EVIDENCE FOR ICE METEOROIDS BEYOND 2 AU

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Humes et al. (1974) deduced from the P-10 (Pioneer 10) meteoroid penetration data that the spatial density of 2×10^{-9} g and larger meteoroids was nearly constant (or possibly increasing) with increasing heliocentric distances between 2 and 5 AU from the sun. With an assumed mass density of 0.5 g/cm^3, P-10 particles (particles whose mass is $\gtrsim 2 \times 10^{-9}$ g) would have a particle radius in excess of about 10 μm. The observation of a constant, or increasing, spatial density leads to some interesting conclusions regarding the processes that control the population of P-10 particles between 2 and 5 AU from the sun. We shall explore some of these processes below and shall obtain the result that the P-10 meteoroid data can be best understood if many of the penetrating meteoroids are made of ice.

At 1 AU, Whipple (1967) derived a lifetime against collisional destruction of particles in the mass range 10^{-9}g to 10^{-8}g of about 4×10^5 yr. At heliocentric distances from the sun between 2 and 5 AU, the collision lifetimes should be longer than they are at 1 AU because mutual meteoroid impact velocities will be less and because the spatial density of the $\sim 10^{-9}$ g particles is derived by Humes et al. (1974) to be somewhat less than at 1 AU. Thus, a collision lifetime of $\sim 10^6$ yr is derived for the particles that penetrate the P-10 sensors in the heliocentric range $2 < R < 5$ AU.

If we ignore, for the moment, planetary gravitational perturbations by Jupiter, P-R (Poynting-Robertson) drag lifetimes are easily calculated. Using the average solar wind values of Hundhausen (1972) of 9 protons/cm^3 traveling outward at a velocity of 300 km/s and also supposing that the solar wind radiates from 1.5 degrees east of the sun (i.e., the solar wind particles have a slightly prograde motion), a psuedo P-R drag equal to 30% of that caused by electromagnetic radiation is derived. This effect causes the P-R lifetimes given in Wyatt and Whipple to be reduced by the factor 1.3. The time, then, for a 2×10^{-9} g particle of density 0.5 g/cm^3 in a heliocentric circular orbit at 5 AU to drift under P-R drag to 2 AU is 5.7×10^4 yr. This is more than an order of magnitude less than the collision lifetime for all P-10 particles.

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If P-R drag is the dominant influence in changing particle orbits, a heliocentric spatial density of particles varying as $r^{-\alpha}$ is set up. α is equal to 1 for heliocentric regions interior to all sources and α is greater than 1 for all regions where there are sources of the P-10 particles. The sources could include collisional products from larger particles as well as effluents from comets in elliptical orbits passing through the region of interest. Briggs (1962), for example, has deduced the steady state distribution of particles under the action of P-R drag where the particles are assumed to be in temporal equilibrium with source bodies having the orbit distribution of the photographic meteors.

Thus, either Jupiter is somehow controlling the orbit distribution of the P-10 particles so as to give the observed penetration results or some process is causing particles to disappear between 5 and 2 AU. Collisional processes, as we have seen, do not appear to be an adequate particle destruction mechanism. Nor does it seem likely that Jupiter is largely responsible for the observed results. Observations of meteors at one AU, for example, do not indicate that the meteoroids responsible are largely under the direct control of Jupiter. Most meteor orbit aphelia, in fact, lie well inside the orbit of Jupiter (e.g., see Fig. 11 in Dohnanyi, 1978). For the P-10 particles, P-R drag rather quickly removes them from the influence of Jupiter. A P-10 particle with an initial perihelion at 2 AU and an aphelion at 6 AU will reduce its aphelion to 4 AU under P-R drag in a time of about 10^4 yr.

The above considerations do not prove, absolutely, that Jupiter is not directly responsible for the P-10 results between 2 and 5 AU, but do suggest that it is not likely. In any case there is another, more natural, way to explain the P-10 penetration results. That is to assume that many, if not most, of the meteoroids that are penetrating the P-10 sensors between 2 and 5 AU are made of water ice.

Patashnick and Rupprecht (1975, 1977) have shown that pure water ice particles sublimate at a greatly reduced rate for particle radii in a broad neighborhood of sizes near 15 μm and for heliocentric distances beyond about 0.75 AU. They used the real and imaginary refractive indices for both water and ice tabulated by Irvine and Pollack (1968) as well as the ice measurements of Bertie et al. (1969) as inputs for their calculations. The sublimation rate for pure, spherical ice particles with a radius of 15 μm is calculated by Patashnick and Ruppnecht, for example, to be only about 3 μm every 10^4 yr. at 1.25 AU and is rapidly decreasing with increasing heliocentric distance.

The physical reason for ice particles to be especially stable against sublimation in the size range of 15 μm is not difficult to understand. Water and, by analogy, ice have a very low absorptivity for radiant energy in the UV and visible spectrum, but become very absorptive (as well as emissive) in the infrared. Solar radiation in the visible wavelength region passes on through the ice droplets (or crystals) and deposits little energy over the short path lengths associated with small particles. However these same ice droplets efficiently radiate their thermal energy in the far infrared and are thus in equilibrium at a much lower temperature than would a blackbody at the same distance from the sun. For ice bodies much larger than 15 μm, optical path lengths increase causing more UV and visible light absorption without significantly affecting infrared emissivity. Temperatures then become higher and sublimation increases. For bodies much smaller than 15 μm, infrared emissivity at the longer wavelengths decreases (emissivity is poor when $2\pi a/\lambda < 1$) in a manner that more than offsets decreased visible absorptivity and the body again rises in temperature.

Beyond about 1.5 AU, then, pure ice particles with radii in the general neighborhood of 15 μm should be quite stable against thermal sublimation. But the problem posed earlier in this paper was the problem of how to get rid of particles in the heliocentric range of 2 to 5 AU in such a way as to give the observed P-10 penetration results. With ice, this is easy. If there are impurities in the ice, the impurities will increase the absorption of solar radiation and warm the ice up causing it to sublimate more rapidly. Thus, the original ice size distribution and "dirtiness" of ice can be adjusted to match the P-10 results.

Solar wind sputtering is another mechanism that ablates ice particles. Lanzerotti et al. (1978) estimate that the solar wind erosion rate for pure water ice is about 10Å per year at 1 AU and falls off with the inverse square of the heliocentric distance. Their estimate was based on laboratory ice sputtering experiments carried out at proton energies near one MeV and so must be considered approximate. Such a sputtering rate would have the effect of reducing the radius of an ice grain by a factor of 3 (independent of original radius) during the time it spiraled via P-R drag into 2 AU from a 5 AU circular orbit.

The ice sputtering rate estimated by Lanzerotti et al. is very much higher than the ∿0.03Å/yr sputtering rate at one AU determined for silicate materials by McDonnell (1977). It may be too high. T. Mukai (personal communication) estimates that the 1 AU ice sputtering rate is about 3Å/yr. This rate would only reduce the radius of an ice grain by about 25% while spiraling under P-R drag from a 5 AU circular orbit to 2 AU. In any case, solar wind sputtering provides another possible mechanism for the destruction of ice particles beyond about 1.25 AU.

Are there adequate sources of ice particles? Delsemme and Miller (1971), in order to explain cometary halo observations, suggest that comets must be giving off considerable abundances of ice particles. Patashnick et al. (1974) made use of the transformation of ice near 140°K from a very dense amorphous form to a cubic crystalline form to explain cometary outbursts. Thus, it does not seem improbable that comets are a prolific source of water ice particles as well as of silicate grains.

It may now also be easier to understand the Pioneer 10 zodiacal light measurements (see Hanner et al., 1976). Single ice crystals have a very low surface reflectivity (though a high transmissivity). Thus a low geometric albedo may not be unexpected. Also the size distribution of ice particles may be more weighted toward small diameters than are the silicate grains. This would obviate requiring the very low geometric albedos derived by Cook (1978) who assumed the particle size distribution did not change with increasing heliocentric distance.

In summary, it is concluded that meteoroids made of ice (Ice-oids?") are very probably responsible for many, if not most, of the penetrations of the Pioneer 10 meteoroid penetration sensor beyond 2 AU. They could represent, in number, 80 to 90 percent of all interplanetary particles near 5 AU.

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DISCUSSION

Cook: At the next sunspot minimum we should look from any spacecraft going out there to examine the corona due to forward scattering from these particles. This will provide a check on whether or not they are there.
Zook: I agree. If ice particles do represent an important fraction of meteoroids beyond 2 AU, their Bond albedo must be high for them not to absorb so much solar radiation that they heat up and evaporate. However, P-10/11 zodiacal light measurements show that little sunlight is being scattered through large scattering angles. Therefore most scattered light should show up at small scattering angles.

Misconi: In your study of Lanzerotti's estimate of the solar wind sputtering have you included the effect of enhanced density in the solar wind during the passage of shock waves emanating from solar flares, and if you did not, are they important enough to alter your result?
Zook: Lanzerotti et al. averaged over a variety of solar wind conditions including both high and low velocity winds. I am not sure how important the uncertainties are compared to the uncertainty introduced by estimating the solar wind erosion rate by extrapolating from laboratory experiments carried out at higher impacting ion energies.

McDonnell: It may be tempting to suppose that ice may have a high sputter efficiency, but most materials of non-metallic nature have a similar sputter yield ratio. The lunar observational data on sputtering at 1 AU give a value of some 0.03 Å yr^{-1}, a factor of 30 less than the data of Lanzerotti to which you refer. Sputter effects would therefore appear negligible compared to evaporation.
Zook: The sputter rates for ice estimated by Lanzerotti et al. also seemed high to me. However, I am not an expert on sputtering and showed his results to demonstrate that even at these high sputter rates, ice particles of original radius 20 to 40 μm will survive until P-R drag brings them to ~2 AU. The resulting particles will be reduced in radius of course.

Mukai: Recently Schwehm and I (see Mukai this volume) have investigated in detail the mass loss rate of grains due to sputtering and sublimation. We conclude that a water-ice particle of radius >1 μm suffers a significant erosion by solar wind particles as it drifts under P-R drag toward a solar distance of about 3 AU; then suddenly evaporates near 2-3 AU. A grain of radius <1 μm however, cannot drift toward the sun because of a short lifetime due to erosion.

Singer: Have you checked whether your assumed size distribution and planetocentric velocity are consistent with the impact rates observed by Pioneer 10/11 within Jupiter's gravitational field?
Zook: I am inclined to believe that the Pioneer 10/11 results near Jupiter derive primarily from penetrations by particles in bound orbits about Jupiter. These are probably silicates. I have not carried out detailed calculations to support my suspicions. The size distribution

of ice meteoroids I have here suggested is not well defined except for the relative penetration rate of the Pioneer 10 and 11 sensors.

Hughes: I am a bit worried about suggesting comets as a source, because the large majority of the cometary contribution to the cloud comes from small perihelion comets, or at least close to perihelion, this being inside about 1 AU.

Zook: This is an important point but not one I have worried much about. I consider that comets like Schwassmann-Wachmann, whose perihelion lies outside the orbit of Jupiter, could well be prolific producers of ice crystals.