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MICROWAVE INTERFEROMETRY OF SATURN: APPLICATION TO THE BRIGHTNESS TEMPERATURE OF THE RINGS

I plan to speak about radio interferometric measurements of Saturn and Saturn's rings. This will limit my remarks to observations at longer wavelengths ($\lambda \gtrsim 3$ cm), because until recently there were no interferometers operating at shorter wavelengths that were capable of observing Saturn. However, Mike Janssen has informed me of one exception: there are some existing measurements made with the Hat Creek interferometer at 1.2-cm wavelength, but it is not yet clear whether they are of sufficient quality to be of scientific value.

Table I lists the existing interferometer measurements of which I am aware, with the exception just noted, in chronological order. Since there are relatively few measurements, they can be discussed individually.

However, we should first consider the model visibility functions shown in figure 1. These may appear confusing at first, but they will help in understanding what follows. The curves represent the interferometer amplitude response V as a function of baseline length β. The latter is a normalized quantity obtained by multiplying the length (in wavelengths) by the radius (in radians) of the circular disk being observed. If the disk is elliptical, then $\beta = [(aA)^2 + (bB)^2]^{1/2}$, where a and b are the major and minor axes, respectively, and A and B are the corresponding baseline components.

The solid curve is the response to a uniform disk with a flux density of unity, and it passes through zero amplitude just beyond $\beta = 0.6$. For a very small baseline there is no resolution, which simply means that the disk subtends a negligible part of an interferometer fringe on the sky. When the response begins to drop, one knows that the size of the disk is no longer negligible compared to the fringe spacing. When the response finally reaches zero, that means the power is equally distributed between the positive and negative portions of a fringe.

The other two curves in figure 1 apply specifically to Saturn if there is also power being received from the rings. For each of the curves, it is assumed that

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TABLE I.—*Existing interferometer measurements of Saturn.*

λ, cm	Dates	B	Instrument	Reference
10.4	September 29–October 11, 1965	+ 5°	Owens Valley interferometer	Berge & Read (1968)
9.0	September 19–26, 1966	− 1°		
21	October 29–November 10, 1970	− 22°	Owens Valley interferometer	Berge & Muhleman (1973)
21	November 1970	− 22°	Westerbork array	Jaffe (unpublished)
3.7	August 1971	− 25°	Owens Valley interferometer	Muhleman & Berge (unpublished)
21	August 12–15, 1971	− 25°	NRAO interferometer	Briggs (1973)
3.7, 11	April 1972	− 26°	NRAO interferometer	Briggs (unpublished)
6	December 1972	− 26°	Westerbork array	Jaffe (unpublished)

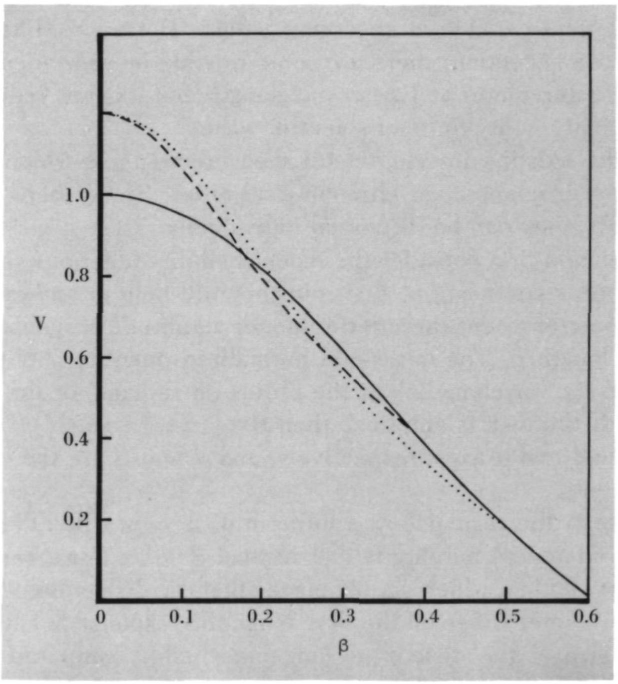

FIGURE 1.—*Sample visibility functions. Solid curve: uniform elliptical disk. Dotted curve: uniform circular disk with uniformly bright A and B rings. The ring contribution is 20 percent as large as the disk contribution, and the baseline is parallel to Saturn's equator. Dashed curve: same as dotted case but with uniformly bright rings extending to 3 Saturn radii.*

the baseline is parallel to Saturn's equator and that the additional flux density provided by the rings is 20 percent of that provided by the disk. The dotted curve assumes that there is uniform radio brightness for the area of the visible A and B rings. It appears that the best way to distinguish between the dotted and solid curves is to compare observations at $\beta \approx 0$ with observations at $\beta \approx 0.2$ or 0.3. The dashed curve makes the same assumptions as the dotted curve, except that the uniformly bright rings extend to 3.0 Saturn radii instead of only 2.3 radii. In this case everything happens on a shorter scale in β.

I won't say very much about the first two entries in table I except to quote the final result. At the time the observations were made, the tilt of the rings was very small so that the angle subtended by them was small, and the upper limit to their brightness temperature was therefore quite large. The rings were not detected, and the upper limit just mentioned was 40 K at 10.4 cm.

Figure 2 shows averages of all of our 21-cm Saturn data (the third item in table I). The amplitude scale has not been normalized to unity; it represents the flux density that would be measured if the Earth-Saturn distance were 8 A.U. The three filled circles are the most accurate data points. The others are less accurate and were taken almost a year earlier. Because the latter are of poorer quality and because there may have been changes in that 1-year period, I'll consider only the filled circles.

The lower curve is simply a fit to the point with smallest β, assuming a uniform disk the size of Saturn. This curve matches the other filled circles very well. This, then, is the scheme for looking for ring emission. If part of the total emission were from a region the size of the visible rings, we would have expected less flux

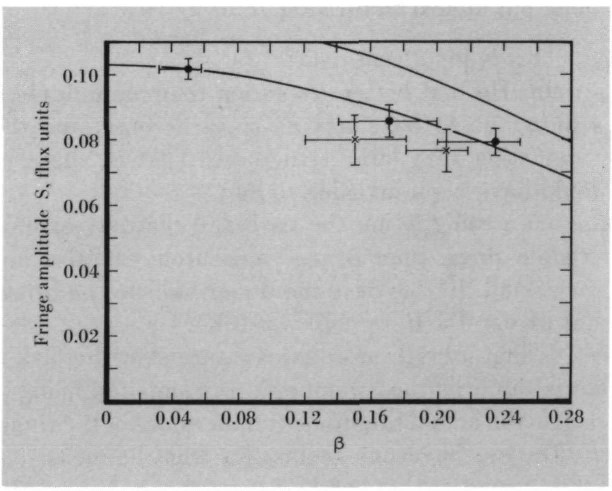

FIGURE 2.—*Averaged 21-cm Saturn data. Crosses are from February 1970 and filled circles are from October and November 1970. The interferometer baseline was east-west. The lower curve is described in the text; the upper curve may be disregarded.*

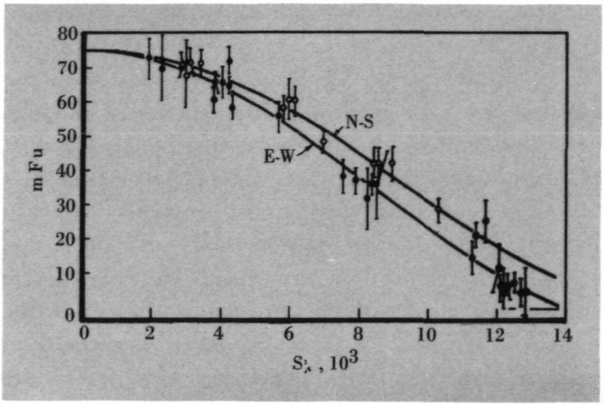

FIGURE 3.—*Observed 21-cm visbility function for Saturn. Filled circles are for a baseline approximately parallel to Saturn's equator and open circles are for a baseline approximately parallel to Saturn's rotation axis. The curves are the expected response for the two cases assuming a uniform elliptical disk.*

density at the larger values of β. However, a uniform disk the size of Saturn with no contribution from the rings fits these data perfectly well. The uncertainties could allow a small ring contribution to be present, so we determined an upper limit to this contribution. The upper limit to the brightness temperature of the rings at 21 cm (for $B = -22°$) was 10 K.

Figure 3 shows the corresponding observations by Briggs (1973). He has plotted every point without taking averages. Neither axis has been normalized. You can see that he has gone out almost to the first zero.

William Irvine This is his 21-cm data?

Berge That's right. He had better resolution than we did. On the other hand, his observations didn't go to baselines as short as ours, and therefore he was less sensitive in detecting very large structures. That is, there could be a very large ring that would have been invisible to him.

Assuming that such a thing is not the case and that any extended emission is confined to the visible rings, then Briggs' measurements also indicate that this contribution is very small. In this case the upper limit to the brightness temperature of the rings at 21 cm (for $B = -25°$) was 6 K.

Von Eshleman Is that a brightness temperature over the disk of Saturn?

Berge No, that is the brightness temperature computed using the angular size of the rings. Thus, it is the actual brightness temperature of the rings.

James Pollack Do you have any feeling for what happens to these results if you don't allow the portion of the disk of Saturn that is behind the rings to come through the rings?

Berge I'll get to that in a minute.

The main point I am making here is that we have some very low upper limits to the brightness temperature of the rings, if we can assume that the model we have used for the rings is correct. If, on the other hand, the emission should extend to a much larger radius than the visible rings, we would be less sensitive to seeing it. Briggs, in particular, would be less sensitive because he doesn't go to such short baselines. An interesting effect of the model fitting is that if the assumed size of the rings is allowed to increase, then even though the upper limit on their flux density contribution rises significantly, the upper limit for the brightness temperature may stay about the same.

Walter Jaffe is with us today, and I have talked very briefly with him about his results. By looking qualitatively at the results, he sees no obvious evidence of rings. However, he has not interpreted the data quantitatively yet in terms of upper limits. If you have any questions, I think perhaps he might be willing to answer them later.

Pollack Jaffe's observations are at what wavelength, Glenn?

Berge He has measurements at 6 cm and at 21 cm.

At this point I am going to go beyond the scope of my title a little bit. I am going to leave the subject of the brightness temperatures and consider the question that Jim Pollack raised a moment ago. Namely, what happens if there is extinction at radio wavelengths by the rings so that, at a time like the present when part of the disk is substantially obscured by the rings, there is a dark strip across the disk of Saturn? Obviously, the best way to observe this sort of effect is to have a baseline oriented in the direction of Saturn's polar axis. Then it should be quite a simple matter to see the modification of the visibility function. In fact, I believe Briggs has some data of this very type obtained in 1972. I don't know what his results are or if he has any yet.[2]

However, even in the case of the east-west measurements, there is also a modification of the visibility function. For example, in the summer of 1971 when Briggs observed at 21 cm and we observed at 3.7 cm, the B ring and perhaps a little of the A ring were obscuring the higher latitudes in one hemisphere of Saturn. Since the part that is obscured has a smaller east-west size than the disk, the overall size should increase. I find that for the situation existing in the summer of 1971, the east-west size as measured by the position of the first zero in the visibility function should increase by about 5 percent due to this effect, assuming that the extinction is total. It's roughly linear in the sense that if the extinction is only 50 percent, then I would expect the zero crossing to move only by 2.5 percent instead of 5 percent.

Irvine Why does the overall size appear to increase?

Pollack I think the point is that if you consider strips parallel to the equator, the mean length of those strips will be bigger when you delete the poles than when you include the poles.

Berge The polar regions are smaller in their east-west extent. I think you can see that if I could extinguish both polar regions, then what remains is broader

[2] Editors' note: Briggs, in a paper recently submitted to the Astrophysical Journal describing his 3.7- and 11-cm measurements made in 1972, does find considerable extinction by the rings.

than the disk as a whole, and taking out just one of them does the same thing qualitatively.

Gordon Pettengill Wouldn't it have a greater effect north-south?

Berge Yes, and that is why I mentioned before that one should really use polar baselines.

It is interesting to note that in Briggs' results at 21 cm, the size that he fits for the disk is in fact a bit larger than the visible disk. When he fits his data, he finds that the curve comes down and crosses zero a little bit earlier than expected, which indicates a size slightly larger than the visible size. This occurs whether he simply fits to the disk or whether he fits to the disk plus the ring. In either case he gets a result that is about 2 percent too large for the size of the disk.

Moreover, that is based on the radius given in the *American Ephemeris and Nautical Almanac,* which is perhaps a bit too large. I notice that in a review paper by Cook, Franklin, and Palluconi (1973), they suggest a radius that is 1 percent less. That would mean that Briggs' result for the size is 3 percent too large.

Pettengill You say this occurs whether or not he fits with the rings included?

Berge That's right.

Pettengill How does he include the rings? What weight does he give to the extinction and emission? It certainly wouldn't be true if he assigned the rings the same value as the disk of Saturn.

Berge I see what you mean, I think. What he is fitting in one case is simply the size of the disk and its temperature. In the other case he is fitting the size of the disk, its temperature, and the temperature of the rings. He is then adding an extra parameter.

Pettengill He must be assuming something because surely if he assigned unit emissivity for the rings it would make a gross difference.

Berge No, he doesn't have to assign an emissivity, because he is simply solving for the observed brightness of the rings. He does assume that where they cover the disk, the temperature is the disk temperature plus the ring temperature, and this requires zero extinction.

Hugh Kieffer Is it not possible to maintain a constant enough calibration to see a difference in the total flux as the planet is obscured by the rings? In other words, how much does the total flux from the entire system at these wavelengths decrease?

Berge Well, this is the sort of thing that Mike Janssen (see contribution by Janssen) was talking about for shorter wavelengths.

Kieffer It hasn't been done at longer wavelengths?

Berge To date, there hasn't been sufficient accuracy or sufficient repeatability to do that sort of thing, especially at 21 cm. At this wavelength the confusion from background sources is comparable to the total flux density from Saturn for both of the instruments. Clever techniques have been used to remove it, but it is still a big problem in measuring the total flux density, at least at such a long wavelength.

Perhaps I am spending too much time on this point because the 2-percent discrepancy that Briggs finds is only a one σ result, although if you make it 3 percent, then it is 3 ± 2 percent.

The interesting thing is that at 3.7 cm at the same time we get almost the same result. That is, compared to a radius 1 percent smaller than the American Ephemeris value, it appears that the east-west radio size is 3 percent too large. Based on the scatter of our data, the error is slightly less than 1 percent, but systematic errors may increase this significantly.

One thing I should have mentioned earlier when I was talking about temperatures is that for the 3.7-cm measurements just discussed, we have also set some limits for the temperature of the rings. We find that the ring contribution compared to the disk contribution is about 3 ± 3 percent. But we also find that if we raise the size of the rings to an outer radius of 2.65 Saturn radii, a fit to the data gives a ring contribution that is almost significant. The formal result is 8 ± 3 percent for the ratio of ring contribution to disk contribution. Even so, this amounts to only about 5 K for the brightness temperature for the rings.

Brad Smith You say the data would fit if you increased the radius of the rings?

Berge That's right.

Smith You would include ring A?

Berge Yes, if we include the B ring and the A ring, and then something else that goes out to 2.65 Saturn radii in such a way that the whole system is uniformly bright, then we get the numbers that I quoted.

Smith Where does ring A fall? This is beyond the edge of ring A, then?

Pollack The A ring terminates at 2.23 Saturn radii.

Berge Yes, we are treating the ring system, B, A, and D′, let's call it, as uniformly bright.

Smith Optically, ring A falls off in brightness considerably from the Cassini division to its outer edge.

Berge That's right. So our model is probably wrong in detail.

George Morris Did that diameter optimize the temperature of the rings?

Berge Yes, that radius provides the maximum ring temperature.

Pollack And what is that temperature in degrees Kelvin?

Berge 5 K.

Pollack Eight percent is 5 K?

Berge Yes, using the angular extent of this extended ring system.

Pollack Does this analysis allow for obscuration of the disk by the rings?

Berge No, this analysis does not allow for the obscuration. Another point is that the size we determine for the disk from our data is also apparently well separated from whatever we do to the rings. We seem to need a larger size for the disk no matter what we do to the rings. No one should place too much weight on the result I just discussed because systematic effects may be giving us a fictitious result. My purpose in mentioning the result was to point out that, for our data, it appears that a small ring contribution is consistent with a ring of larger dimensions than the visual rings.

I was planning to say something about the possibility and value of observing an occultation of a radio source by Saturn's rings. However, we have already covered that subject pretty well, and I think some people are interested in it. It seems to me to be a valuable thing to do if one can survey beforehand to look for appropriate sources to be occulted.

Mike Janssen mentioned the subject of scattering of disk emission by the rings, which one would expect to be a few percent. We are certainly at the level of a few percent now, and, with any increase in accuracy, one should expect to see, if not emission, at least radiation scattered by the rings from the disk.

I don't think that I need to go into any physical interpretation of these results, because that was done quite thoroughly in the previous presentation.

It seems clear that the radar and radio results are by no means inconsistent, but between them they certainly offer some strong constraints on ring models.

DISCUSSION

William Irvine Glenn, have any of the 3.7-cm results been published?

Glenn Berge No. The 3.7-cm observations that we have are still in the stage of being interpreted. I don't know how soon Briggs' new measurements might be published.

Hugh Kieffer How far are we in terms of experimental observations from the point where, by looking for the reflected thermal energy from Saturn, you could make a statement as to whether the reflection coefficient of the planet-rings-Earth was less than the required radar reflection coefficient? How far is the experimental technique from being able to say something about the reflection phase function which the rings might have?

Gordon Pettengill How would you distinguish reflection from the direct emission?

Kieffer I am assuming we can separate them. You do expect to see something from the rings, even if it's only radiation from the disk reflected off the rings.

Berge My colleague, Duane Muhleman, has made some scattering calculations, but of course they require some assumptions. For example, if you assume that the ring is composed of isotropic scatters and there is no shadowing, then the scattering one expects to see is 5 percent of what you get for the disk itself, and we are certainly at that level now.

Kieffer It seems to me we are at the point here of having an additional technique or additional way of interpreting the data which may lead to the light.

Pettengill You have to take a guess at what the effective scattering is in the bistatic geometry of the disk-rings-Earth.

Berge Yes, that's the tough part.

Sam Gulkis Have you done the Saturn limb-darkening calculation at the long wavelengths? I am wondering whether or not the effective disk size is really smaller and the effects you are seeing are even larger than the 3 percent.

Berge That is a good point, Sam. I should have mentioned that one can explain these size results by assuming limb brightening, but that isn't likely. There is limb darkening, probably, and limb darkening makes the size discrepancy even larger. One could indeed have total extinction for the rings and still be consistent with the data if you put in adequate limb darkening.

Irvine You could have preferential darkening toward the poles.

Berge That would make it look larger east-west and smaller north-south to the interferometer.

Irvine But isn't that the kind of thing that you get with ring extinction?

Berge That's right. Polar cooling is qualitatively the same as the obscuration effect. That is another possibility that I didn't mention.

Irvine Do you have any idea what the magnitude of that might be from the models you have used?

Michael Janssen It should be small. In the major planets, ammonia absorption, as we understand it, is quite an effective thermostat. While you might physically have a great change in the temperature as you go toward the poles, the ammonia will just shift around such that it will tend to cancel out the effect. There is no reason to expect polar cooling on Saturn or Jupiter.

James Pollack The point is that optical depth unity usually is found in a very narrow range of possible temperatures.

Gulkis That isn't necessarily true at the longer wavelengths where you're off the saturation curve. Once you break through the ammonia cloud, you are again tied very closely to the lapse rate and NH_3 abundance in the atmosphere.

Dave Morrison Glenn, did you give the transmission of the ring if we accept the uniform disk and the 3-percent discrepancy in radius?

Berge If there is no polar cooling and if there is no limb darkening, then the transmission is 2/5, using these very tentative data.

Pollack That's like an optical depth of unity, as good as the observations are.

Robert Murphy The models you used contain ammonia. But there is no direct evidence of ammonia on Saturn. If it is not there, I gather, we are in worse trouble, because then you should get a higher temperature from deeper in the atmosphere. Is that correct?

Berge Yes.

Murphy We should bear in mind that there is no evidence for ammonia.

Berge Perhaps the radio data is the best evidence at the moment.

Murphy If we could understand the rings under those assumptions, yes.

REFERENCES

BERGE, G. L.; AND READ, R. B.: The Microwave Emission of Saturn. Astrophys. J., vol. 152, 1968, pp. 755–764.

BERGE, G. L.; AND MUHLEMAN, D. O.: High-Angular Resolution Observations of Saturn at 21.1-Centimeters Wavelength. Astrophys. J., vol. 185, 1973, pp. 373–381.

BRIGGS, F. H.: Observations of Uranus and Saturn by a New Method of Radio Interferometry of Faint Sources. Astrophys. J., vol. 182, 1973, pp. 999–1011.

COOK, A. F.; FRANKLIN, F. A.; AND PALLUCONI, F. D.: Saturn's Ring—A Survey. Icarus, vol. 19, 1973, pp. 317–337.