THE INTERPLANETARY MICROMETEOROID FLUX AND LUNAR PRIMARY AND SECONDARY MICROCRATERS

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Abstract

We are gaining an increased awareness and understanding of Earth-orbiting space debris. Meteoroid experiments in near-Earth orbit must therefore now be able to differentiate between interplanetary meteoroids and space debris. Space debris impacts are not thought, however, to have significantly affected near-Earth meteoroid measurements carried out in the early 1960's. New experimental evidence also makes it appear very probable that most impact pits on lunar rocks with pit diameters smaller than 7 micrometers have been generated by lunar secondary ejecta impacts, and not by primary meteoroid impacts. In addition, ages determined from solar flare tracks in lunar rocks are not considered secure. Lunar crater production rates are more reliably deduced from meteoroid space experiments and not from solar flare track ages. When all of the above qualifications are taken into account, however, a rather satisfactorily self-consistent meteoroid flux versus mass distribution is obtained.

1. Introduction

Hanner et al.(1976) and Leinert et al.(1981) have determined broad features of the heliocentric distribution of meteoroids from zodiacal light observations between 0.3 and 3 AU. It is difficult, however, to derive much information about the size distribution of meteoroids from only the zodiacal light data obtained to date. Even the relatively easy question of whether or not sub-micron grains scatter a significant fraction of the observed zodiacal light is not similarly answered by everyone. Lamy and Perrin(1980), for example, suggest submicron grains could contribute significantly to scattered light, while Leinert et al.(1980) noted that the zodiacal light spectrum that they observe is reddened relative to the solar spectrum, rather than the reverse that would be expected if contributions by submicron grains were significant.

It is therefore necessary to make use of direct measurements such as the photographic and radar meteor data, the spacecraft in situ meteoroid sensing data, and the lunar impact crater data to obtain a relatively complete picture of the size distribution of meteoroids. Detailed orbital information is also better obtained through direct measurements. It is direct measurements that give rise to our knowledge of meteor streams, beta meteoroids(Berg and Grün,1973; Zook

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and Berg,1975), and alpha meteoroids(Grün and Zook,1980).

Our primary purpose in this article is to point out that considerable care is required, however, to properly interpret either the spacecraft in situ data or the lunar crater data. Not all lunar craters are due to direct meteoroid impacts. (Note: in this paper, "crater" denotes central pit, if it exists, plus surrounding spall zone.) Analyses of the near-Earth data are similarly complicated by impacting Earth-orbiting debris.

2. In Situ Sensing of Meteoroids

Naumann(1966) carried out a most thorough analysis of meteoroid penetration data obtained with the Explorer XVI, Explorer XXIII, Pegasus I, Pegasus II, and Pegasus III Earth-orbiting satellites, as well as an analysis of the photographic and radar meteor data. From these data he derived that the slope of the log(number) versus log(mass) curve for meteoroids continuously decreased with decreasing meteoroid mass. Early examination of spacecraft windows for impact pitting (Zook et al.,1970; Cour-Palais,1974) confirmed the trend of the flux-mass curve established by Naumann; namely that the low level of observed window pitting was consistent only with a meteoroid flux-mass curve that "flattened" for meteoroid masses below about one milligram.

Hallgren and Hemenway (1976) and Nagel et al.(1976) noted, however, that a disturbing number of the impact craters found on the S-149 meteoroid impact experiment(flown during the 84 day Skylab IV mission in 1973) were coated only with aluminum in the pit interior. Clanton et al.(1980) also found, in a new analysis of impact craters found on the outer surface of the Skylab IV Command Module windows, that many of the smaller impact pits were coated with an aluminum-rich liner. They postulated that these craters resulted from impacts by aluminum oxide sperules that had been deposited in near-Earth space by ignition of solid rocket motors. Clanton et al. also found titanium in one pit. The titanium was postulated to result from a hypervelocity impact on the window of a flake of white thermal paint. It appeared that, for impact pits smaller than 20 micrometers in diameter, impacts by orbital debris contributed an important fraction of the total number of observed craters.

There is also an important debris population at larger particle sizes. Kessler and Cour-Palais(1978) noted that, at particle masses greater than a few hundred grams and at altitudes between 700 and 1200 km, the flux of derelict spacecraft and spacecraft fragments greatly exceeds the flux of meteoroids. More recently, Taff et al.(1984) used the two 0.8 meter telescopes associated with the M.I.T. Lincoln Laboratory Experimental Test System near Socorro, N.M. to search for centimeter-sized orbital debris. They detected several such objects for each hour of observation. According to Kessler (1984), the near-Earth orbital debris flux resulting from the Taff et al. study is at least one order of magnitude above the meteoroid flux for particle diameters in excess of one centimeter.

It is clear from the above evidence that it is absolutely necessary to be able to distinguish between orbital debris and meteoroids in order to determine an uncontaminated near-Earth meteoroid flux. Therefore it is proper to ask if the flux established by Naumann(1966) is a valid meteoroid flux. We believe that the flux determined by Naumann is, indeed, a valid flux for the following reasons:

1. The meteor data, with well determined trajectories, are clearly uncontaminated by orbital debris.

2. When corrected for Earth(or Moon) shielding, the Explorer XVI and Explorer XXIII 25 micrometer thick sensors were penetrated at a rate 2.3 times greater than were similar sensors on the five Lunar Orbiter spacecraft(Grew and Gurtler,1971). Such a near-Earth increase is entirely to be expected just due to the near-Earth gravitational focussing of meteoroids(see Zook,1975 for uncertainties in the expected gravitational increase). Thus the meteoroid penetration measurements taken in the early 1960's appear not to have significantly suffered from penetrations by space debris.

3. Brownlee et al.(1974) discovered two hypervelocity appearing impact pits on 800 square centimeters of aluminum foil that was exposed for 67 days during the Skylab IV mission. The two craters were 26 and 75 micrometers deep, respectively, and under chemical analysis, contained meteoritic material. As noted by Zook(1980), the near-Earth flux obtained from these two craters is 0.04 impacts/(square centimeter-year). This flux completely agrees with that obtained by Cour-Palais(1974) although the statistical weight of two impacts is not great. More important, the chemical analyses showed that, in this size range, impacts during 1973 were <u>not</u> largely caused by space debris.

3. The Lunar Microcrater Data

Most of the rocks returned from the Moon during the Apollo missions showed abundant evidence of meteoroid impact pitting. It was quickly understood that, in those cases where crater superposition was not a problem, the observed pit size distribution probably reflected the impacting meteoroid mass distribution. Because nearly all of the impact craters were hypervelocity-appearing, with glass-lined central pits, it was felt that very few of the observed pits were likely to have been caused by secondary lunar ejecta impacts. This feeling was strongly reinforced by the results of Schneider's (1975) laboratory experimental study on cratering due to secondary ejecta. Schneider created the high speed ejecta with a hypervelocity impact of a steel ball at normal incidence onto a glass plate. Before we further examine the question of secondary ejecta-caused craters, we first mention the differing impact crater size distributions obtained on lunar rocks by two different investigator groups.

Fechtig et al.(1974) compiled a variety of impact pit data on lunar rocks to obtain, using associated solar flare track ages, a composite meteoroid flux versus mass(or pit diameter) curve. Morrison and Zinner(1977) found that lunar rock 12054, collected during the Apollo 12 mission to the Moon, exhibited an unusually steeply increasing surface density of microcraters with decreasing pit diameter, for pit diameters below about 7 micrometers. They argued that this and other lunar rocks with similarly steep micron-to-submicron micropit distribution curves were the best candidates for the "true" lunar microcrater production curve. That is, they felt that these particular rock surfaces must not have been coated with the very thin layer of lunar dust that was often postulated to be causing a suppression of the creation of submicron pits on most lunar rocks--such suppression as would give rise to the "flatter" distribution observed by other groups, such as the Fechtig group. Both groups of investigators noted that the meteoroid fluxes that they derived were lower than the satellite-obtained meteoroid flux.

We now address the problem of the microcrater production rate. The microcrater production rate on a lunar rock is conventionally derived as follows: 1. The surface density of microcraters on the rock is measured; 2. The solar flare track density is measured versus depth into the same rock; 3. Using a track versus depth profile on a separate rock with an independently established exposure age as a standard, the solar flare track "exposure age" of the rock is obtained; 4. The crater production rate is then calculated by dividing the track age in item 3 into the crater surface density determined in item 1.

The solar flare track production rate is not, however, reliably known. The fact that different groups of investigators obtain contradictory results is one cause for caution. Zinner and Morrison(1976) report, for example, that there is a factor of 50 difference between the ratio they obtain for the surface microcrater density to the track density at 100 micrometer depth, and the corresponding ratio obtained by Hutcheon(1975). The reason for this difference is not yet understood. Furthermore, researchers such as Storzer et al.(1973) and Hutcheon et al.(1974) have obtained a very steep increase in solar flare track density as they proceeded from the interior of the lunar rock outward toward the surface, while Blanford et al.(1975) and Morrison and Zinner(1977) obtain a much smaller increase. That is, no "standard track density versus depth profile" has yet been agreed upon by workers in this field. Finally, Zook et al.(1977) and Zook(1980) argue that the solar flare track production rate could well have been higher about 20,000 years ago than is presently true. Such a time variation would give rise to excessive apparent surface exposure ages. Thus, one should use the direct in situ meteoroid sensing data, qualified as they are, rather than the track data to give the current impact pitting rate on lunar rocks.

We next wish to address the question of impact pitting by lunar secondary ejecta. Flavill et al.(1978) and Allison et al.(1981) reconsidered ejecta cratering, using both the Schneider(1975) data and new oblique angle impact data obtained with a Van de Graf accelerator(Flavill et al.,1978), but with a different primary mass distribution curve. They found that both their own data and the data generated by Schneider would suggest that many of the pits on lunar rocks between 1 and 10 micrometers in diameter were caused by impacting secondary ejecta.

Significant new experimental data have been recently obtained by Zook et al.(1984) using a light gas gun to propel glass and basalt projectiles at oblique angles onto sawed basalt rock surfaces. The impact velocities were typically in excess of 6 km/s and the ejecta were permitted to impact onto glass witness plates. These shots gave ejecta pitting rates that were two orders of magnitude higher than were obtained at normal incidence(by either Schneider, or Zook et al.). The resulting secondary impact pits look very similar to pits observed on lunar rocks, and the size distribution approaches the steepness observed by Morrison and Zinner(1977). Thus it now seems very probable that the lunar microcrater population for micron-sized pits(<7 micrometers in diameter) is usually dominated, depending on the particular lunar rock exposure geometry, by secondary ejecta cratering and not by primary interplanetary meteoroid cratering. The variations among different microcrater size distributions obtained from different lunar rocks may be due, not to variable lunar dust obscuration as often thought previously, but to variations in lunar rock surface exposure geometry relative to the primary and secondary cratering environment. Impact craters on lunar rocks with central pits larger than 7 micrometers are still believed to be directly caused by impacting meteoroids.

4. Conclusions

1. Earth-orbiting space debris generates impacts on Earth-orbiting sensors that can be mistaken for meteoroid impacts. It is not thought, however, that Earth-orbiting meteoroid experiments carried out in the early 1960's were significantly contaminated by debris impacts. Future studies will need to use either particle trajectory information or particle chemistry to separate meteoroids from man-made debris.

2. The lunar impact crater data is very probably dominated by secondary ejecta craters for impact pit diameters smaller than 7 microns. Also, the solar flare track ages established for lunar rocks are probably incorrect, and therefore should not be used to establish impact crater production rates.

3. The meteoroid mass distribution obtained from data on lunar impact pits larger than 7 microns closely fits the early satellite-obtained meteoroid data, as shown by Grün et al.(1984). Thus the lunar data, when properly interpreted, are of great value, and nicely complement the satellite and the zodiacal light data.

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Discussion

R. Walker: I would like first to comment and then ask a question. 1. Microcraters are found not only on lunar rocks but also on crystals removed from the bottom of core tubes. In some cases we know (from isotopic measurements) that the crystals were exposed at the surface of the Moon at least $5x10^8$ to $1x10^9$ years ago. Thus the interplanetary dust has been a more or less constant component of the solar system for a good fraction of its total lifetime. 2. The contribution of secondary craters should be measurable by measuring crater populations on different parts of a large glass deposit. Glass on the very top of a rock should have the least secondaries, that on the side of a rock -- the most. Have you thought about this and is there an appropriate rock?

H. Zook: The answer is yes. Lunar rock 12054, returned during the Apollo 12 mission to the Moon, would be an excellent rock to use for this type of investigation. Its lunar orientation is well known, and its remarkably smooth glass surface faces in a variety of directions, including vertically where, presumably, secondary impacts should be rare or non-existent. Don Morrison (in Hartung, et al., 1978) did look at a chip from the top of this rock and found no craters smaller than 10 microns in diameter. A more complete study would be easy to do and should be carried out.