Frank Don Palluconi

SATURN'S RING PARTICLES AND SPACE VEHICLE DESIGN

I will discuss two primary areas: design, as Saturn's rings affect the mission and spacecraft, and ring particles, with particular emphasis on material outside of ring A and the hazard this might imply to spacecraft crossing the ring plane beyond ring A.

MISSION AND SPACECRAFT DESIGN

There are a number of factors that affect mission design: the scientific objectives, the capabilities that can be built into the scientific instruments and built into the spacecraft, and the natural environment. In some cases potential hazard from the natural environment has an effect on trajectory selection. In the case of the MJS project, at least in the initial specification, the trajectories have been constrained to pass no closer to the planet nor to cross the ring plane more closely than 4 Saturn radii. This points up why a description of particulate matter beyond ring A is important. The opportunities that are available as a function of trajectory will be discussed by Dr. Penzo (see following contribution).

In spacecraft design, there are three areas where Saturn's rings may have some influence: thermal control, celestial sensors, and particle shielding.

With respect to thermal control, the existing information we have about the amount of radiation emitted at thermal wavelengths from the rings, the scattered light from the rings, and, of course, the dimensions of the rings makes it possible to decide what the thermal input to the spacecraft from the rings will be. Preliminary calculation indicates the thermal input will be small compared to the heat budget of the spacecraft itself, and so it is very likely that Saturn's rings themselves, at least from a thermal standpoint, will not have a direct impact on thermal control. In particular, the spacecraft is to be designed so that it operates independent, from a thermal-control standpoint, of the environment. The thermal

design is really set by the extremes in the natural environment, which occur near Earth just after launch and near Saturn prior to encounter.

Scattered light from Saturn's rings is a problem for celestial sensors. Two sensors are used for providing attitude reference: a solar tracker and a Canopus tracker. The solar tracker will not be affected by scattered light from the rings. It will only be affected by occultation of the Sun by the planet or by the rings, and in this case an inertial reference will be provided. The Canopus tracker is more sensitive with respect to scattered light. The information that exists from ground-based observations is sufficient for design of this tracker. In this case, as well, if the rings intrude too far into the field of view, inertial reference will be provided.

With respect to both of these areas, thermal control and celestial sensors, information about the basic properties of the bright rings, which already exists, is probably sufficient to come up with a good design.

At this time there is no plan to burden the spacecraft with shielding, which is primarily intended to provide protection against Saturn ring particles. Our understanding and modeling of material beyond ring A is sufficiently poor that this kind of exercise would not be profitable. Rather, the emphasis has been placed on selecting a judicious trajectory, which minimizes in itself the hazard to the spacecraft. This doesn't mean, however, that the spacecraft won't be provided with some shielding that would be effective against particles, including any encountered near Saturn.

There are a number of ways in which this will come about. The first and most obvious is the basic structure of the spacecraft, which will provide some shielding both for subsystems and science instruments. In addition, two natural environments, interplanetary meteoroids and charged particle radiation from the Jovian radiation belts, solar-type protons, and onboard radiation sources may require shielding, which would also be effective against particles. There are also several additional problems—producing an electromagnetically clean spacecraft and accounting in some way for the possible effects of differential electrostatic charging—that may require design features which would be effective in producing some kind of shielding.

PARTICLES BEYOND RING A

Turning to Saturn's rings themselves, table I presents the dimensions of the system. I would like to use this table not so much to discuss the dimensions of the ring system, which come from a compilation by Cook et al. (1973), but rather to discuss the regions of Saturn's rings where there are thought to be relatively few particles and which are possible candidates for crossing by a spacecraft. The three regions that one might initially consider are the ring D region, named following a suggestion by Guerin (1970), Cassini's division, and the entire region outside of ring A, which I have labeled the D' region in order to maintain some connection with previous terminology.

A number of estimates for optical thickness have been made for these regions. One I would like to mention in particular was based on an analysis by Cook

TABLE I.—*Saturn's ring dimensions.*

Ring	Feature/ring boundary	Distance from center of planet, km	Nominal distance in equatorial radii, R/R_s
Ring D	Equatorial radius	59 800 ± 350	1.00
Ring C	Inner C boundary	72 000 ± 3500	1.21
Ring B	Inner B boundary	91 400 ± 700	1.53
	Outer B boundary	116 700 ± 700	1.95
	Width of Cassini's division	$4\ 800\ {+1400 \atop -2800}$	
Ring A	Inner A boundary	121 600 ± 700	2.03
D'region	Outer A boundary	137 100 ± 700	2.29
	Outer limit to D'ring region	239 200 − 358 800	4–6

and Franklin (1958) of observations made by Barnard of the shadowing of Iapetus by ring C. This led to a deduction for the optical thickness of ring C, including its inner boundary, closer to the planet than any condensations have been noted during ring plane passage. At the inner edge of ring C, the optical thickness was felt to be small, on the order of 10^{-2} or so. This certainly represents an upper limit to the optical thickness of the material within the ring D region and very likely is a conservative upper limit for the optical thickness of any material outside ring A.

So far as I know, there has never been any serious consideration of trajectories that pass either through the Cassini division or the ring D region, apart from some suggestions made at the time the Grand Tour missions were considered. The prime purpose of passages through Cassini's division or ring D was to reduce the transit time to planets beyond Saturn.

The primary interest with respect to the MJS project is in the region outside ring A extending to $4\ R_S$ or $6\ R_S$ or beyond, where there is some evidence for material.

I would like to discuss essentially the totality of information that exists with respect to material beyond ring A. There are a number of visual sightings of a narrow ring just outside of ring A; two sequences of photographs that show the presence of a line representing, perhaps, extended ring material; and the recent radar detection of Saturn's rings.

The visual sightings were reported primarily during two periods of time. The first, in the period 1907–1909, followed the 1907 ring plane passage of the Earth across the ring plane (Alexander, 1962, chapter 28). The second followed the 1950 passage of the Earth across the ring plane in the years 1952 and 1954. The earliest

reports indicated a narrow ring just outside of ring A. It was seen both in front or near the planet and in the ansae. There were some anomalies with respect to these observations. The ring width deduced from observations near the planet did not correspond to the width in the ansae. The suggestion made at that time was that perhaps this was evidence for extraplanar particles.

The second set of observations refers to the period following the 1950 ring plane passage, during which a number of observers reported seeing material just beyond ring A. For the most part, these observations and the earlier ones were made with small telescopes less than 16 in. in diameter, although during 1952 there was one observation by Cragg (1954) using the 60-in. reflector at Mt. Wilson. Cragg reported a narrow ring immediately adjacent to ring A, with a width of about 6000 to 10 000 km and an overall brightness about one-half the brightness of ring C.

There have been negative findings during both these time periods as well. Barnard, aware of the reports of a narrow ring outside of ring A, used a 40-in. refractor to carefully scrutinize the region just outside ring A in about 1909 and concluded that he could find no evidence whatsoever for this external ring. A similar occurrence happened in 1954 when—I think within about a month of one of Cragg's observations—Kuiper (1973) made observations with an 82-in. reflector and with the 200-in. reflector, again carefully scrutinizing the region just outside ring A. He was able to find no evidence for an exterior ring and felt from at least the 82-in. observations that the brightness of any material had to be less than 1/40 the brightness of ring C.

There is also a point I would like to make with reference to work done by Franklin et al. (1971). They looked at the properties of the rings from a dynamic standpoint, considering the perturbing effect of Saturn's satellites. In this work they were able to show that it is possible for relatively stable particle orbits of small eccentricity to exist in the region just outside of ring A. I would like to emphasize, however, that the existence of such stable orbits does not imply anything about their being populated by particles.

The most extensive evidence for material beyond ring A consists of photographs. I would like to defer discussion of those for a moment and make one point about the recent radar detection of Saturn's rings, which will be considered in more detail by Dr. Morris (see contribution by Morris). There is a low doppler shift portion to the radar return. Among several explanations for this low doppler shift portion, and probably not the most likely, is that it refers to reflections from particles that are orbiting outside of ring A. The point I would like to make is that those observations don't in themselves imply or place any requirement that this material be in the same plane as the principal rings. I think it is useful in the context of this workshop to at least entertain the suggestion that there may be particles with nonzero inclination. This aspect is particularly relevant in determining the hazard from external ring material.

So far as I know, there are two sets of observations in which the photographs taken show a narrow spike extending outside the bright rings. These observations were made by Feibelman (1967) and Kuiper (1973 and 1972). A brief summary of this material is given in table II. Both sets of observations refer to the same

TABLE II. — *Summary of photographs of extended ring material.*

Observer	Telescope	Observing period	Exposure time	Radial extent	Brightness, mag/sq sec of arc	Effective reflecting area
W. A. Feibelman	30-in. refractor	October, December, January 1966–1967	5–30 min	$> 4 R_S$	$\simeq 15$	—
G. P. Kuiper	61-in. reflector	October, December, January 1966–1967	10–60 s	$\simeq 6.3 R_S$	$\simeq 15$ Definite decrease with increasing radial distance	3×10^5 km^2

time period — the 1966 passage of the Earth across the ring plane — and in particular to the observing period of October, December, and January. Between about October 29 and December 17, the Earth and the Sun were on opposite sides of the ring plane, and on December 17 the Sun and the Earth returned to the same side of the ring plane.

Feibelman designed his program specifically to search for the existence of external ring material. He used a 30-in. refractor and very long exposure times, ranging from 5 to 30 min. He did not publish or attempt to publish reproductions of his photographs. Rather, he made photodensitometer tracings across the ring plane on several photographs and felt that he could see a definite indication of material or an increase in density of the negatives as the ring plane was crossed. He felt that this material extended as far as 4 Saturn radii, and perhaps beyond. He also estimated the brightness of this faint line at something like 15 magnitudes per square second of arc. He made no estimate of the reflecting area that could be inferred from this type of observation.

Dr. Kuiper's observations were made at the same time using a 61-in. reflector. He used much shorter exposures, ranging from 10 to 60 s, and felt he could detect the presence of this ring somewhat farther out than Feibelman, perhaps to the orbit of Dione or to about 6.3 Saturn radii. His estimate of the brightness of the faint extension was essentially the same as Feibelman's. In addition, he was able to detect a definite decrease in brightness with radial distance from the planet and a definite thickening in this faint extension as the inclination of the observer above the ring plane increased from 0.1° to 0.5°. He also estimated the total line brightness and, based on an assumption of the albedo, deduced an effective reflecting area for this material of something like 3×10^5 km^2. This material is essentially in the same plane as the principal rings of Saturn.

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Brad Smith   How does this brightness compare with the brightness, say, of ring B or ring A?

Palluconi   It is appreciably fainter.

I would also like to mention at least one negative photographic observation. Rosino and Stagni (1969) made extensive observations of the Saturn ring system at the time of ring plane crossing in October, December, and January 1966–1967. They were aware of Feibelman's report and made photodensitometer tracings normal to the ring plane at about the same distance that Feibelman did, between 3 and 4 Saturn radii. They were unable to detect the presence of any external ring material. In addition, Focas and Dollfus (1969) and Sekiguchi (1968) have taken an extensive number of photographs at this time, and, so far as I know, they have not reported detecting any exterior ring material.

Smith   I would like to add another negative observation. This was made in New Mexico in 1966 at the time of the crossing through the ring plane, and, although I haven't yet worked this out in terms of magnitude per square second of arc, it must be something on the order of 15.

Dr. Kuiper has kindly supplied me with a copy of the manuscript which contains reproductions of his photographs and in addition a copy of a "Lunar and Planetary Laboratory" publication which also contains some reproductions, which I will make available to the participants of this workshop.

I would also like to mention a brief program carried on at JPL for the purpose of trying to place some kind of limit on the amount of material that may exist outside ring A at the time when the rings are fairly wide open. This is a much more difficult observation, and for this purpose a silicon-imaging photometer was used. This instrument has several advantages. In particular, its large dynamic range and linearity make calibration with respect to the planet and bright rings relatively easy. The digital form of the output makes it susceptible to computer manipulation and makes possible an attempt to eliminate the effects of scattered light from Saturn and the bright rings.

One thing which I don't think the photographic evidence makes particularly clear is the radial distribution of material. That is, it is possible that the photographic observations could be adequately represented by one or more narrow rings with, perhaps, one extending to 6 or so Saturn radii. If in fact the density in narrow regions were appreciably above that implied by these observations on the average, then making observations when the ring plane is fairly wide open might have some value. I think it would be appropriate in the discussion session to be held tomorrow to consider continuing or extending these observations.

THE HAZARD FROM PARTICLES OUTSIDE RING A

What I would like to do next, particularly with respect to the estimate of reflecting area made by Dr. Kuiper, is to consider a simple framework that enables one to make a rough estimate of what the hazard might be in crossing the ring plane with this amount of material.

I have constructed a very simple framework that enables one to estimate the hazard:

$\alpha \equiv$ fractional area occupied by particles

$\pi r^2 \equiv$ area of particle

$A \equiv$ effective area of spacecraft

$\theta \equiv$ inclination of trajectory to ring plane

$$\frac{A \cdot \alpha}{\sin \theta \ \pi r^2} = \text{number of impacts}$$

The first quantity is α, which I have taken to be the fractional area occupied by the particles in a planar geometry when you view the ring normally. It can effectively be equated with the optical thickness. Next, I have assumed that the particle area can be represented by πr^2, where I have taken the particles to be a single size for any particular consideration. This assumption, of course, is wrong. One would expect that there would be a dispersion in particle size, in which case it would be important to know what that dispersion was in order to use the appropriate moment. In addition, I have identified A as the effective area of the spacecraft and θ as the inclination of the trajectory to the ring plane, measured from the ring plane. With those four quantities, one can very simply estimate the number of impacts. The quantity I have indicated by $\alpha/\pi r^2$ represents the surface density of particles, and A divided by $\sin \theta$ simply gives the effective area swept out by the spacecraft in crossing the ring plane.

Figure 1 utilizes this expression and gives the number of impacts as a function of particle radius for a number of values of α. The number of impacts is displayed on the ordinate. The abscissa indicates the particle radius, ranging from a millimeter to a meter. For the purpose of being explicit with respect to numbers, I have made two choices, one with respect to the area of the spacecraft, which I have taken at 10 m², and the other the angle of inclination, which I have taken to be 90°. If, for example, one had a trajectory that was inclined only 1° with respect to the ring plane, the number of impacts would increase by approximately a factor of 55 over those shown.

I have also indicated by the horizontal dashed line the probability of no impact, which is constant for a given number of impacts. It is essentially the exponent of the number of impacts. If you have a description of a potentially hazardous natural environment, it is common to decide on some other basis what constitutes an acceptable level of risk, perhaps expressed as a probability of no impact, and then look at the environment and develop a strategy based on what the probability of no impact is for a particular set of assumptions.

What I would like to do is take the estimate which Dr. Kuiper made of 3×10^5 km² as the effective reflecting area represented by this observation and uniformly distribute that material from the outer edge of the A ring to 6 Saturn radii. If we do that, the value of α, or the optical thickness, is on the order of 10^{-6}. As can be seen from figure 1, there may or may not be a significant hazard depending on the dominant particle size. The point I would like to make with this figure is that
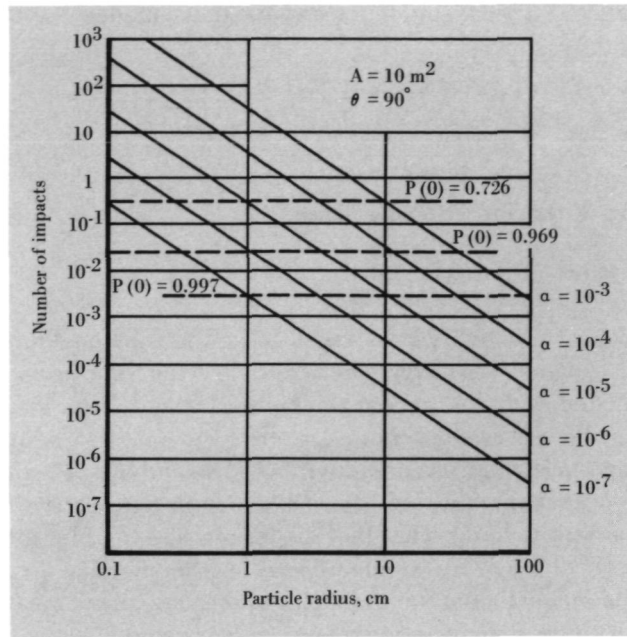
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FIGURE 1. — *Number of impacts vs particle radius. Solid lines are labeled by fractional area occupied by particles, α; dashed lines are labeled by probability of no impact, P(0).*

it is not sufficient in itself to have a very small optical thickness; one also needs to know or make some argument about the particle size.

Three kinds of descriptions of the particles outside ring A can be made, any one of which would be of appreciable help in making an assessment of the hazard.

The first one is an assessment that there is no material there or an insignificant amount of material. For purposes of this workshop, I think that it would be well to consider the possibility that the whole of the existing observational information could in fact have some alternate explanation which does not require material or particles outside of ring A.

A second kind of description would be partial. This is a less detailed solution but nevertheless one which presents some important information. It could take, for example, the form of regions to be avoided. The region immediately outside of ring A, for perhaps 0.1 R_S, might be one such region. The converse would be regions that are safe. In that regard, crossing at the orbit of one of the inner satellites of Saturn might be such a possibility. Mimas, which has the largest eccentricity of the five inner satellites — excluding Janus — is a candidate.

The third case would be a full model or a full description of the particulate matter found in this region. This would basically consist of an estimate of the spatial density of particles, and, if it were felt that there was a possibility that not all the particles were in ring plane, this would include the spatial density as a function of inclination. In addition, it should contain the dispersion in particle size and an estimate of particle density.

36   *The Rings of Saturn*

The final point I would like to make is that, with respect to the whole problem of the existence and form of material beyond ring A, any contribution this workshop can make in one form or another to a description of this material will be helpful not only to outer planet projects in general but of particular importance to the MJS project at this time.

DISCUSSION

Brad Smith Did you say that you have made or are going to make vidicon observations?

Frank Palluconi I think the word is "have made." We had three nights in the winter of 1973. These observations were made under the direction of Dr. A. Goetz from Mt. Wilson using the 60-in. telescope and an instrument that had been put together at JPL. We had a significant problem: interference from the many transmitters on Mt. Wilson produced records that were unusable for the purposes that we had intended. This problem has been corrected by readjusting grounding points, and hopefully this is now a relatively insignificant problem.

Smith So you can't give any upper limits of the brightness of this D' ring relative to ring C or ring B at this time?

Palluconi Not based on those observations.

William Irvine Do I understand, Brad, that your observations are not necessarily inconsistent with Kuiper's — that they are at about the same level?

Smith Well, I would have to see what our limiting magnitude is, but I would estimate that it is of that order. But, of course, a magnitude one way or the other could make a lot of difference. We found no evidence whatsoever of any extension beyond the edge of ring A. Furthermore, we have done some preliminary photometry on photographs that were taken last year. Photographs being so nonlinear and having such a small dynamic range, it is difficult to put upper limits on the brightness of the so-called D' ring. We are still working on it, and our first guess is that the brightness cannot be any greater than 1 percent of the brightness of ring C at the distance of Mimas.

Robert Murphy Don't you have to work at about 20 magnitudes per square second of arc or less in order to do this properly now because of the tilt change?

Palluconi Yes, as I mentioned, it is very much more difficult. If the observations in fact represent uniformly distributed material, it would be extremely difficult if not impossible to set a useful upper limit. I think the value of observations at present is in answering the question, "Are there any narrow rings of increased spatial density which would represent regions to be avoided?" In that regard the observations might be quite helpful. If one could really effectively handle the scattered light problem it would be possible to make observations that refer to brightness levels limited only by the sky background. That's where we would like to be able to work. The problem with many of the photographs already in existence is that scattered light from Saturn's rings and from Saturn itself precludes setting very restrictive limits on the brightness from this exterior region.

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