BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: The Spacecraft Debris Cloud and Optical Environment - Case 710

DATE: April 19, 1968

FROM: C. Buffalano

## ABSTRACT

Previous calculations of the brightness of the debris cloud surrounding a spacecraft have greatly overestimated the difficulty of studying dim astronomical sources during the daytime. The largest source of scattered light in these estimates is micron sized ice crystals which are formed from the water vapor in the cabin gas which leaks out of the spacecraft. This document reports strong counterarguments showing that the formation of large crystals should not occur and that more reasonable size estimates lead to particles too small to cause significant scattering. While the magnitude of the total optical environment problem will not be determined until flight measurements are evaluated, it would seem more fruitful in the mean time to turn our attention to contaminants other than the leaked cabin atmosphere.

It is certainly premature to contend that daylight observations of dim sources will not be possible from manned spacecraft.

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MEMORANDUM FOR FILE

## INTRODUCTION

A spacecraft is a source of many kinds of debris. The vehicle leaks cabin atmosphere, man and machine wastes are dumped overboard, thrusters are fired periodically, and the surface outgases. Once free of the spacecraft, the debris is subjected to several forces - collisions with molecules in the ambient atmosphere, self collisions, the gravitational attraction of the earth and spacecraft, radiation pressure, and, if during its lifetime the debris becomes charged, electrodynamic forces due to any spacecraft charge as well as electric and magnetic fields of geophysical origin. Under the action of these forces, the debris forms a cloud around the spacecraft until swept away by the same forces. This is indicated schematically in Figure 1.

All the debris in the cloud scatters light to some extent, and a major problem is the determination of the radiance or brightness of this cloud and its effect on daytime studies of faint astronomical sources such as the solar corona, zodiacal light, and very faint stars. Several investigators have calculated upper bounds on the radiance of the debris cloud. [Ney and Huch (1966), Newkirk (1967), and Kovar et al. 1967, 1968] Subject to their assumptions, they calculated that a cloud radiance as high as one hundred times the coronal and zodiacal level might be possible. Levels this high would make it impossible to study these important dim sources during the day and were invoked to explain the fact that astronauts have had varying degrees of difficulty visually acquiring even first to fourth magnitude stars during the day. (Roach et al. 1966) Alternate explanations which do not require a bright debris cloud are also current, however. Dunkelman (1967), Ney and Huch (1966) and Schmidt (1967) have suggested that glare on the windows, cabin lights, or physiological phenomenon could be the cause.

The largest source of scattered light in the calculations of Newkirk and Kovar et al. is micron sized ice crystals which are assumed to have been formed from the water vapor in the leaked cabin atmosphere. To make an upper bound calculation of radiance they assumed 100% conversion of water vapor to ice crystals of large size (.2 - 10μ radius). Because the brightness of the debris cloud is extremely sensitive to these assumptions, this investigation will consider their validity and center around the questions of whether or not condensate forms in the leaked cabin gas and, if it does, what size it might have.

It has been argued that since homogeneous nucleation occurs in supersonic wind tunnels we might expect it to occur in spacecraft leaks. We will show that the appearance of condensate in supersonic wind tunnels is irrelevant to the spacecraft problem. It may be argued that gas passing through small leaks will condense on the inner surfaces of the channel where it may grow to a large size and be blown out. We will show that this is unlikely to interfere with most observations even if it does occur. Finally, the appearance of condensate in free jets has been used to suggest the possibility of ice formation as molecules leak out of the spacecraft. We will show that a representative size for such condensate can be estimated and that it is so small that scattering is unimportant.

These conclusions are not new. On thermodynamic grounds, a Ball Brother's ATM contamination study (1967) concluded concerning gaseous effluent, "It can be seen that the formation of droplets by homogeneous nucleation is an unlikely event except under unique circumstances. We know of no report of seeing fog or droplet formations caused by small leaks into a vacuum system. Condensation on salt particles and charged particles improves the chances for droplet formation, but it is still unlikely to happen in the low pressure region about the spacecraft. Small leaks are considered not to be a source of scattering particles, and no remedial action is needed."

IS THERE SUPPORT FOR THE ASSUMPTION THAT HOMOGENEOUS NUCLEATION PRODUCES ICE CRYSTALS WITH RADII IN THE .1 TO 10 MICRON RANGE FROM THE WATER VAPOR IN THE LEAKED CABIN ATMOSPHERE?

To justify the assumption that ice particles form in the leaked cabin atmosphere, Kovar et al. contend, (Sky and Telescope, 1968).

> "The thermodynamic state of the escaping water can also be found from a Laval-nozzle analysis. Experiments with gases such as carbon dioxide or water vapor in supersonic wind tunnels have shown that particle formation occurs downstream from the nozzle throat, even though no foreign condensation nuclei are present. Thus, we may assume that water vapor leaking through the cabin walls will form ice particles upon reaching space."

It is our contention that the flow of the leaked cabin gas does not resemble the flow in a supersonic wind tunnel at all and therefore the argument from this experimental data is specious. The flows are not analogous because in a supersonic wind tunnel the effects of the walls containing the flow are confined to a relatively small boundary layer while, for the type of leak occurring in a spacecraft, the wall effects predominate.

Consider a supersonic wind tunnel with a throat diameter of ten inches. Humid air enters the inlet, is accelerated in the converging part of the nozzle to Mach 1 and is subsequently expanded to higher velocities while the temperature drops continuously. Somewhere downstream of the throat homogeneous nucleation occurs and ice particles are formed. Suppose the wind tunnel diameter is reduced to only one inch and the experiment is run again. How will the change in the throat diameter effect the size and density of the particles formed? The answer is that it will not effect the size or the density at all because while the walls are much closer, the boundary layer thickness is essentially unchanged and still small compared to the throat diameter. The gas near the center of the wind tunnel cannot tell the difference between the ten inch and the one inch throats. In this sense both flows are analogous or scalable. If, however, one makes the throat so small that the boundary layer fills it completely, nucleation occurs by a different physical process which is controlled by the walls. In the Wegener and Pouring (1964), and H. Thomann (1966) wind tunnel experiments cited by Kovar et al., throat sizes were chosen specifically to reduce these wall effects. The purpose of these experiments was to study homogeneous nucleation which occurs in the absence of foreign nuclei or walls, and not heterogeneous nucleation which occurs in the presence of walls. Can homogeneous nucleation occur in a spacecraft leak? Are the holes large enough to have small boundary layers?

If there were a supersonic nozzle in the spacecraft wall, the total mass loss of the Apollo CSM ($10^{-2}$gm sec$^{-1}$) could be accounted for by a single hole with a throat diameter of $10^{-1}$cm. Actual hole sizes are much smaller, of course, because there is not one hole but many in the spacecraft. In the experiments of Wegener and Pouring the boundary layer thickness was experimentally determined to be $.5\times10^{-1}$cm in a throat of 5cm. Since this is larger than actual spacecraft hole sizes it seems clear that the holes do not have small boundary layers and therefore analogies with supersonic wind tunnels are unfounded.

Homogeneous nucleation could also occur, however, if spacecraft leaks were similar to free jets. A free jet is a nozzle cut off at the throat. K. Bier and O. Hagena (1963) using such a device in molecular beam experiments found condensate in the beam but particles had only 2 to $2 \times 10^3$ molecules depending on operating conditions. In the worst case estimates of Newkirk and Kovar et al. particle distributions with minimum radii of .2 - .4 microns and a maximum radius of 10 microns were assumed. A .2μ particle contains $10^9$ $H_2O$ molecules, a 10μ particle $10^{14}$! We are faced here by enormous differences between the size of ice particles one might reasonably expect and those previously postulated. Are there mechanisms in the free jet to bridge this gap? The following considerations indicate that there are not.

Condensation is an inelastic collisional process and large agglomerates appear only after many collisions have occurred. This process takes time but, in a free jet, there is very little time because, as the molecules stream from the jet, they fan out into space reducing their density until finally collisions cease. The ultimate size of particles is controlled by the number of collisions which can occur before the interactions stop.

To estimate an upper bound on particle size, a calculation has been made based on the following assumptions which in every case overestimate the number of collisions a particle undergoes.

a) Every binary collision between molecules causes accretion. The conditions for accretion in real gases are more complex with some aggregates being broken down at the same time as others grow. This assumption greatly overestimates the growth rate.

b) There is only one hole in the spacecraft. By concentrating all the mass loss in a single hole one minimizes the effect of the decreasing density as particles fan out in space. This maximizes the number of collisions which occur and therefore the ultimate particle size.

In actual spacecraft, of course, there are probably thousands of very small leaks rather than a few large ones which greatly reduces the maximum size of particles.

c) The jet is always in local thermodynamic equilibrium. We have calculated collision frequencies based on the assumption that many collisions occur in the gas as it expands into space. Just the opposite is true. The gas is only in equilibrium for a very small distance from the exit. Beyond that distance, particle mean free paths are comparable to the hole dimensions so that thermal equilibrium collision rates are not realized. This further reduces the size of agglomerate.

Subject to these maximizing assumptions, the calculation presented in the Appendix shows that a typical ice crystal contains less than $2 \times 10^3$ molecules not the $10^9$ to $10^{14}$ molecules assumed in the previous estimates. This huge discrepancy removes homogeneous nucleation as an important mechanism for producing large scattering from the leaked cabin gas.

HOW SENSITIVE IS THE CLOUD RADIANCE TO THE SIZE OF THE DEBRIS?

The preceding considerations assume a great deal of importance in view of the sensitivity of the cloud radiance to the size of the debris. The radiance of the debris cloud can be estimated by assuming that the expansion of the ejecta is roughly spherical and by using some limit to the size of the cloud to account for the sweeping away of the debris (Newkirk, 1967). This assumes a relatively large number of spacecraft leaks reflecting the belief that leaks are highly dispersed and small. We will show that these particular simplifications are acceptable because the radiance is much more sensitive to the particle size than to the detailed dynamics of the particles.

The radiance of the debris cloud due to scattered sunlight is frequently written as:

$$\frac{B}{B_\odot} = \Omega_\odot \bar{\sigma} M$$

where $\Omega_\odot$ is the solid angle subtended by the solar disc ($6.8\ 10^{-5}$ sterad), $\bar{\sigma}$ is the total scattering cross section per unit mass, and M is the mass column density. The measure of brightness used in this discussion is $B/B_\odot$ which compares the radiance (B) of an extended source to the radiance of the sun ($B_\odot$). Radiance B is defined as the amount of energy crossing a unit area of detector in a unit time and coming from a unit solid angle of source. (The radiance of the sun is $2.04 \times 10^{10}$ ergs $cm^{-2}$ $sec^{-1}$ $sterad^{-1}$.) Shown in Figure 2 is the radiance of coronal and zodiacal sources as a function of solar elongation. It is obvious that debris radiance must be smaller than this value if one wishes to study these sources in visible light during the day. The mass column density is given by

$$M = \int_{R_{min}}^{R_{max}} dR \int_{a_{min}}^{a_{max}} da\ m(a)\ N(R,a)$$

5<

where R is the distance to a scatterer, $R_{max}$ is the extent of the debris cloud and $R_{min}$ is the distance to the nearest scatterer. ($R_{min}$ is usually taken as the size of the spacecraft.) Each scatterer has a radius a and a mass m(a). N(R,a) is the size distribution function of scatterers i.e., N(R,a) da is the number of scatterers in a unit volume with radii between a and a+da. The mass column density M is just the total mass contained in a column with a unit area base extending along the line of sight. If the expansion is spherical so that densities fall off as $1/R^2$, then it follows that:

$$M = \frac{Q}{4\pi U_o R_{min}} \left[ 1 - \frac{R_{min}}{R_{max}} \right]$$

where Q is the total mass efflux of scatterers from the spacecraft, and $U_o$ is their ejection velocity. It is now clear why the detailed dynamics are relatively unimportant. The dynamics of the ejecta can be considered to be represented by $R_{max}$, the extent of the cloud. The function $1-\frac{R_{min}}{R_{max}}$ is insensitive to $R_{max}$ unless $R_{max}$ is very nearly $R_{min}$ which, for the altitudes and sweeping mechanisms considered, is not the case. A detailed investigation of $R_{max}$ is given by Newkirk and $R_{max}/R_{min}$ values of fifty are typical. An upper bound on M (corresponding to the total absence of sweeping as $R_{max}\rightarrow\infty$) and a very good estimate is,

$$M \lesssim \frac{Q}{4\pi U_o} R_{min}$$

Total mass leak rates on the order of $10^{-2}$ g/sec were typical for the Gemini (Cape Kennedy Archives). Assuming an efflux velocity of 500 m/sec. based on thermal effusion from a small hole and an $R_{min}$ of 200 cm. one obtains

$$M \lesssim \frac{10^{-2}\ \text{gm/sec}}{4\pi\ 5\ 10^{4}\ \text{cm/sec}\ 200\ \text{cm}}$$

$$\lesssim\ 10^{-10}\ \text{gm/cm}^2$$

of which roughly $10^{-10}$ gm/cm$^2$ are oxygen and $10^{-12}$ gm/cm$^2$ are water molecules.

The most sensitive parameter is $\bar{\sigma}$, the total scattering function, given by

$$\bar{\sigma} = \int_{a_{min}}^{a_{max}} da\ \ \sigma(a,\theta) \int_{R_{min}}^{R_{max}} dR\ \ \frac{N(R,a)}{M}$$

where $\sigma$ is the relative scattering function, and $\theta$ is the angle between the line joining the scatterer and the sun and the line joining the scatterer and the observer. It is also equal to the elongation of the observer as shown in Figure 1.

For spherical ice particles with radii smaller than a few hundred angstroms and with a refractive index (m) equal to 1.3, Rayleigh scattering at optical wavelengths is appropriate and the relative scattering function is (Van de Hulst 1957),

$$\sigma(a,\theta) = \frac{1+\cos^2\theta}{2} \left(\frac{2\pi}{\lambda}\right)^4 \left(\frac{m^2-1}{m^2+2}\right)^2 a^6$$

where $\lambda$ is the wavelength of the incident light ($\sim$4000 Å). If all the particles have the same radius $a_o$, performing the integration indicated in the expression for $\bar{\sigma}$ gives,

$$\bar{\sigma} = \frac{3}{4}\ \frac{1+\cos^2\theta}{\rho_{ice}\ \lambda} \left(\frac{2\pi a_o}{\lambda}\right)^3 \left(\frac{m^2-1}{m^2+2}\right)^2$$

It is now apparent why $\bar{\sigma}$ is so sensitive to debris size. It is proportional to the cube of the particle radius. Thus doubling the estimate of the particle radius will increase the radiance an order of magnitude. Figure 3 shows the range of $\bar{\sigma}$ for Rayleigh scattering from particles with radii up to 100Å at zero elongation ($\theta$=0), as well as the values used by Newkirk and Kovar et al. for larger particles. For these, Rayleigh scattering is inappropriate at optical wave lengths because of the large size and the more complete Mie scattering theory was used to obtain numerical results. Newkirk used values calculated by Bullrich et al. (1962) while Kovar et al. used results of a digital computation of their own. The important feature in Figure 3 is that a very large range of $\bar{\sigma}$ has been used, a range which carries the brightness from values so low as to be inconsequential to values so high as to be overwhelming. In Figure 2 $B/B_{\odot}$ is shown as a function of elongation for 10, 50, and 100Å particles as well as the very large particle distributions of Newkirk and Kovar et al. The calculations of Newkirk and Kovar et al. differ not only in $\bar{\sigma}$ but also in the mass column density. The $\bar{\sigma}$ differences are due to differences in refractive index and particle distribution functions while the differences in mass column density are due to differences in the assumed mass flow rates.

It is important to note that even for 100Å particles which contain $10^5$ molecules (100 times more than presently seems possible) the maximum brightness is always at least three order smaller than the coronal and zodiacal light! For smaller particles (10Å, $10^2$ molecules) it is nearly five orders smaller!

## HETEROGENEOUS NUCLEATION

Since homogeneous nucleation inside a spacecraft leak has been shown to be unlikely because of the small size of the holes, and since homogeneous nucleation in the leaked gas in space has been shown to lead to particles too small to scatter light significantly and since it is clear that wall effects are predominant in the physics of the leaked cabin atmosphere, let us consider the possibilities of heterogeneous nucleation. If the spacecraft walls were cold enough, it might be possible for condensate to form on the walls confining the leak, coalesce, freeze, and be ejected as ice. In order for the walls of the leak to be cold, the leak must either be on the unlit side of the spacecraft or in constant shadow on the lit side. Since the aerodynamic drag force acting on a debris particle is parallel to the local orbital velocity it follows that an ice crystal ejected on the unlit side of the spacecraft stays on the unlit side and is unlikely to cross into the sun-lit side. This means that if the telescope line of sight lies on the lit side of the spacecraft no debris will be visible.

On the other hand, the earth occults a significant part of the sky in the anti-solar direction so the major interference with viewing would be in the direction roughly normal to the orbital plane.

We are presently investigating the degree to which heterogeneous nucleation may be responsible for debris.

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Attachments
- Appendix
- References
- Figures 1-3

## APPENDIX

1. Calculate the number of $H_2O$ molecules in a .2μ radius spherical ice particle

$$\text{mass of .2μ particle} = \frac{4}{3}\pi\,(.2 \times 10^{-4}\text{cm})^3\ \frac{\text{gm}}{\text{cm}^3}$$

$$= 3 \times 10^{-14}\text{gm}$$

$$\text{number of } H_2O \text{ molecules} = \frac{3 \times 10^{-14}\text{gm}}{18\ \text{amu}}\ \frac{\text{amu}}{1.659\ 10^{-27}\text{kg}}\ \frac{\text{kg}}{10^3\text{gm}}$$

$$= 10^9\ H_2O \text{ molecules}$$

2. Calculate the number and mass density of $H_2O$ in the cabin.

Assuming that $O_2$ constitutes 97% and $H_2O$ 3% by mass of the cabin atmosphere, that the cabin pressure is 1/3 atmosphere and that the temperature is 68°F, the perfect gas law gives

$$\text{number density} = n_{H_2O} = \frac{P\ \text{cabin}}{M_{H_2O}\ (R_{H_2O} + \frac{100}{3} R_{O_2})\ T}$$

$$\text{and mass density} = \rho_{H_2O} = \frac{P\ \text{cabin}}{(R_{H_2O} + \frac{100}{3} R_{O_2})\ T}$$

Since

$$R_{H_2O} = 85.81\ \frac{\text{ft lbf}}{\text{lbm °R}}$$

$$R_{O_2} = 48.31\ \frac{\text{ft lbf}}{\text{lbm °R}}$$

$$n_{H_2O} = \frac{1}{3}\left|\frac{14.7\ \text{lbf}}{\text{in}^2}\right|\frac{\text{lbm °R}}{1700\ \text{ft lbf}}\left|\frac{}{528\ \text{°R}}\right|\frac{\text{in}^3}{1\ \text{lbm}}\ \frac{27\ \text{gm}}{\text{cm}^3}\left|\frac{\text{ft}}{12\ \text{in}}\right.$$

$$\times \quad \frac{H_2O \text{ molecule}}{18 \text{ amu}} \left| \frac{\text{amu } 10^{27}}{1.659 \text{ kg}} \right| \frac{\text{kg}}{10^3 \text{ gm}}$$

$$= \quad 4 \times 10^{17} \; H_2O \text{ molecules/cm}^3$$

and $\quad \rho_{H_2O} = 1.2 \times 10^{-5} \text{gm/cm}^3$

3. Calculate the mass flow rate through a .1 cm. diameter sonic nozzle.

$$\text{mass flow rate} = \rho_o \, a_o \, A \, \frac{\rho}{\rho_o} \, \frac{v}{a} \, \frac{a}{a_o}$$

where the zero subscript refers to cabin conditions and the unsubscripted quantities are taken at the throat. For a sonic throat

density ratio $= \frac{\rho}{\rho_o} = .634$

sound speed ratio $= a/_{a_o} = .913$

Mach number $= v/_a = 1$

} Mechanical Engineer's Handbook p. 11-92

In the cabin:

$$\rho_o = \frac{100}{3} \rho_{H_2O} = \frac{100}{3} \left| \frac{1.2 \; 10^{-5} \text{gm}}{\text{cm}^3} \right.$$

$$= 4 \times 10^{-4} \text{gm/cm}^3$$

$$a_o = \sqrt{\gamma RT} = \sqrt{1.4 \;\; 48.31 \; \frac{\text{ft lbf}}{\text{lbm } ^oR} \; 528 \; ^oR \quad \frac{\text{lbm}}{\text{lbf}} \frac{32 \text{ ft}}{\text{sec}^2}}$$

$$= 1070 \text{ ft/sec}$$
$$= 3.2 \times 10^4 \text{cm/sec}$$

These values give

$$\text{mass flow rate} = \frac{4\ 10^{-4}\text{gm}}{\text{cm}^3}\left|\frac{3.2\ 10^4\ \text{cm}}{\text{sec.}}\right|\frac{\pi\ 10^{-2}\text{cm}^2}{4}\left|.634\right|.913\left|1\right.$$

$$= 5.8 \times 10^{-2}\text{gm/sec.}$$

This calculation neglects the boundary layer which is very large here. The mass flow rate should be divided by a small integer like 2 or 3. Even then the mass flow rate is comparable with the total mass flow rate of the entire vehicle.

4. Calculate the cabin collision frequency for $H_2O$ molecules.

The collision frequency for $H_2O$ - $H_2O$ collisions in the cabin is (Chapman and Cowling)

$$\frac{1}{\tau_c} = 4\ n_{H_2O} \left(\frac{\pi k T}{M_{H_2O}}\right)^{1/2} \sigma^2$$

$$\frac{\pi k T}{M_{H_2O}} = \pi \left|\frac{1.38\ 10^{-23}\text{joule}}{{}^\circ K}\right| 293\ {}^\circ K \left|\frac{10^7\text{amu}}{1.659\ \text{kg}}\right|\frac{}{18\ \text{amu}}$$

$$= (650\ \text{m}/_{\text{sec}})^2$$

Taking $\sigma$ the molecular diameter at 2 Å

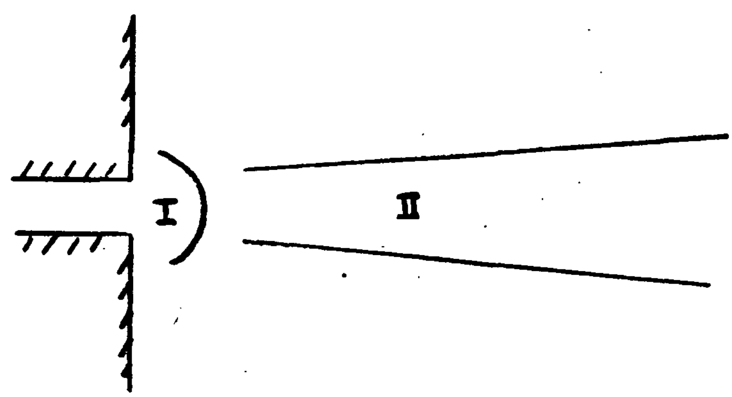
$$\frac{1}{\tau_c} = 4\left|\frac{4\ 10^{17}\ \text{molecules}}{\text{cm}^3}\right|\frac{6.5\ 10^4\text{cm}}{\text{sec.}}\left|4\ 10^{-16}\text{cm}^2\right.$$

$$= 4 \times 10^7\ \text{collisions/sec.}$$

5. Estimate the size of condensate in a free jet.

The reaction chain which occurs during condensation is extremely complex. It is our purpose to make an estimate which will place a reasonable upper bound on condensate size without considering these details.

Consider the jet shown below:




In some small region (I) near the jet, the gas is still collision diminated and the time between collisions of particles of type 1 and type 2 is (Chapman and Cowling)

$$\frac{1}{\tau_{12}} = 2\, n_2 \left\{\frac{1}{2}(\sigma_1 + \sigma_2)\right\}^2 \left[2\pi kT \frac{M_1 + M_2}{M_1 M_2}\right]^{1/2}$$

If we consider the gas which leaves the jet to be composed of $O_2$ and $H_2O$ monomers only, then we can calculate the time required for an $H_2O$ molecule to collide with another $H_2O$ molecule. If we assume that every collision leads to the formation of a polymer we will certainly overestimate the condensation rate. Further, let us assume that in the first collision time every monomer collides with another monomer and forms a dimer. Then let us assume that in the next collision time all the dimers $(H_2O)_2$ collide and form $(H_2O)_4$, in the next collision time $(H_2O)_8$, etc. with the size doubling every collision time. Of course, the actual condensation process is much more complicated. In the first period not only dimers but trimers are formed and subsequently all the polymers not represented in this condensation scheme (i.e., 3, 5, 6, etc.). Without actually solving for time histories of the various polymers, we cannot say with certainty that the proposed process overestimates the size of condensate; however, it seem physically reasonable to assume that it is magnitude correct. We are presently developing a detailed calculation which gives the complete time history of each polymer. Preliminary results show that the scheme used here estimates the mean size of condensate at each instant thus supporting the view that this simplified process is acceptable for order of magnitude estimates.

Using this simplified condensation scheme, the time to form large polymers can be estimated and compared with the convection time in the jet to determine the spatial concentration of polymers.

Since in this scheme, collisions are always between similar polymers, the collision time can be simplified by noting that

$$\sigma_1 = \sigma_2 = \sigma_o N^{1/3}$$

and

$$M_1 = M_2 = M_o N$$

where $\sigma_o$ and $M_o$ are the diameter and mass of water monomers and N is the number of molecules in a polymer.

The continuity condition gives

$$\frac{n(H_2O)_N}{n_o} = \frac{Q_{H_2O}}{\Omega \rho_o U_o R^2 N(R)}$$

where Q is the total mass flux, Ω is the opening solid angle of the jet, $U_o$ is the efflux speed, $\rho_o$ is the cabin density of $H_2O$, $n_o$ is the cabin number density of $H_2O$ and N(r) is the size of polymers which exist at R. According to our condensation scheme only one N will exist at any R. Monomers will exist near the jet and polymers will exist farther away. Combining all these we obtain,

$$\frac{1}{\tau} = 4 n_o \sigma_o^2 \left(\frac{L}{R}\right)^2 \left(\frac{\pi kT}{M_o}\right)^{1/2} N^{-5/6}$$

where

$$L^2 = \frac{Q_{H_2O}}{\Omega \rho_o U_o}$$

The collision frequency will be maximized and condensate size maximized if T in the above equations is taken to be the cabin temperature. Furthermore, L measures the size of the jet and is the boundary of Region I. For values of R smaller than L, L/R will be taken as unity. Finally, we recognize the cabin collision frequency $\tau_o$

$$4 n_o \sigma_o^2 \left(\frac{\pi kT}{M_o}\right)^{1/2} = \frac{1}{\tau_o}$$

so

$$\tau = \tau_o \left(\frac{R}{L}\right)^2 N^{5/6} \quad R \geq L$$

$$= \tau_o N^{5/6} \quad R \leq L$$

Since the larger number of collisions occurs in Region I before the density begins to fall, we can maximize the final size by overestimating L.

As we have already seen, a hole .1 cm in diameter would account for all the mass lost from the spacecraft, so we will take L $\sim$ .1 cm. For comparison, if there were only 100 holes in the spacecraft and each jet had a solid angle of only 1/10 $4\pi$, one would obtain

$$L^2 = \frac{10^{-2}}{\frac{1}{10}\,4\pi} \cdot \frac{10^{-4}\text{gm}}{\text{sec.}} \cdot \frac{\text{cm}^3}{1.2\ 10^{-5}\text{gm}} \cdot \frac{\text{sec.}}{5\ 10^4\text{cm}}$$

$$= (1.14 \times 10^{-3}\text{cm})^2$$

which is two orders smaller.

Assuming particles stream from the jet at $5 \times 10^4$ cm/sec the size of condensate at the end of Region I is given by the solution of

$$\sum_{\substack{P = 0 \\ N = 2^P}}^{P_{MAX}}{}' N^{5/6} = \frac{L}{V\tau_o}$$

$$= \frac{10^{-1}\text{cm sec}}{5\ 10^4\text{cm}} \cdot \frac{1}{.25\ 10^{-7}\text{sec.}}$$

$$= 80$$

For six collision times (P = 6) the sum is 71 and for seven (P = 7) it is 125. This corresponds to condensate of either 64 or 128 molecules. We will take 128 to represent the condensate size at L = .1 cm. since it maximizes the ultimate size of the condensate. In Region II where $R \geq L$, the incremental distance the condensate travels between collisions (mean free path) is

$$\Delta R = 1.25\ 10^{-3}\text{cm}\ \left(\frac{R}{.1\ \text{cm}}\right)^2\ N^{5/6}$$

Beginning at R = .1 cm with a particle of 128 molecules only 4 more collisions are possible before the mean free path reaches 2000 km. Thus the maximum size attained is only 2 x $10^3$ molecules.

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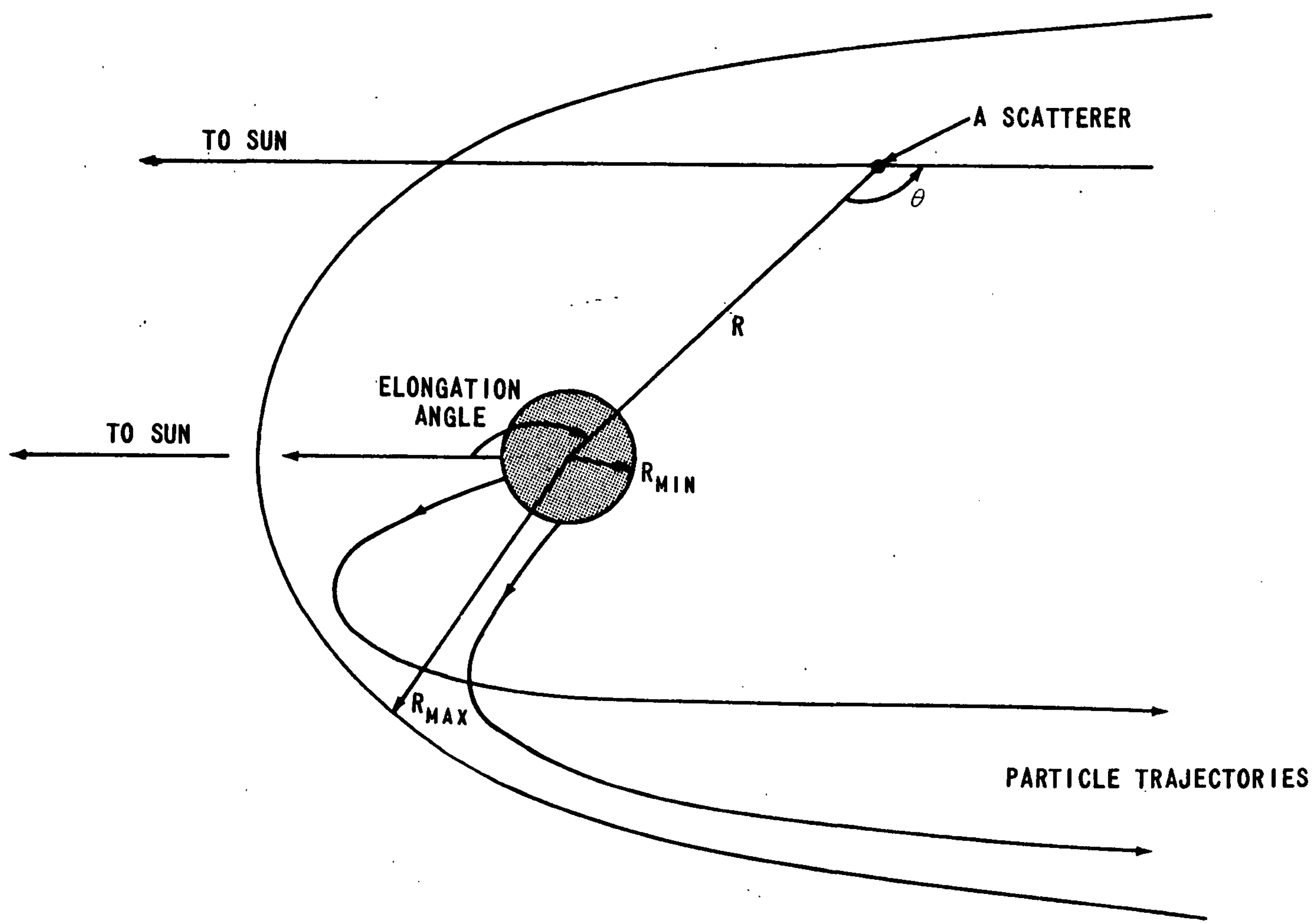


FIGURE I - A SCHEMATIC OF THE DEBRIS CLOUD AROUND A SPACECRAFT. VARIOUS ANGLES AND QUANTITIES USED IN THE TEXT ARE SHOWN.

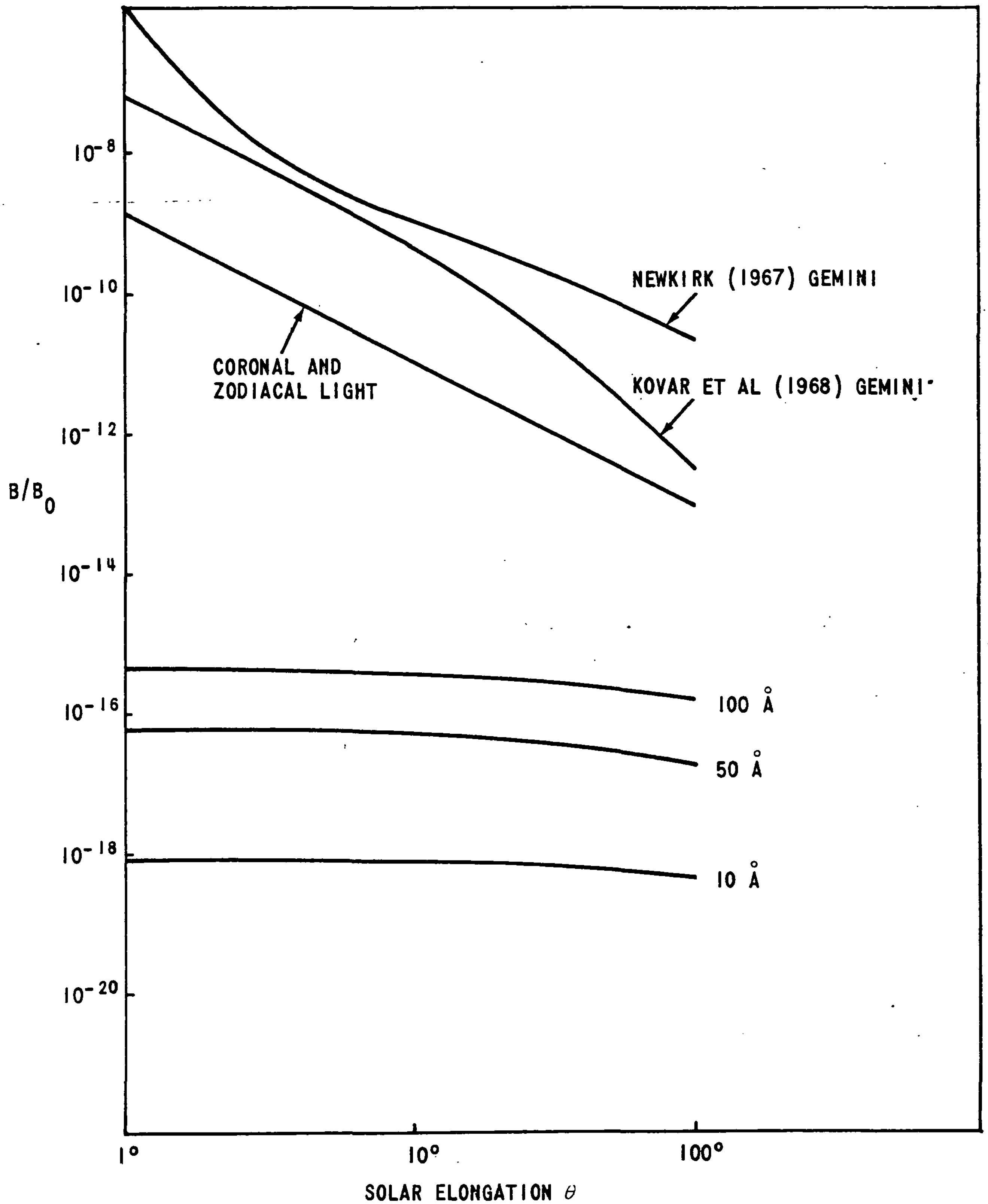


FIGURE 2 - DEBRIS CLOUD RADIANCE AS A FUNCTION OF SOLAR ELONGATION

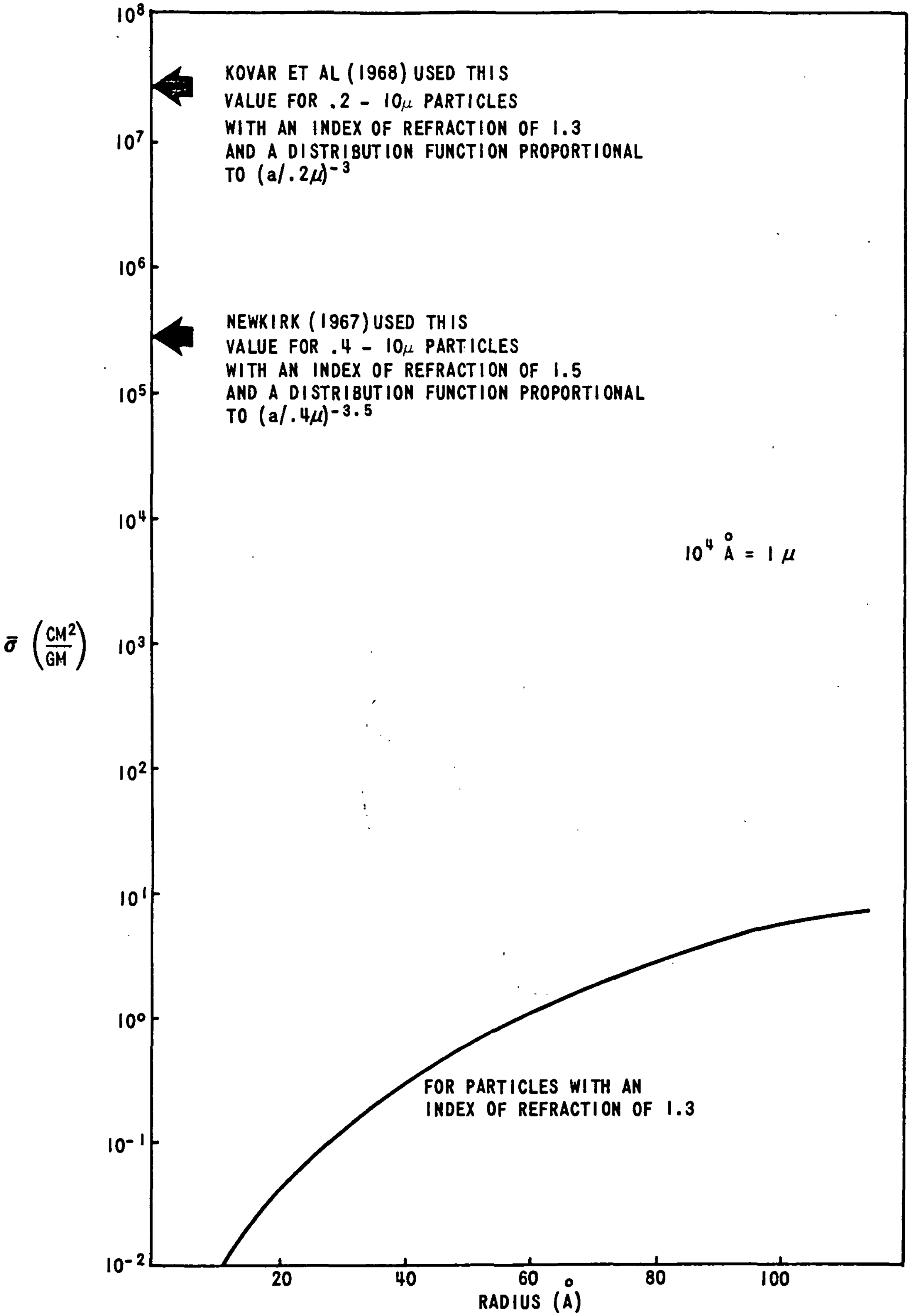


FIGURE 3 - THE TOTAL SCATTERING CROSS SECTION PER UNIT MASS AS A FUNCTION OF PARTICLE SIZE

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