Michael A. Janssen

SHORT WAVELENGTH RADIO OBSERVATIONS OF SATURN'S RINGS

So far we have not discussed the connection between the radar results for the rings and the rather interesting constraints supplied by passive radio measurements of Saturn. I will try to broach this subject here. This and the next presentation will be concerned with passive radio observations of Saturn's rings. The useful observations cover the wavelength range from about 1 mm out to 21 cm. I am going to talk in particular about the shorter wavelength results—from about 1 mm to about 2 cm—and Dr. Berge (see following contribution) will subsequently discuss the longer wavelength measurements.

This division of wavelength measurements is primarily due to the different instrumental techniques that are used for the two wavelength ranges. The most sensitive way of looking for radio emission from Saturn's rings uses the interferometric technique, whereby we may actually attempt to observe the brightness of the rings themselves as opposed to some combination of disk plus ring emission. Single antennas at radio wavelengths simply don't have the resolution to separate the ring contribution from the disk contribution. This has to be done with the only means that are available, e.g., waiting for the ring inclination to vary or trying to guess what the disk contribution alone will be. I will concentrate primarily on these points in order to define the constraints—or better, lack of constraints—which currently exist in this important wavelength range.

Now, with the possible exception of a couple of measurements near the 1-mm wavelength, the results of all the radio observations are consistent with the simple hypothesis that the rings don't exist at all. It is important to keep that clear in the following discussion. The classical and obvious interpretation of this fact has been that the rings become optically thin at radio wavelengths. This would occur if ring particle sizes were less than radio wavelengths. The radar result of course upsets this interpretation and requires a rethinking of the interpretation of the passive radio observations. Since the radar measurements are quite new,

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my contribution to the rethinking is still pretty much in a preliminary stage—I make no pretense of a definitive analysis here.

The radar result appears to pose an interesting problem. It obviously indicates that there is a strong interaction with radio waves. The passive results give the opposite impression, and it is not immediately clear whether or not these are compatible results. The simplest case I can think of is shown as example 1. I would emphasize that this is a very simple-minded analysis, which I would like to use as a springboard to a bit more detailed discussion.

Example 1

A = area of isotropically scattering surface (Saturn disk area = 1)

R = reflectivity

T = physical temperature

From 13-cm radar:

$$AR = 1.2 \times 0.62 = 0.75$$

Contribution to Saturn disk temperature:

$$\Delta T_D = A(1 - R)T$$

Eliminate A:

$$R = \frac{1}{1 + (1/0.75)(\Delta T_D/\mathrm{T})}$$

Best radio limit:

$$\frac{\Delta T_D}{T} = < 0.1 \Rightarrow R > 0.88$$

Simple dielectric case:

$$R = \left(\frac{n-1}{n+1}\right)^2 \Rightarrow \begin{array}{l} \eta > 33 \\ \epsilon > 1000 \end{array}$$

Possibilities:

Iron meteorites?

Enhanced radar backscattering?

Small, low-loss particles?

I assume that there is something in the neighborhood of Saturn that can be described in essence by an area and a reflectivity. Let us assume isotropic scattering for this thing, and let us assume some physical temperature. Rephrasing the 13-cm radar results, we get the product of the area times the reflectivity to give the ring radar cross section area that Dr. Morris (see preceding contribution) just gave us. Now, we can solve for the thermal emission from this reflector with the same model if we make some assumptions about the connection between reflectivity and emissivity. The contribution to the disk temperature of Saturn should be the area times the emissivity times the temperature. If we now eliminate the area between these two equations, we can solve for the reflectivity in terms of the contribution that we would expect for the disk temperature. (Note that I normalized the areas to the area of Saturn's disk.)

The best radio limit is that the contribution from the rings relative to that of the disk is on the order of 0.1. This gives us a reflectivity of about 0.88. Now, if we assume that this is due to a dielectric surface (e.g., if we want a physical model, we can think of large dielectric objects), we can take the Fresnel equation and solve for the refractive index. We find that the refractive index has to be greater than 33, or, in other words, the dielectric constant has to be something greater than 1000. Obviously this is a simple model. It is interesting that it fails to work by such a large factor.

Gordon Pettengill This assumes that some of the radio waves are getting absorbed. But suppose that the waves rattle around inside, as I suggested (see discussion in preceding contribution by Morris); there would be relatively little loss, and there would be no contribution to the temperature.

Janssen Yes. As a matter of fact, there are several ways around this, which I hope to lead into. This could be due to polished copper balls or something of the nature you suggest. The two sets of results could be made consistent with iron meteorites, for example, if the conductivities can be made high enough. Also, earlier we were discussing the possibility of enhanced radar back-scattering; one can imagine extreme cases. A third possibility which I find interesting is a model that Dr. Pollack has suggested and Dr. Pettengill has anticipated in his remark. That is, we simply have low loss particles, large enough to reflect 12-cm radar according to the Fresnel law but with little or no effective absorption and hence reduced emission.

Pettengill The Fresnel law merely says that one minus what you see as a reflection in the radar case had to come from inside or go inside reciprocity holds and that just isn't true in your example.

Janssen I would point out that for the case of most dielectrics of meter size, the internal rays are absorbed as, for example, with silicates.

Pettengill They are dry and cold. In the case of the Moon, they talk about hundreds of wavelengths, don't they?

James Pollack No, in the case of the Moon, it is more like 5 or 10 times the wavelength of observation.

Pettengill Of course, the Moon isn't as cold as this material is.

Pollack No, it is not. And that fact will probably lower the imaginary part of the index.

Pettengill But if you are talking about 10 cm to meter particles, surely at 6- or 10-mm wavelength you wouldn't encounter that limiting case, would you?

Janssen Well, meter size particles are 100 wavelengths already. The dielectric constant, the loss tangent I have looked up for common materials, gives very significant attenuation over such distances.

Pettengill At these temperatures?

Janssen Yes.

Irvine That is probably for homogeneous particles. If you have some kind of a conglomerate with a lot of internal reflecting planes, such as a snowball at optical wavelengths, then it seems to me that you could significantly increase the reflectivity.

Janssen I would like to emphasize that the purpose of this example is to show that the simplest case you can use to explain these two sets of radio data runs into serious problems. In detail, it is obviously a very complicated problem. From this example, I think it is clear that in the general case we would expect to see some thermal emission. In the following, I want to concentrate on a somewhat more elaborate model, which I will use to reexamine the present millimeter wavelength limits on the ring brightness temperature. The passive radio data are not taken in such a way that we simply measure a ring contribution or a ring brightness temperature separately from Saturn's disk temperature. We need a model to extract this information, and I want to elaborate on a very simple model that can be made consistent with the high radar reflectivity.

There are two ways of separating out the ring contribution from the disk flux. First, we may look for variation in the total flux from Saturn over a long period of time in which the inclination of the rings varies significantly. The rings, when fully open, present a cross section area comparable to the disk area of Saturn.

Irvine Are there long-term programs to look for such an effect?

Janssen As far as I know, only Eugene Epstein of Aerospace has carried out a consistent program to observe Saturn. I will show you his data in a minute.

A second way of singling out the ring emission for a single observation is to estimate the disk contribution on an a priori basis and assign the difference between the expected disk contribution and the actual observed flux to the rings. This is obviously a very shaky technique, but it nevertheless supplies some kind of restraint. We will deal with this point first.

Table I lists the disk temperature measurements of Saturn that have been made over the last several years. These are depicted as a function of wavelength in figure 1. I have excluded some observations for which the errors were larger than 15 or 20 percent. Shortward of 2 cm, this effectively summarizes the data that presently exist. I would point out that there is a great question of calibration in these measurements since the millimeter flux scale is very uncertain. The error bars are those given by the experimenters, and no attempt has been made in this figure to find a common flux scale. Those cases where the experimenters make no attempt to give an absolute uncertainty are represented by open circles.

According to these data, the disk temperature of Saturn, taken to include the ring contribution, appears to be about 140°. Model atmosphere calculations of Saturn's disk temperature predict about this value for Saturn alone. The thermal emission from Saturn is believed to be due to the presence of ammonia in small amounts in the atmosphere. Ammonia is a very good microwave absorber and has a strong inversion band at about 13 mm. At the pressures involved, this microwave absorption is broadened into the far wings and gives absorption over a broad range of wavelengths. Ammonia saturates in regions of the atmosphere cooler than about 160°. Detailed calculations for both Saturn and Jupiter, allowing for the many uncertainties about the atmospheres of these planets, do not allow for a disk temperature much colder than about 140°. To get a disk temperature of 100°, for example, we would have to have some mechanism for getting microwave

TABLE I.—*Measurements of Saturn's disk temperature, 1 mm–2 cm.*

λ, cm	B, degrees	T_D♄, K[1]	T_D♄/T_D♃[2]	Reference
0.12	+10	140 ±15	0.90 ±.14	Low & Davidson (1965)
.12	−26.4	169 ± (10)[3]	1.15 ±.10	Harvey & Werner (1973)
.14	−26.4	194 ± (8)	1.29 ±.06	Rather (1973)
.21	−21	164 ±12	1.00 ±.10	Ulich et al. (1973)
.31	−21	148 ±11	.82 ±.10	Ulich et al. (1973)
.33	−1.5	125 ± (4)	.817±.026	Epstein et al. (1970)
.33	−6.9	124 ± (2)	.810±.013	Epstein et al. (1970)
.33	−12.7	123 ± (2)	.804±.013	Epstein et al. (1970)
.33	−17.9	129 ± (2)	.843±.013	Epstein et al. (1970)
.33	(4)	125 ±13	.82 ±.02	Epstein et al. (1970)
.35	−15	132 ± (6)	.94 ±.04	Pauliny-Toth & Kellermann (1970)
.8	+9	132 ± (9)	.92 ±.06	Kutuza et al. (1965)
.82	−17	132 ± (4)	.92 ±.03	Kuzmin & Losovksy (1971)
.84	−18	151.1±7	.96 ±.03[5]	Wrixon & Welch (1970)
.9	−24.8	134 ± (5.4)	.921±.037	Gary (1973)
.9	−26.6	147 ± (4)	1.010±.028	Gary (1973)
.9	(4)	142.4± (3.2)	.98 ±.02	Gary (1973)
.95	−15	127 ± (3)	.91 ±.02	Pauliny-Toth & Kellermann (1970)
.96	(6)	126 ±6	.80 ±.06	Hobbs & Knapp (1971)
.98	−18	138 ±6	1.06 ±.04[5]	Wrixon & Welch (1970)
1.18	−17	130.8±6	.94 ±.04[5]	Wrixon & Welch (1970)
1.27	−18	127.2±6	.935±.03[5]	Wrixon & Welch (1970)
1.46	−17	133.2±8	.92 ±.07[5]	Wrixon & Welch (1970)
1.53	+10	141 ± (15)	.94 ±.10	Welch et al. (1966)
1.95	0	145 ±4	.884±.05	Pauliny-Toth & Kellermann (1970)
2.07	−26.5	162 ±3.8	.938±.04	Gary (1973)

[1] Saturn disk temperature errors without parentheses indicate authors' estimate of absolute error. Errors in parentheses are relative errors with no absolute error given.

[2] Errors in the ratio measurement are calculated where possible on the basis of relative rather than absolute errors.

[3] Measurement relative to Venus assuming T_D♀ = 285 K. Ratio to Jupiter assumes T_D♃ = 150 K.

[4] Averaged over preceding data.

[5] Ratio to Jupiter based on data in Wrixon et al. (1971).

[6] No data given.

absorption at a level of the atmosphere that cold. There doesn't seem to be a way to do it. In a gross attempt to remove some of the uncertainties about model atmospheres and the flux scale, I have ratioed the Saturn measurements to Jupiter where possible. These are shown in figure 2. We would expect Jupiter and Saturn to have approximately the same disk temperature, and the experimental uncertainties are reduced since we don't have to contend with calibration uncertainties. Interestingly enough, temperatures appear to lie somewhat to the cool side of Jupiter; all but about 3 points are below unity in figure 2. There are two interesting points significantly greater than unity, however. Both are recent measurements near 1 mm, one by John Rather (1973) at Kitt Peak with the 36-ft telescope and the other by Harvey and Werner (1973) of Cal Tech using the 200-in. telescope. Both were made with the rings wide open, and they do seem to show an excess. Observe that Low and Davidson's (1965) old 1-mm point, made at about the time the rings were seen edge on, is below the line.

It is not worthwhile to look too closely into the data represented in this fashion, since the measurements were made at different ring inclinations and there are spectral effects quite likely contained in those data. What I intend to do now is

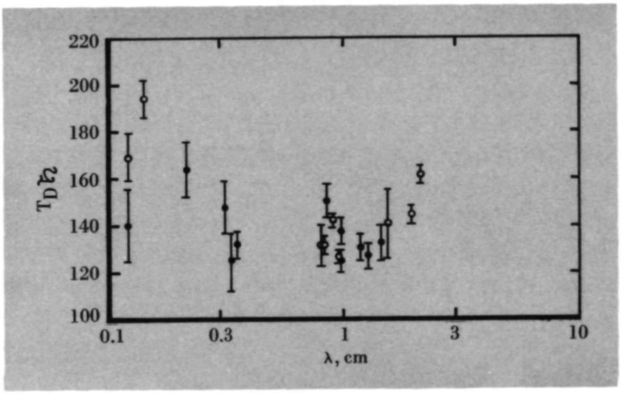

FIGURE 1.—*Microwave spectrum of Saturn, 1 to 20 mm. See text for distinction between open and filled circles.*

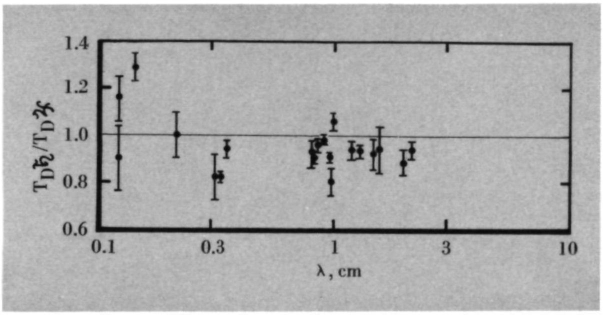

FIGURE 2.—*Observed ratio of the brightness temperature of Saturn to that of Jupiter for the wavelength range 1 to 20 mm.*

reinterpret these data in terms of a model suggested by the radar results. The classical interpretation has been that the rings are highly transparent at radio wavelengths, in which case the obvious approach would be to set an upper limit to their optical thickness. The radar results strongly imply that the rings are in fact optically thick, however, and to explain these small thermal contributions we postulate instead a low surface emissivity for the rings. Such a model may subsequently be interpreted in terms of small or moderate-size low loss dielectric particles; however, I will not attempt such an interpretation here.

Example 2 outlines a simple model in which I assume for simplicity that the rings are infinitely thick in the radio range. I will treat the ring surface as being characterized by an emissivity E such that the brightness temperature is proportional to the emissivity times the physical ring temperature. This is obviously much too simple a model for a detailed inquiry into its physics. My primary intent is to interpret the existing microwave observations, and I think the model, although it contains many implicit and undoubtedly erroneous assumptions, is compatible with the present uncertainty of the data.

Example 2

Rings:		*Disk:*	
Solid angle (A and B rings)	Ω_r	Ω_s	Solid angle
Temperature	T_r	$\Omega_{s\phi}$	Unobscured solid angle
Surface emissivity	E	T_s	Brightness temperature

Optically Thick Rings:

$$T_D = \{\overbrace{\Omega_s T_s}^{\text{Disk}} + \overbrace{E\Omega_r T_r}^{\text{Rings}} + \overbrace{f(1-E)\Omega_r T_s}^{\text{Disk reflected from rings:}}\}/\Omega_{s\phi}$$

The net disk temperature I have written as the sum of three terms: the product of the solid angle of the unobscured disk times the temperature of the Saturn disk (which I assume to be uniform); the product of the emissivity times the area of the rings times the ring temperature; and, since the reflectivity of the rings is high, the thermal emission from the disk reflected from the ring. This last term amounts to about 2 or 3 percent, which I would note is in principle measurable by interferometric techniques. I have normalized the disk temperature according to convention by dividing by the solid angle of the disk of Saturn.

Figure 3 shows the results of some computations based on this model. I have assumed that the temperature of Saturn's disk—the radio brightness temperature—is 150°, and that the physical ring temperature is 100°. These are simply round numbers and are not to be taken too seriously. I did the calculation implied

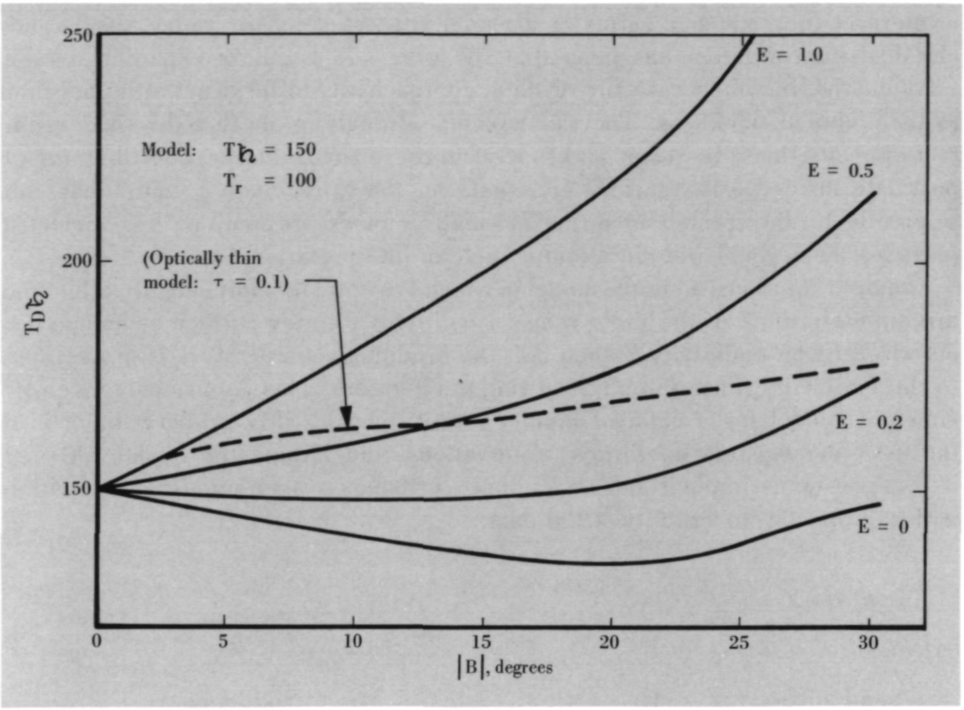

FIGURE 3.—*Variation of apparent Saturn disk temperature with ring inclination for several values of emissivity* E.

in example 2 to obtain the variation in disk temperature with ring inclination for several choices of the emissivity.

Now, as the rings open up, we see more ring area. If the rings had a large emissivity, we would expect to see a large contribution, as much as doubling the apparent disk temperature. If the rings are simply scatterers, however, as the rings open up their effect is only to obscure a portion of the disk. We won't see any thermal emission from the disk, and hence the disk temperature will appear to decrease. Beyond about 20° the outer ring begins to go off the disk and the disk temperature begins to go up in either case. It is interesting to note that, except for small but finite contributions from the rings, we don't get much of a variation until we get well out into very high inclinations.

This model can be criticized from several points of view. We are assuming a constant physical ring temperature, and of course we might allow that to vary as suggested previously. Another point is that if we treat more correctly the multiple scattering problem implied here, the emissivity is not really expected to be constant as we vary the angle at which we look at the rings; the emissivity will decrease somewhat, depending on the albedos of the individual particles in the medium. Third, we are taking the extreme limit of a large optical depth. For the case of an intermediate optical depth, as the rings open up the effect is in the opposite direction, and the curves will tend to have less slope to them as we approach the case of optically thin rings illustrated by the dotted line. Notice that if we have an optically thin model, as soon as the rings open up slightly, we have an almost constant contribution and see no large effect with the ring inclination. Of course, we always have a positive contribution to the disk temperature in that case.

I am going to ignore these points and continue on with the basic case I discussed to see what interpretation we can make of the data. Figures 4 through 7 illustrate an attempt to fit the data I showed you previously in terms of this model. Here I have divided the data into four batches according to wavelength and plotted them as a function of the ring inclination. We will continue to work with the Saturn/Jupiter ratio measurements to remove as many uncertainties as possible. In fitting the model curves to the data, there are really two parameters we have free. In addition to the emissivity, there is a choice as to what the unobscured disk temperature of Saturn should be. We would expect it to be somewhere around unity.

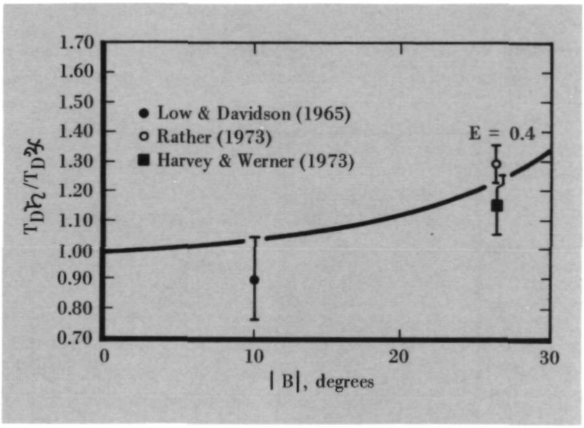

FIGURE 4.—*Brightness temperature ratio as a function of ring inclination for observations near 1 mm.*

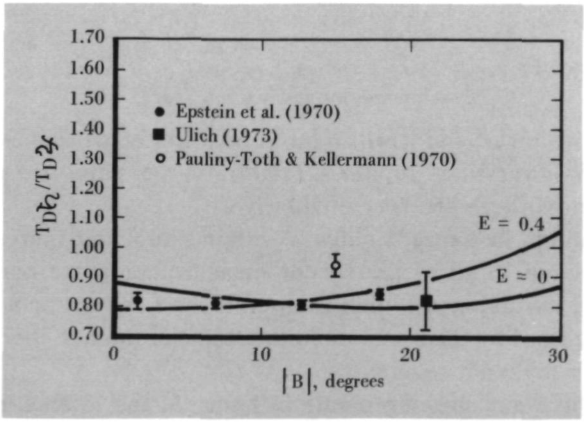

FIGURE 5.—*Brightness temperature ratio as a function of ring inclination for observations near 3 mm.*

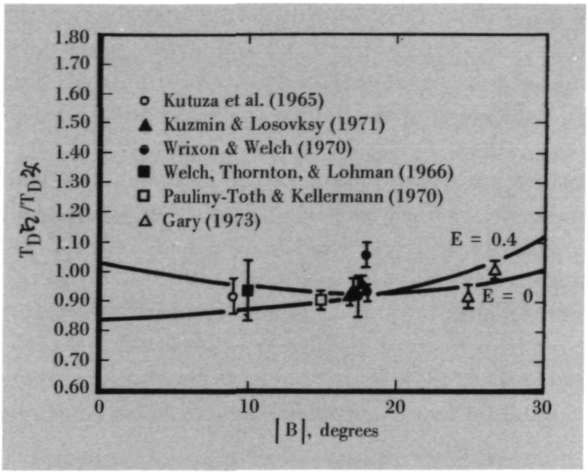

FIGURE 6.—*Brightness temperature ratio as a function of ring inclination for observations between 8 and 15.3 mm.*

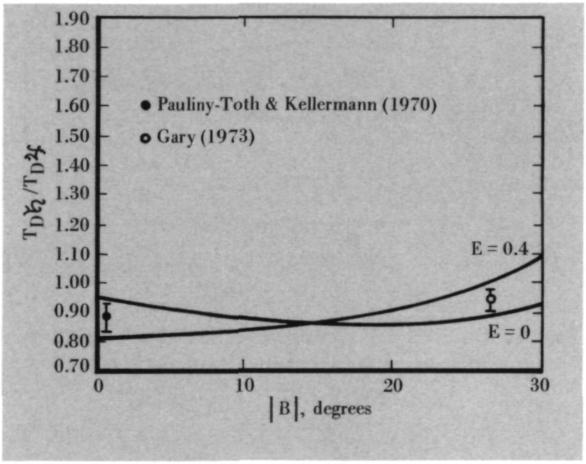

FIGURE 7.—*Brightness temperature ratio as a function of ring inclination for observations near 2 cm.*

It can be higher or lower, and it will want to be lower as we can see in the figures. As it gets much lower than Jupiter's brightness temperature, it becomes less likely. But the limits there are very qualitative.

The measurements in figure 4 show a rather significant increase as the rings become fully opened. Both of the recent measurements are consistent with an emissivity of 0.4, assuming the disk temperature of Saturn should be 150°. If it is less, as is suggested by the 3 mm and other measurements, the emissivity could actually be rather higher.

Referring to the 3-mm measurements in figure 5, the interesting points are by Epstein et al. (1970). He has made measurements from the period of about 1966 through the present, although he has only evaluated the data up to about 1969.

The ratio measurements he has made with Jupiter are very precise. His error bars are much smaller than any other errors in these figures. Nevertheless, with this small range they are still consistent with a large range in emissivity. There is no apparent effect with inclination, yet the model still fits the data for emissivities as high as 0.4. The best fit is about 0.25 for the emissivity.

The data from about 8 to 15 mm shown in figure 6 are much less conclusive. There are a good deal more data here, but there are no observations near the edge-on case. I have shown two recent points by Gary (1973) which may indicate an upturn as the rings open up, although one can still fit a large variety of curves through these points. And, again, for the 2-cm data, there is a statistical argument one can make with the data points as they are, and anyone can see that they cover about the same range of cases.

Epstein made measurements this last year, and it will be interesting to see those data reduced. I think that is probably the major improvement that can be make taking the present approach.

Note that the zero emissivity case for the simple model I have taken doesn't give the best fit to the data. Essentially the data, except for the 1-mm case, are consistent with a straight line. For the model I have taken, where we actually have a decrease and then an increase with the ring inclination, the fact that the data are flat gives us an indication that the rings are contributing to the disk temperature of Saturn. On the other hand, that is also saying that they are consistent with the absence of any rings at all; this is consistent with the optically thin case but not with the radar result. The best fit in all these cases, except perhaps near 1 mm, is in the neighborhood of $E=0.2$. Emissivity as high as 0.4 is less likely on the basis of the data, but it is certainly not excluded.

The limits at longer wavelengths are much tighter than this. The only indication that we have that the rings do exist at radio wavelengths are the high 1-mm points, and the inference may be that the rings gradually or suddenly disappear through the millimeter range with no really very strong constraints. For example, it is not clear that they have decreased in emissivity between 1 mm and 3 mm on the basis of present data. It will be shown in the next presentation, however, that beyond 2 cm we definitely have $E < 0.4$.

In summary, the most obvious interpretation of these data is that the rings disappear beyond 1 mm. However, it is shown here that we obtain a reasonable interpretation if we assume that the optical depth can be large while the effective emissivity of the rings is low. Generally, the limits on the thermal emission are not very strong in the millimeter-to-short-centimeter range.

Two things can be done in the near future to improve this state of affairs. First, the 3-mm points can be examined in their entirety. Also, an emissivity of 0.4 at 8 mm would suggest that there is something more than a 20-percent brightness contribution from outside the disk of Saturn. This should be easily detectable if it is present. We at JPL are presently developing an interferometer to work at this short wavelength which will be capable of detecting a much smaller ring contribution.

Finally, there remains a question as to whether such a model is really applicable at all. This model does make definite predictions about what the microwave appearance of Saturn should be. There is at least one possible test here; the optically thick, low-emissivity rings would give the appearance of a cold band across the disk of the planet, and this could be searched for with an interferometer. In any case, there would be a minimum brightness temperature for the rings. If they are totally reflecting, they must reflect some thermal emission from the disk. That limit seems to be around the 2- or 3-percent level, which is marginably detectable at present by interferometric techniques.

DISCUSSION

Dennis Matson What is the relationship between the emissivity E you use and the effective radiometric emissivity for your model?

Michael Janssen The emissivity times the physical temperature of the rings, assuming that they are optically thick, gives me the spectral brightness temperature.

Matson At optical wavelengths, the rings are absorbing a certain amount of energy that must be disposed of.

James Pollack The emissivity could be very different at infrared wavelengths. Most of the radiation from Saturn's rings is emitted at infrared wavelengths. He (Janssen) is not giving an integral over all wavelength space. He is simply saying at a particular radio wavelength the emissivity could be very small. In his model, E is an unknown that he will try to deduce from the existing observations.

Gordon Pettengill Does 0.4 really seem so low when one takes into account all the other facts that we heard today? It doesn't sound so low to me.

Janssen Yes, it is interesting. I did do some multiple scattering calculations, assuming a thick isotropically scattering medium of small particles. I obtained some calculations from John Martonchik here at JPL for the case of varying optical depths at an inclination of about 25°. The emissivity in this case could be related directly to the particle single scattering albedo, assuming isotropic scattering. The single particle albedo for the optically thick case with an emissivity of 0.40 is 0.93.

Pettengill Suppose they are not optically thick at radio wavelengths. I don't think we have any evidence which convincingly demonstrates that they are. Optical wavelengths are one thing, and radio wavelengths are quite another. An experiment that detected a radio source through the rings would certainly be a nice way of settling it.

Janssen If we take a τ of 0.5 and an emissivity of 0.4, a single scattering albedo of 0.75 is required. The single scattering albedo doesn't go down tremendously fast with decreasing optical depth.

Pettengill The A and C rings likely possess a lower optical depth than ring B. The effective optical depth at radio wavelengths for the rings as a whole may well be less than 1.

Janssen However, if we go to very low values of optical depth, which are suggested by the longer wavelength interferometric data, an emissivity of 0.1 implies a much higher single scattering albedo. In the extreme case, you require something in excess of 1.

Pettengill It may well be that the radio optical depths are relatively small.

Pollack I think you have to be a little bit careful because the radar observation places severe constraints. If you make the optical depth much less than 1, you will never get the observed radar reflectivity.

Pettengill That is with your model. (See contribution by Pollack for a description of this model.)

Pollack If you want to get a large radar return at one wavelength, then for all wavelengths shorter than that the optical depth must have some reasonable value.

Pettengill I am suggesting that if these objects have a certain physical temperature, their ability to radiate effectively depends on the optical depth. That optical depth may be down around 0.1, in which case you won't see very much ring emission.

William Irvine You are using optical depth for absorption or emission.

Pettengill That's right.

Irvine Jim (Pollack) is using it as the total extinction optical depth, including that provided by the scattering.

Pettengill I am saying the objects are largely decoupled from their environment because they possess small absorbtivity.

Pollack That is my model. I certainly won't disagree with you.

Pettengill Maybe your model with multiple scattering will do it, but I am not personally convinced that it is absolutely necessary to invoke the external multiple scattering effect.

Janssen The ring particles must be good scatterers in order to produce the radar return. The loss for ice at 1 cm at about 100 K is, as I remember, about 10^{-3} to 10^{-4} per cm. That gives you a path length for an eight-fold attenuation of many meters. So ice particles can be fairly large. I think the numbers you used in your calculation, Jim (Pollack), are a little more pessimistic, which says ice is more absorbing.

Pollack I was hoping very much that that would be the case. I used something that would be representative at room temperature, and I would be very delighted to hear your values at 100 K.

Pettengill I don't see why a high radar cross section requires a high emissivity.

Robert Murphy There is always the possibility that Saturn itself has changed temperature as a function of time.

Janssen That's true; I should have mentioned that when you ratio the Saturn measurements to those of Jupiter you do not avoid the problem of temporal changes in the temperature of either planet.

Murphy Yes; I wanted to point out that there are spatial variations on Jupiter that are significant. They are associated apparently with some cloud features. Saturn is just too small to really be sure.

Janssen Those aren't, however, necessarily related to the microwave brightness temperature.

Murphy Because the temperature is tied to the ammonia saturation level?

Janssen Yes. The problems associated with taking ratios could be avoided by making a set of measurements interferometrically, looking directly for emission from the rings. Then you don't have these ambiguities.

Irvine Is Epstein's the only long-term measurement set?

Janssen That's right. It is the only consistent effort that has been made to observe the rings over the full range of ring inclination. Otherwise all we can do is take the data and try to ratio it to take out systematic errors, as I have shown.

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