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REPLY TO DAVIS AND NAKAMURA ET AL.

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Frank et al. (1986a,b) interpret transient, localized decreases of the earth's ultraviolet dayglow intensities in terms of a large flux of previously undetected small comets in the vicinity of the earth. On the basis of the number of meteoroid impacts observed with the Apollo lunar seismic stations Davis (1986) and Nakamura and coworkers (1986) find that the flux of these small comets must be orders of magnitude less than that given by Frank and co-workers. We show here that this discrepancy may be traced to the insensitivity of the lunar seismic stations for the detection of the impacts of tenuous, weakly bound comets relative to those of dense, stony meteoroids.

Consider the collision of a small comet with mass $\sim 10^8$ gm and density ~ 0.1 gm/cm^3 with the lunar surface as depicted in Figure 1. A lower limit for its tensile strength of ~ 0.1 dynes/cm^2 is previously given by Frank et al. (1986b) from considerations of the tidal forces exerted on the small comets due to the earth's gravitational field. Further analysis of the thermal stability of these small comets at heliocentric radial distances of 1 A. U. yields tensile strengths in the range $\lesssim 10^4$ dynes/cm^2 (Frank et al., 1986c). Because the tidal forces due to the Moon are orders of magnitude less than the latter tensile strengths, it is likely that the small comets impact the Moon before disruption. Upon impact with the Moon the fluffy water snow is converted to liquid, a shock wave propagates in the water away from the lunar surface, and a large amplitude pressure wave, a weak shock, is transmitted into the Moon. The water is compressed with an increase in temperature and elastic energy and subsequently expands rapidly with cessation of the incoming momentum of the cometary water snow. Ideally the amplitude of the seismic wave is calculated from an accurate assessment of the partitioning of energy among the thermal energies of the water and lunar rock, elastic energies of these media, and their kinetic energies. A reasonably accurate, quantitative evaluation of the amount of energy that is partitioned into wave energy in the lunar rock is considered difficult at best, in view of the small fraction of the total energy that is given to the seismic waves and the lack of direct observational knowledge of such transfer for water-rock impacts. On the other hand it is more straightforward to estimate the maximum seismic wave amplitude from considerations of the conservation of linear momentum and the known physical properties of water and lunar rock under high pressures. This amplitude is now estimated.

We assume first that the lunar impact of the water snow with density 0.1 gm/cm^3 and speed 10 km/sec is equivalent to that for liquid water with density 1 gm/cm^3 and speed 1 km/sec in order to conserve mass and momentum fluxes. The dynamic equation of state for water for the appropriate pressure range is determined with laboratory experiments (Lyzenga et al., 1982; Mitchell and Nellis, 1982; Ree, 1982). The pressure within the post-shock water is dependent upon the equation of state of the target material, i.e., the lunar rock. Shock compression measurements, e.g., Hugoniot P-V relationships, are available for feldspars (Ahrens et al., 1969) and lunar anorthosite (Jeanloz and Ahrens, 1978), for examples. For the pressure range of interest here, $\lesssim 10^{11}$ dynes/cm^2 (10^{11} dynes/cm^2 = 100 kbars $\simeq$ 10 GPa), the shock wave velocity in the lunar rock is nearly the same as that for the elastic body P-wave. The above information, along with material and pressure continuity at the water-lunar rock interface, allows the determination of the post-shock pressure within the water (Al'tshuler et al., 1958). The pressure P at the water-rock interface is found by graphic means. This pressure is $\sim 3 \times 10^{10}$ dynes/cm^2 (30 kbars).

The above calculation of pressure at the lunar surface is obtained with the assumption that the initial state of the water is continuous with density $\rho = 1.0$ gm/cm^3 and with no significant thermal pressure. The post-shock temperature of the water is expected to be in the range of 500 to 1,000 K (Ree, 1982). However, the initial state of the water is porous water snow. Due to the low initial density of the water snow, most

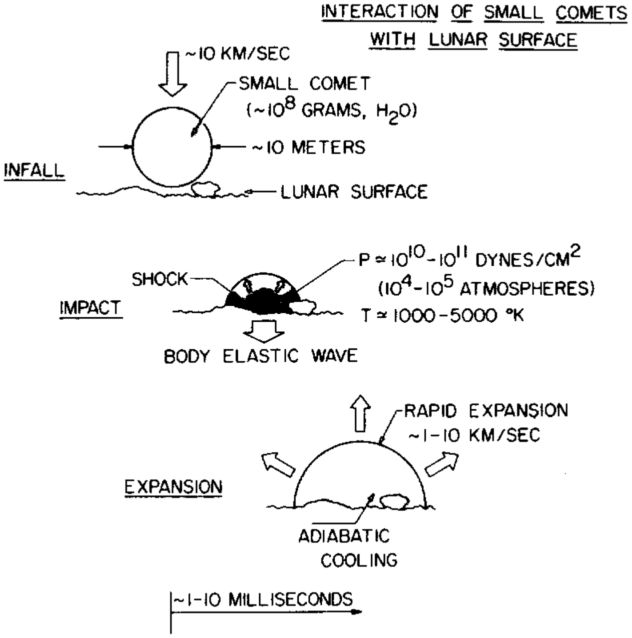

Fig. 1. Several features of the impact of a small comet with the lunar surface.

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of the kinetic energy of the water snow, ~ 10 eV per H_2O molecule, is converted to thermal energy in the post-shock fluid (cf. Zel'dovich and Raizer, 1967). Because the heat of fusion for water, 3.3×10^9 ergs/gm, is small relative to the specific kinetic energy, 5×10^{11} ergs/gm, the effects of the conversion of water snow to vapor are neglected here. If we assume the extreme case for which the entire kinetic energy of the comet appears as thermal energy in the post-shock fluid, the water temperature behind the shock is ~ 10,000 K. We use the specific heat of compressed water $C_V \simeq 4 \times 10^7$ ergs/gm-K at these temperatures (cf. Ree, 1982). Because molecular dissociation is expected to be important at temperatures of several thousands of K, the post-shock water temperature is estimated by us to be limited to ~ 5000 K (cf. Mitchell and Nellis, 1982). For example, the bond strength for H-OH is 5.2 eV. For a temperature of ~ 5000 K and a density of 1 gm/cm^3, the post-shock thermal pressure is $nkT \sim 2 \times 10^{10}$ dynes/cm^2, or a factor of 5 less than the upstream dynamic pressure. Thus the post-shock water is most likely a hot fluid at a pressure $P \simeq 30$ kbars with significant molecular dissociation. The pressure estimate is considered to be accurate to within factors of 2 or 3. Because the recombination times in the fluid are greatly less than the post-shock adiabatic release time, the resulting hot water vapor leaves the lunar surface with relatively little dissociation. It is of considerable relevance to this topic to extend the shock experiments for compressed water ice as performed by Lange and Ahrens (1983) to low-density water snow. The terminal flow speed of the post-shock water cloud can be expected to be in the range of ~ 5 to 10 km/sec. Escape speed from the moon is only 2.4 km/sec.

The displacement of the lunar surface, and hence the maximum amplitude of the seismic waves, may now be estimated. Because the comet's diameter is ~ 12 meters and the comet's speed is ~ 10 km/sec, the duration of the collision is $\tau \simeq 10^{-3}$ seconds. The wave speed V_l in lunar anorthosite is ~ 5.8 km/sec (Jeanloz and Ahrens, 1978) and the bulk modulus K of this rock-type is $\sim 8.6 \times 10^{11}$ dynes/cm^2 at a pressure of 10^{10} dynes/cm^2 (Beblo et al., 1982). The amplitude of linear compression, ΔZ, is taken as the maximum seismic amplitude at the boundary of the impact zone, $A_c(r_o)$, where r_o is the zone (comet) radius. Effects of Poisson's ratio for the rock are neglected. This surface displacement at the boundary of the impact zone is then $A_c(r_o) \equiv \Delta Z = V_l \tau P/K \simeq 20$ cm. This result is not strongly dependent on rock type (cf. Beblo et al., 1982). The impacts of the third stages of the Apollo booster vehicles onto the lunar surface show that the amplitude of the seismic wave as a function of distance from the impact site varies as r^{-n}, where r is the chord length and $n \simeq 2.15$ (Latham et al., 1973). Thus the maximum amplitude $A_c(r)$ of a seismic wave at a chord distance r away from the impact site of a small comet is

$$A_c(r) \simeq A_c(r_o) \times (r_o/r)^{2.15}\ ,\ \text{or}$$

$$A_c(r) \simeq 1.9 \times 10^7/r^{2.15} \qquad (1)$$

where A_c and r are in units of cm.

For comparison the relationship between the amplitude of seismic waves, A_m, due to impacts of meteoroids with mass 10^8 gm and the chord length r from impact site to seismometer is obtained from Latham et al. (1972) with energy scaling,

$$A_m(r) \simeq 1.3 \times 10^{13}/r^{2.15} \qquad (2)$$

where A_m and r are in units of cm. This equation is derived in part from laboratory measurements of seismic waves generated by the impact of projectiles into loose and epoxy-bonded sand, and subsequent energy scaling for meteoroid impacts on the Moon (McGarr et al., 1969). These impacts are treated as surface explosions.

We can now compute the rate of comet impacts that is expected to be recorded at the lunar seismic stations. The flux of comets at 1 A.U. and outside of the earth's gravitational field is $F \simeq 3.6 \times 10^{-20}$ comets/cm^2-sec (cf. Frank et al., 1986d). Because relatively few of their perihelia penetrate deeply inside 1 A.U. and the orbits are prograde (Frank et al., 1986b,c), the flux at the Moon is best described as a stream. Thus the lunar cross-section B for cometary impacts is approximately πR_m^2 where R_m is the Moon's radius. The impact rate on the lunar surface is $BF \simeq 3.4 \times 10^{-3}$ comets/second, or ~ 300 comets/day.

The amplitude for the seismic wave expected for an explosive meteoroid impact, 10^8 gm, at a chord distance 2 lunar radii away from the seismic station is given by equation (2). This amplitude, A_m, is 6×10^{-6} cm. The fundamental frequency of the seismic wave from this explosive meteoroid impact is similar to that observed from terrestrial surface motions due to underground explosions. This frequency is ~ 1 Hz (cf. Carder and Cloud, 1959). The threshold sensitivity of the seismic stations is $\sim 3 \times 10^{-8}$ cm for these frequencies (Latham et al., 1973). Thus if the comet impact is equivalently that of a stony meteoroid, all lunar impacts are detected and the rate is ~ 300 events/day, or ~ 10^5 events/year.

The amplitudes for the comet impacts, $A_c(r)$, are given by equation (1). The combined duration of the pressure wave and rarefaction wave is ~ 2 ms, or a fundamental frequency of ~ 500 Hz. At this frequency the threshold sensitivity of the seismic station is at least a factor of 10^6 less than that cited above for 1 Hz (Latham et al., 1973). Increasing attenuation of the seismic wave with increasing frequency is not considered here. In order to establish an upper limit to the seismometer event rate due to these small comets, we assume conservatively that the wave frequency is only 20 Hz. The corresponding threshold amplitude for detection is 10^{-6} cm. From equation (1) then the maximum chord distance from the lunar seismic station for detection of a comet impact is 1.5×10^6 cm, or 15 km. This distance corresponds to an area $A_s \simeq 700$ km^2 centered at the seismic station. The maximum number of events recorded at this station is then $A_s/4 \times F \simeq 6 \times 10^{-8}$ events/sec, or ~ 2 events/year. A qualitatively similar result is obtained if $A_c(r) \propto r^{-1}$ near the seismic stations. The observed rate of meteoroid impact events at a lunar seismic station is ~ 200 events/year (Latham et al., 1973). Thus the lunar seismic observations are not inconsistent with the influx of small comets as proposed by Frank et al. (1986b).

The effects of impacts of these small comets with the lunar surface are unlike those of the explosive scenario that accompanies the impact of a relatively high-density meteoroid with tensile strength similar to that of the lunar surface. The densities of the small comets, ~ 0.1 gm/cm^3, are factors of 20 to 50 less than those for the meteoroids. Similarly the tensile strength for the small comets, $\lesssim 10^4$ dynes/cm^2, is to be compared to the dynamic tensile strength of various rock types, ~ 5×10^8 to 2×10^9 dynes/cm^2 (cf. Cohn and Ahrens, 1981; Grady and Hollenbach, 1979). The pressure at the contact surface between the cometary water and lunar rock is relatively low and is less than or near the Hugoniot elastic limit for at least several rock-types (cf. Ahrens et al., 1969). Thus the impact of the comets with the lunar surface is not expected to create a crater in regoliths of these strengths. A shallow, flat-bottomed crater with diameter of the order of 10 meters may occur for weaker material. Because each point on the lunar surface suffers approximately 10^3 impacts over a geological time of 3.5×10^9 years, surface fatigue may be anticipated. The effects of this fatigue could extend to depths of tens of meters. Certainly the rapid expansion of the water vapor with speeds ~ 5 to 10 km/sec after the impact can scatter local lunar dust over large areas of the Moon.

The anticipated surface effects arising from the impact of a small comet with the lunar surface as discussed above can be compared to those for stony meteoroids, i.e., surface explosions. The kinetic energy of a small comet with mass 10^8 gm, initial speed 10 km/sec is 5×10^{19} ergs, or about 1 kiloton TNT equivalent. An explosion of 1 kiloton of TNT at a position just above the surface of desert alluvium produces a crater with depth ~ 0.5 m and diameter ~ 4 m (Chabai, 1965). It is likely that a stony meteoroid penetrates to shallow depths before release of its energy. For an explosion of 1 kiloton TNT at a depth of ~ 1 m in the desert alluvium the crater depth is ~ 2 m and the diameter is ~ 12 m. This large disruption of the surface integrity relative to that for a small comet can be probably accounted for in part by the fact that the dynamic tensile strength of the surface material increases with higher rates of stress change with time (see Lange and Ahrens (1983) and references therein). For small comets the pressure duration time is ~ milliseconds, and that for the explosions is about 1 second if the frequency of the surface waves is indicative of the duration of the pressure pulse. Thus the surface integrity of the moon suffers considerably less damage from the impact of a small comet relative to that from a meteoroid with an equivalent kinetic energy.

The radiation spectrum from the shocked water is a continuum and can be approximated by that from a blackbody (Lyzenga et al., 1982). The temperature of the post-shock water is estimated above to be in the range ~ 1000 to 5000 K. For the convenience of researchers interested in observing the lunar surface for visible light flashes from the comet impacts we integrate the Planck function over the area of the comet (diameter = 12 m) and the impact interval (10^{-3} second) for various blackbody temperatures. For a visual wavelength range of 400 to 700 nm, the total photon emission is 4×10^{16} photons at 1000 K, 6×10^{19} at 1500 K, 2×10^{21} at 2000 K, 1×10^{23} at 3000 K and 3×10^{24} at 5000 K for an individual comet impact. For the lower temperatures the color is dominated by red emission. It is of interest to note that the bright flash on the lunar surface as observed by the pilot of the Apollo command module at large distances from the seismic stations, and not seen in the seismographs (Latham et al., 1972), may have been due to the impact of a small comet.

The relative insensitivity of the lunar seismic stations for the detection of impacts of objects with low density and low tensile strength may be the source of the discrepancy in the fluxes of large meteoroids as determined by the lunar seismometers and by earth-based observers. For example, the cumulative fluxes of meteoroids impacting the Moon with individual masses $\geq 10^6$ gm are found to be almost a factor of 10^4 less than the fluxes of similarly massive objects entering the earth's atmosphere as observed with the Prairie Network (cf. Latham et al., 1972; Dohnanyi, 1978). A substantial fraction of the Prairie Network fireballs are associated with objects of low compressive strength, ~ 10^5 dynes/cm^2, and low densities, $\lesssim 1$ gm/cm^3 (Wetherill and ReVelle, 1982; Ceplecha and McCrosky, 1976). The seismic wave amplitudes from the impact of these objects with the lunar surface would be similar to those computed above for small comets. We suggest here that the large discrepancy in infall rates of massive meteoroids as detected on the Moon and in the earth's atmosphere is due to the insensitivity of the lunar seismometer for the detection of the impacts of comet-like objects. The responses of these seismometers may be almost entirely due to the explosive impact of stony meteoroids.

The impacts of the small comets on the Moon and the subsequent outflow of water molecules produce a diffuse atomic hydrogen cloud that is similar in many respects to the hydrogen coma of a comet. For an impact rate of 3.4×10^{-3} comets/sec, each with mass 10^8 gm, the averaged outflow at the lunar surface is ~ 3×10^{10} H_2O molecules/cm^2-sec. If the average outflow speed from the lunar surface is 7 km/sec, then the density is ~ $4 \times 10^4/r^2$ H_2O molecules/cm^3 where r is in units of the Moon's radius, 1738 km. The column density of water molecules as viewed from the earth to the lunar surface is ~ 10^{13} H_2O molecules/cm^2. Detection of the emission from water molecules at 6.3 μm for such column densities is within the capabilities of helium-cooled infrared telescopes above the earth's atmosphere, ~ 10^{12} H_2O molecules/cm^2 (cf. Fazio, 1978). Quantitative measurements of these emissions can be expected to provide an accurate assessment of the water influx onto the lunar surface and into the earth's atmosphere. Whether or not a small fraction of these high-speed water molecules can condense in cold traps in the Moon's polar regions remains an open and interesting issue (cf. Arnold, 1979).

Dissociation of the outwardly flowing H_2O molecules from the Moon by solar ultraviolet radiation produces the hydrogen coma that resonantly scatters solar Lyman-α radiation. The total outflow from the Moon is ~ 10^{28} H_2O molecules/sec. Because the average outflow speed is similar to that expected for atomic hydrogen from comets, the distribution of atomic hydrogen in the coma of the Moon can be estimated from that derived from cometary models. We use the model for Comet Halley at heliocentric radial distance 1 A.U. as given by Meier and Keller (1985). The maximum Lyman-α brightness of the coma, i.e., as viewed looking towards the Moon's center and from large distances outside the coma, is $\sim$ 80 Rayleighs (R). As viewed from this position, the radial distance from the Moon's center at which the apparent brightness of the coma is a factor of 5 less than maximum brightness is $\sim 10^6$ km, or $\sim 150\ R_E$. The earth is then positioned within the Moon's hydrogen coma and the Lyman-α intensities as viewed from the earth are in the range of $\sim$ 30 to 60 R. Because the background Lyman-α intensities due to the interstellar wind in the vicinity of the sun are in the range $\sim$ 300 to 500 R (Thomas and Krassa, 1971), detection of the Moon's coma with an earth-orbiting spacecraft is difficult. One opportunity for such detection in the presence of this relatively bright sky background may arise from the response of the Moon's coma to the large variations of the fluxes of small comets along the earth's orbit around the sun (cf. Frank et al., 1986e).

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