Meteors over the Moon

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Abstract: There is a high degree of probability that in the relatively near future, on a timescale of perhaps several hundreds of years, the Moon will be engineered to support a substantial atmosphere. Once the mass of any artificial lunar atmosphere exceeds some 10^8 kg, it will be both long-lived and dynamically maintainable. One of the key advantages of producing a lunar atmosphere will be that it will provide protection to ground-living communities against meteoroid impacts as well as solar and cosmic radiation. We find that a lunar atmosphere with a mass in excess of 10^{11} kg will provide ground protection against even the highest possible velocity (that is for bound solar system orbits) kilogram-mass meteoroids.

1. Introduction

Current NASA plans call for the return of astronauts to the Moon by 2020, and the eventual establishment of a permanently staffed Moon-base over the ensuing decades. The problem of building structures on the Moon's surface is accordingly an area of great current interest, and concomitant to this is the interest in making such structures as safe as is reasonably possible from meteoroid impacts (Benaroya and Bernold, 2008). Indeed, the habitable structures will need to shelter humans from meteoroid impacts, cosmic rays, solar radiation, and the extremes of temperature experienced on the Moon. One of the most commonly discussed methods of structural shielding is regolith enshrouding. In this

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scenario a layer of lunar soil, several meters thick, is built-up around and over a building thereby providing a ‘natural’ barrier with which to absorb meteoroid impact energy and radiation – additionally, the regolith is also readily available without the need for any substantial transportation costs. The debate on building construction and protection is far from complete, and will certainly develop and change over the next many years (figure 1).

Figure 1. An early concept design for an inflatable Moon dome, power generation plant and surface vehicle maintenance yard. NASA graphic number S89-26097 (March 1989).

For individual, relatively small structures impact protection by regolith covering is certainly a reasonable approach to adopt. The situation is less clear in the deeper future, however, when the large scale, cityscape inhabitation of the Moon is in full progress (Landis, 1990). Under these circumstances it might make more sense to try and construct an artificial lunar atmosphere. Such an atmosphere might provide the entire Moon with a natural protective barrier from small meteoroids as well as protection from harmful solar and cosmic radiation. By the construction and maintenance of a lunar atmosphere we are not specifically invoking the idea of terraforming (Beech, 2008; Fogg, 1995), but rather we envision an entirely un-breathable atmosphere made predominantly of (perhaps) industrial waste gases and directed out gassing. Indeed, on the Moon we potentially have the enviable situation where the more industrial pollution generated the better, a circumstance that will not, of course, please lunar astronomers, but by the time such developments are likely to take place the Moon will probably no longer be an ideal location for making observations anyway.

2. An artificial lunar atmosphere

The Moon has no natural, long-lived atmosphere, its surface gravity is simply too low to constrain in place any gas with the characteristic temperature of a body at 1AU from the Sun (Hughes, 1978). The present lunar exosphere has a measured surface density of about 10^{10} particles per meter cubed and a total instantaneous mass of about 10^4 kg. Such conditions indicate that the exosphere is collision-less with the constituent atoms moving along ballistic trajectories. The loss of material from the Moon's exosphere is therefore a thermal process such that any atom of mass *m* having a velocity $V_{thermal} = [2\, k\, T / m]^{1/2} > V_{escape} = 2.38$ km/s, where *T* is the Moon's surface temperature and *k* is the Boltzmann constant, will soon, on a timescale of order hundreds to thousands of years, be lost into space.

In addition to the thermal loss process, a highly efficient mass removable mechanism related to the solar wind also operates on the Moon. In this case atmospheric ions produced through interactions with solar UV radiation become entangled within the electric field produced by the motion of the solar wind past the Moon. In this manner, it turns out, half of the ions are driven into outer space and half are driven back to the Moon's surface. In this situation the mass loss rate is controlled by the ionization lifetime which is typically of order a few tens to perhaps a hundred days – this is a timescale many orders of magnitude smaller than the thermal mass loss mechanism. Richard Vondrak (1974) has studied the ionization mass loss mechanism in some detail and finds that a critical mass loading of the solar wind occurs at a mass flux of about 0.03 kg/s. Here then lies the possibility for producing a lunar atmosphere. Detailed calculations indicate that if gases are released from the Moon's surface with a mass flux in excess of about 50 kg/s, then an atmosphere can be built up with the exosphere being pushed upwards and away from the lunar surface. Vondrak (1974, 1992) finds that a long-lived (that is on a timescale of thousands of years) lunar atmosphere can be created once its total mass exceeds 10^8 kg – this corresponds to a four orders of magnitude increase in the mass of the present lunar exosphere.

The Moon is certainly rich in resources that might in principle be mined, and/or vaporized to produce, and then feed the artificial atmosphere. The challenge to produce such a mass increase, however, is formidable. If we take Vondrak's (1992) estimate of about 50 kg/s of out gassing being required to produce an artificial lunar atmosphere, and also assume that it should be in the form of oxygen then of order 50 million metric tons of regolith would need to be mined per year (Taylor, 1992) – this calculation assumes a 5% efficiency in extracting oxygen from regolith material containing 5% ilmenite = iron titanium oxide: $FeTiO_3$). This number perhaps sounds large, and of course economically speaking it is, but it is actually 100 times smaller than the current annual coal extraction rate on Earth (http://www.worldcoal.org/).

3. Meteoroid filtration

The surface pressure P_S that results from an atmosphere of mass M_{atm} is given by the relationship P_S (Pascal) = (5.31 x 19^{-12}) (M_P / R_P^4) M_{atm}, where M_P and R_P are the mass and radius of the host planet / moon. For the Moon we have P_S = (4.28 x 19^{-14}) M_{atm}(kg). At height h above the Moon's surface the pressure $P(h) = P_S \exp(-h / H)$ where $H = k T / m g$, where H is the pressure scale height, k is Boltzmann's constant, T is the temperature, m is the mass of the representative atmospheric atom, and g is the gravitational acceleration at the Moon's surface. For a perfect, isothermal gas, the pressure can be related to the temperature and pressure via the relationship $P = (R / \mu) \rho T$, where R is the gas constant and μ is the mean molecular weight of the representative atmospheric atom/molecule. In the calculations that follow we take $\mu = 32$, technically this value corresponds to an oxygen atmosphere although our intention here is to use this purely as a representative number. Different composition atmospheres will produce either higher or lower values for the mean molecular weight term and correspondingly lower or higher pressure scale heights.

With the above isothermal, atmospheric model being described we are in a position to consider meteoroid ablation in an artificial lunar atmosphere of total mass M_{atm} (kg). The calculations to be discussed here simply solve for the deceleration and mass loss equations describing the ablation of a solid-body meteoroid. For the sake of argument we assume a vertical impact (Z = 0 – although see Hughes, 1993), a meteoroid density of 3000 kg/m^3 and an ablation coefficient of $\sigma = 8 \times 10^{-8}$ m^2/s (characteristic of stony material). Two encounter velocities, *V* = 25 km/s and 70 km/s, will be considered. The larger velocity is the 1 AU limit for a meteoroid to remain bound to the solar system, while the smaller is representative of the typical sporadic meteoroid encounter speed at the Earth's orbit. We are not specifically interested in the trail length and or lunar meteor brightness in this study; rather it is the evaluation of the surface impacting mass for a given atmosphere. Accordingly, we are looking to determine the meteoroid, with an initial encounter mass of $m(h \approx \infty)$, that has a vanishing mass at the Moon's surface: $m(h = 0) = 0$. The results of our calculations are shown in figure 2. As one would expect, the more massive the lunar atmosphere, so the larger is the minimum meteoroid mass required to satisfy the $m(h = 0) = 0$ condition. For a lunar atmosphere mass of 10^8 kg, the least massive meteoroid capable of just reaching the Moon's surface has a mass of 1.4×10^{-9} kg (dia. = 100 microns). The least massive meteoroid capable of just reaching the Moon's surface when the lunar atmosphere has a mass 10^{11} kg and the encounter velocity is 70 km/s is 1.2 kg (dia. = 9.3 cm). For an encounter velocity of 25 km/s, the least massive meteoroid capable of reaching the Moon's surface is 1.7 grams (dia. = 1.0 cm), when the atmospheric mass is 10^{11} kg. For meteoroids having zenith angles greater than the vertical impacts considered here (i.e., Z > 0), the minimum mass limits for ground impact will increase above those derived for Z = 0 - as indicated by the short-dashed line in figure 2.

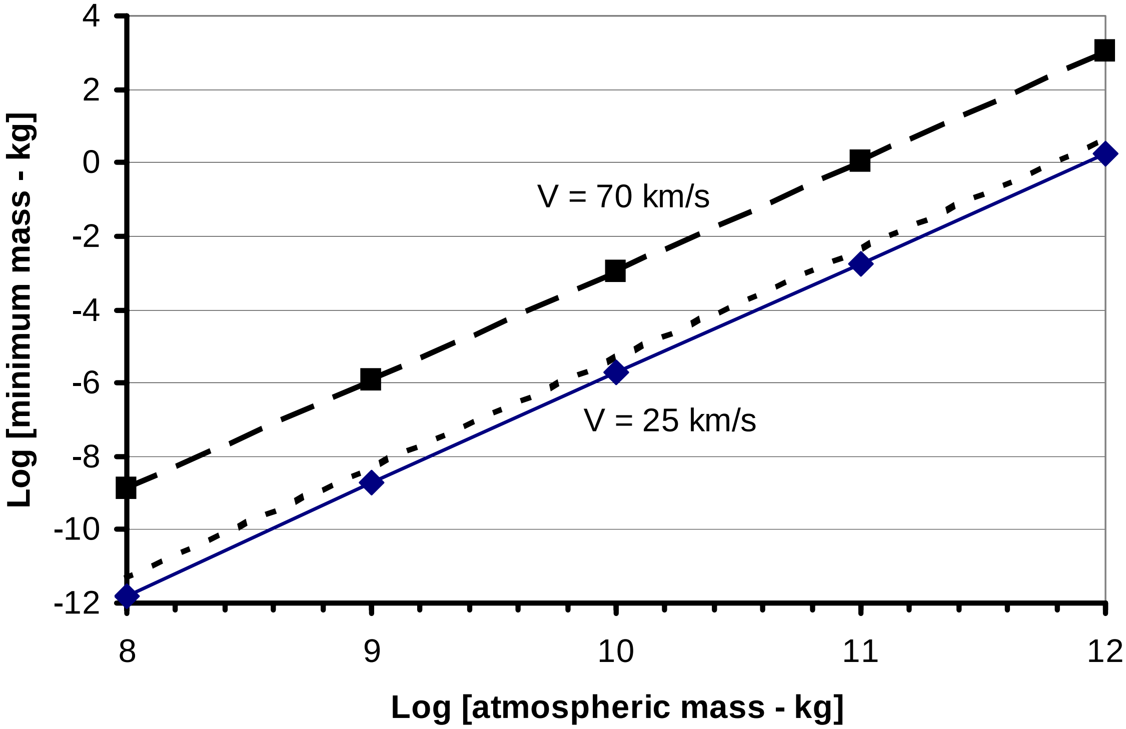

Figure 2. Minimum impact mass for a meteoroid encountering an artificial Moon atmosphere of mass M_{atm} (kg). The upper line corresponds to an encounter velocity of 70 km/s and the lower line to an encounter speed of 25 km/s when the zenith angle is Z = 0^{o}. The short-dashed line corresponds to an encounter velocity of 25 km/s, but with a zenith angle of entry of 45 degrees.

The observed peak of the meteoroid influx at 1 AU occurs at a mass of about 10^{-8} kg (Love and Brownlee, 1993), and accordingly protection from the majority of small mass meteoroids at 1 AU from the Sun can be achieved on the Moon once the lunar atmospheric mass exceeds ~ 10^{9} kg.

4. Discussion

There has been a long history of visual observers apparently seeing meteors in a supposed lunar atmosphere (Beech and Hughes, 2000), but in more recent times there has been the very definite detection of seismic events and surface impact flashes (figure 3) caused by meteoroid strikes (Oberst and Nakamura, 1991; Dunham *et al*, 2000; and see the review article by Bellot Rubio, Ortiz and Sada, 2000). Cooke *et al* (2007) find the lunar impact rate for 1 kg-class sporadic meteoroids to be about one per 11 hours. During the time of maximum activity associated with Earthly meteor showers the lunar impact rate of 1 kg-class meteoroids might increase to as high as 1 per hour. To provide lunar surface module protection against the direct impact of 1 kg-class initial mass meteoroids an artificial lunar atmosphere with a total mass between 10^{11} and 10^{12} kg would need to be generated.

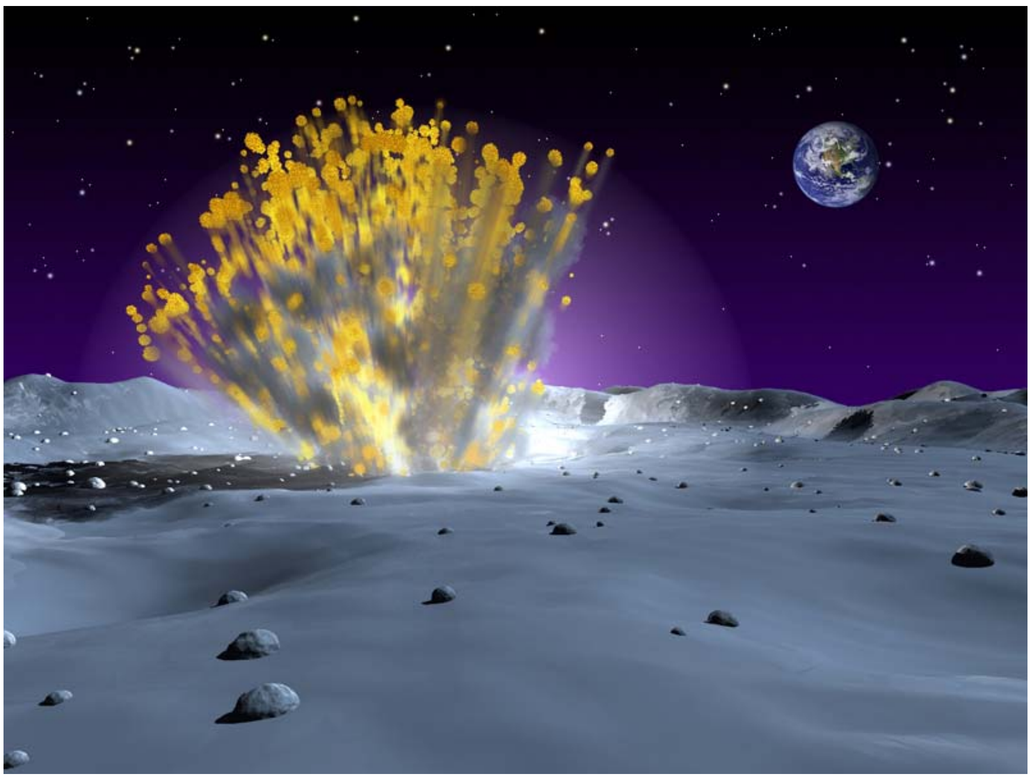

Figure 3. An artist's impression of an impact plume produced by a meteoroid hit upon the Moon's surface. Image courtesy of NASA. Further details at: http://www.nasa.gov/offices/meo/home/index.html.

If a regolith mined oxygen out-gassing rate of 100 kg/s can be realized then a 10^{12} kg lunar atmosphere might be developed within perhaps 300 to 500 years. This end might be achieved on a more rapid time scale if nuclear mining is exploited. Ehricke (1974) has estimated that a 1 kt nuclear device, if embedded and then detonated within the lunar mantle, might produce some 10^7 kg of oxygen. The detonation of 100,000 such devices, by no means a passive release of energy, would then produce the required amount of oxygen to produce an initial, 10^{12} kg lunar atmosphere. The atmosphere would then need to be maintained, at a lower material input rate, through non-nuclear regolith mining. Fogg (1995) has questioned Ehricke's assumptions, however, and suggests that the oxygen release rate per kt of explosive energy is more like 10^5 kg indicating that nuclear mining might not be the easiest or most cost effective way of producing a lunar atmosphere. A pure water-ice cometary nucleus with a diameter of 1.5 km technically contains enough oxygen to 'seed' an initial 10^{12} kg lunar atmosphere - the tricky engineering part, however, would be to release all the oxygen in a non-explosive manner. Simply allowing the entire cometary nucleus to crash into the Moon's surface would produce a much too dissipative impact. If the nucleus can be fragmented into numerous components prior to impact, however, a controlled out-gassing might just be possible. This latter scenario would also result in enhanced regolith degassing, similar in manner but on a much larger scale to the sodium enrichment of the Moon's exosphere observed during the Leonid meteor storm in 1998 (see e.g., Smith *et al* 1999).

It has been speculated by Chernyak (1978) that the Moon might have supported various transient atmospheres throughout most of its history. His argument is based upon the detailed study of lunar regolith core samples gathered by the Russian Space Agency's Luna and NASA's Apollo mission astronaut explorations conducted during the 1970s.

Specifically, Chernyak argues that on the basis that the Moon's regolith is produced by meteoritic bombardment then the relative depletion of very small mass particles might be explained by their ablative destruction in a lunar atmosphere. Indeed, Chernyak suggests that the Moon must have had, on at least one occasion during the past 100 Ma, an atmosphere with a total mass of order 5 x 10^{11} kg to explain the relative depletion of small particles in the lunar regolith samples.

In a solar system full of natural resources there seems to be no reason to doubt that an artificial lunar atmosphere won't eventually be engineered within the next several centuries (Beech, 2008). James Oberg (1981) goes even further and argues, "Because of the Moon's proximity to Earth, it should be considered as an early terraforming project" Indeed, a lunar atmosphere will provide a natural filter against the surface impact of small meteoroids, and for Earth-based observer's there will be the added pleasure of seeing meteors fall across the Moon's disk. Not only will such an atmosphere provide lunar inhabitants with impact protection it will also, if the appropriate chemical composition is maintained (e.g., the emplacement of an upper ozone layer), provide them with protection against short-wavelength solar radiation and cosmic rays.

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