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Detecting meteoroid streams with an in-situ dust detector above an airless body

Jamey R. Szalay[a,*], Mihály Horányi[b,c,d]

[a] Southwest Research Institute, 6220 Culebra Rd, San Antonio, TX 78238, USA
[b] Laboratory for Atmospheric and Space Physics, 1234 Innovation Dr., Boulder, CO 80303, USA
[c] Institute for Modeling Plasma, Atmospheres, and Cosmic Dust, 3400 Marine St., Boulder, CO 80303, USA
[d] Department of Physics, University of Colorado Boulder, 392 UCB, Boulder, CO 80309, USA

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ABSTRACT

The Lunar Dust Experiment (LDEX), aboard NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) successfully mapped the dust density distribution over the lunar surface up to an altitude of ∼ 250 km. LDEX detected dust grains launched off the surface in ejecta plumes generated by impacts of cometary and asteroidal micrometeoroids striking the Moon. While on average LDEX detected particles at a rate of 1 min^{-1}, periodically it measured bursts of particles at a rate exceeding the average value by up to two orders of magnitude. The timing and location of the most intense period of bursts is used here to independently determine the radiant for the Geminids meteoroid stream. The method is proposed to be of general interest to characterize meteoroid streams bombarding any of the airless bodies in the solar system using in-situ dust detectors.

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1. Introduction

Every planetary body in the inner solar system is continually bombarded by interplanetary dust particles (IDP) originating primarily from asteroid collisions and cometary activities. Thick atmospheres protect Venus, Earth, and Mars, ablating the incoming IDPs into 'shooting stars' that rarely reach the surface. The surfaces of airless bodies near 1 AU are directly exposed to the high-speed, $v \gg 1$ km/s, impacts of IDPs with a characteristic radius of $a \simeq 100$ μm and mass flux of $F \simeq 1.5 \times 10^{-15}$ kg/m^2/s (Grün et al., 1985). The total mass influx to Earth is on the order of 10^5 kg/day, hence the Moon is expected to be bombarded by 5×10^3 kg/day of IDPs arriving with a characteristic speed of 20 km/s (Taylor, 1996).

High-speed dust impacts into solid surfaces generate plasma (Dietzel et al., 1973) and neutral (Collette et al., 2014) gas clouds, as well as solid secondary ejecta dust particles (Hartmann, 1985). Ejecta particles with sufficient speeds escape from their parent body and have been identified as sources of planetary rings at Jupiter (Ockert-Bell et al., 1999), for example. Particles ejected with speeds below the escape speed follow bound orbits and return to the surface. Before LDEX visited the Moon, bound ejecta clouds forming dust exospheres were observed only around the icy moons of Jupiter (Krüger et al., 1999) and Saturn's moon Enceladus, though in the latter case active geysers are the dominant source of particles (Spahn et al., 2006). LDEX has since confirmed the existence of an asymmetric dusty exosphere engulfing the Moon, which responds to the local influx of micrometeoroids bombarding the lunar surface (Horányi et al., 2015).

Fully characterizing the meteoroid environment at 1 AU remains a challenging and active area of research. Meteoroid influx at Earth is measured via ground-based visual (Jenniskens, 1994) and radar observations (Brown et al., 2008; Campbell-Brown, 2008), which are highly sensitive to the mass and speed of incoming particles. Until LADEE, meteoroid flux to the lunar surface was monitored by visual light flash observations from large impactors with masses > 1 kg (Suggs et al., 2014). Meteoroid influx was also measured by the Apollo lunar seismic station, which operated from 1969 to 1977 and had an estimated mass sensitivity of 10^{-1} to 10^3 kg (Oberst and Nakamura, 1991) The previous lunar impact observations were able to detect much larger impacts than those that regularly sustain the lunar dust cloud given the larger cross sectional detection area required to measure an appreciable number of such impacts. The Moon acts as a large area dust detector, amplifying the amount of material impacting its surface by ejecting significantly more mass as outgoing solid ejecta (Horányi et al., 2015). LDEX measured the distribution of this impact generated

* Corresponding author at: Southwest Research Institute, 6220 Culebra Rd, San Antonio, TX 78238, USA. Tel.: +1 2105223723.
E-mail address: jszalay@swri.edu (J.R. Szalay).

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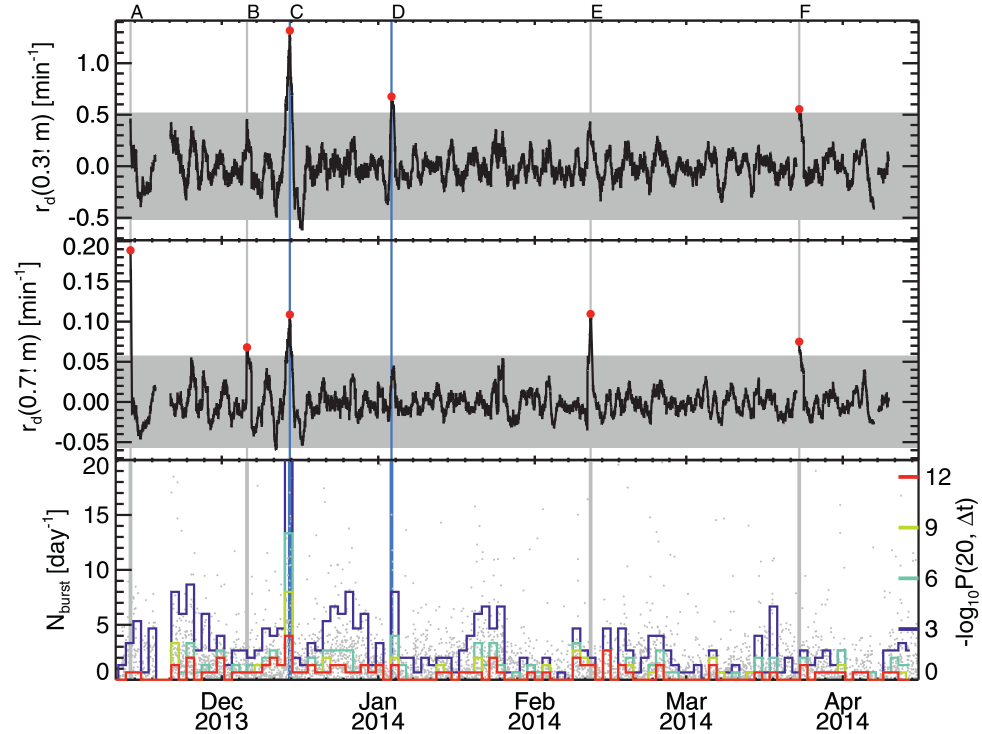

Fig. 1. LDEX impact rates and Poisson probabilities for the duration of the mission. Top and middle: The difference between 1 day and 1 week rolling averages of the impact rate as a function of time for $a > 0.3$ & 0.7 μm, respectively. The gray bar indicates 3σ error bars. Peak rates which exceed 3σ are indicated by red dots. Bottom: Gray dots show $\gamma(20, \Delta t)$ evaluated for each consecutive 20 impacts. A 1.5 day running histogram shows the total number of bursts for probability cuts of $\gamma_0 = 3; 6; 9;$ and 12; in purple, indigo, yellow, and red, respectively. The 6 unusual periods which satisfy Criteria 1 (gray) or both Criteria (blue) are shown with the vertical lines, labeled A–F. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

ejecta cloud and provided a novel way of observing the meteoroid influx to the Earth–Moon system.

1.1. The dust environment at the Moon

The dust environment at 1 AU is dominated by grains shed from asteroids and comets mainly within the orbit of Jupiter. These sources include comets, both long period Halley Type Comets (HTC) and short period Jupiter Family Comets (JFC), asteroids, Oort Cloud Comets (OCC), and the Edgeworth-Kuiper Belt (EKB). At 1 AU, the population of EKB grains is negligible, as most of these grains get ejected from the solar system by Jupiter during their migration towards the Sun (Han et al., 2011; Poppe, 2016). This dust/meteoroid environment is broken up into 2 distinct groups, the meteoroid streams and the sporadic background.

1.1.1. Meteoroid streams

When grains are shed, their initial orbital elements are similar to their parent body's. In addition to the gravitational forces by the Sun and the planets, the dynamics of a small dust particle is influenced by additional forces that are size-dependent, including solar wind and Poynting–Robertson drags, radiation pressure, and the Lorentz force (Han et al., 2011). The combination of these forces causes the ejected grains to decouple from their parent bodies and follow divergent trajectories over time. However, large enough (radii > 100 μm) grains preferentially disperse along the trajectory of their parent body, and may fill its entire orbital loop (Fox et al., 1983).

Once the orbit of a source body has been filled and becomes a 3D 'tube of material', it becomes a meteor stream if the orbit of the Earth intersects the ascending or descending node of this tube. There are hundreds of cataloged meteor showers, including the Geminids producing one of the strongest responses at Earth, first documented in 1862 (Fox et al., 1982; King, 1926).

1.1.2. The sporadic background

Smaller grains that are more susceptible to non-gravitational perturbations disperse, and follow orbits that rapidly diverge from their parent body, forming the 'sporadic background.' The sporadic background has its own structure and is organized by various radiant groupings: (a) the helion/anti-helion; (b) apex/anti-apex; and (c) the northern/southern toroidal sources (Jones and Brown, 1993). The relative contributions from each source vary as a function of solar longitude (Campbell-Brown and Jones, 2006). The variation of the sporadic background fluxes influences the spatial and temporal distribution of the dust ejecta cloud they generate impacting the Moon (Szalay and Horányi, 2015).

2. Impact ejecta plumes

When micrometeoroids impact the lunar surface, an ejecta plume is created that has many times the mass of the impacting particle. For normal impacts on a purely silica surface, the mass yield Y, the ratio of the mass ejected into the plume to the mass of the impacting particle is

$$Y \simeq C m_{imp}^{\alpha} v_{imp}^{\beta} \cos^2 \varphi, \qquad (1)$$

where C=30 for a silicate surface, m_{imp} is the mass of the impacting particle in kg, and v_{imp} is the velocity of the impacting particle in km/s, $\alpha = 0.2$, and $\beta = 2.5$ (Koschny and Grün, 2001; Krivov et al., 2003). The angular dependence is derived from an experimental finding that the material excavated by impacts varies as $\cos^2\varphi$ where φ is angle between the surface normal and the velocity of the incoming particle (Gault, 1973). While this experiment (Gault, 1973) was performed for impacts into solid rock, which may have different impact physics compared to regolith, we still

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