.3.

Pollack So a very low value of bolometric albedo is required.

Kieffer I could have cited the following numbers: for a bolometric albedo of 0.47, you get a q of 1.4, sort of a reasonable number; for a q of 8/3 the bolometric albedo is 0.76. So we are bounding the range we expect the bolometric albedo to lie in, but reasonable bolometric albedos do have appreciable anisotropy associated with them.

Pollack What is the limit we now think there is on bolometric albedo?

Kieffer A reasonable range for bolometric albedo is 0.45 to 0.9.

Murphy It is hard to see how you can match the IR measurements with a bolometric albedo of 0.9.

Pollack The polarization observations[2] are tremendously interesting; have you got any results for either ring A or ring C?

Murphy No, ring A misses the planet entirely at this time, and ring C is substantially smaller. We did not attempt a ring C measurement. You could determine the optical thickness for ring C by direct means without using polarization techniques.

Irvine In the polarization measurements you have to assume that Saturn's disk has a north-south symmetry.

Murphy Yes, that has been studied by Hall and Riley (1969) over a period of years, and they find that it does have north-south symmetry when they can see both halves of the planet. It was Hall, by the way, who suggested this measurement. He has done the same thing at a much shorter wavelength. His preliminary results are in agreement with ours.

Brad Smith That is surprising, because the planet has a very strong north-south dissymmetry in the ultraviolet.

[2] See Kemp and Murphy, 1973, for complete discussion of these observations and the deductions about ring optical thickness.

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