Galactic dust lanes and lunar soil

It has been proposed by McCrea\textsuperscript{1}, Shapley\textsuperscript{8} and Hoyle\textsuperscript{8} that passages of the Solar System through interstellar clouds have appreciable effects on the Earth. McCrea argues that the recurrence of ice epochs\textsuperscript{8} every \(\sim 250\) Myr coincides with the passage of the Solar System through a galactic spiral arm approximately every \(10^5\) yr. We report here studies on the character and grain-size distribution of texturally-mature lunar soils which support these views. The evidence shows that the flux of micrometeoroids (\(\leq 10^{-6}\) g) at the lunar surface has remained in quasi-equilibrium near the present-day value over the past \(2 \times 10^9\) yr, but that significant increases have occurred. Three near-cyclical enhancements are superimposed on the drill core stratigraphy, with separations of \(\sim 10^9\) yr. The magnitudes, durations, and periodicity of the flux increases suggest their origin may be the passage of the Solar System through dust lanes in the galactic spiral arms.

It has been noted\textsuperscript{8} that a segment of the cumulative grain-size distribution of "texturally-mature" lunar soils closely parallels the present meteoroid flux distribution in the soil grain-size range 44–177 \(\mu\)m, at the maximum concentration of impact-derived constructional glass particles, or "agglutinates"\textsuperscript{15,16}. We believe that this segment of the soil distribution provides information on the meteoroid influx distribution that produced it.

Most of the kinetic energy in the present meteoroid flux\textsuperscript{8} is in particles of masses \(< 10^{-6}\) g which strike the lunar soil at a velocity of \(\sim 20\) km s\(^{-1}\) and generate enough heat to fuse a volume of soil. Some melt is as spun during crater excavation, but morphological information in the form of rings (Fig. 1) or bowl-shaped agglutinates\textsuperscript{15} suggests that only one large agglutinate particle is formed by any one micrometeoroid impact. Thus the parallelism between grain size and meteoroid flux is understandable: one simply mirrors the other. Experimental data on the ratio of mass of the melt to mass of the meteoroid at 20 km s\(^{-1}\) is lacking, but theory\textsuperscript{8} suggests that an agglutinate represents \(\sim 5\) times the mass of the impacting micrometeoroid. Using mean agglutinate diameters and a particle density of 3.1 g cm\(^{-3}\) the parallel segment of the soil curve converges to a micrometeoroid mass range of 0.08 - 10\(^{-5}\) - 2.0 \(\times\) 10\(^{-6}\) g.

A meteoroid stream is \(N = \alpha m^n\), where \(N\) is the total number of particles larger than mass \(m\), \(\alpha\) is the intercept and \(\beta\) is the slope of a plot of log flux against log mass for masses larger than \(\sim 10^{-7}\) g (refs 9 and 11). We convert the bulk grain-size distribution for the 45–177-\(\mu\)m range from weight \(\alpha\) to number equivalent assuming spherical particles. The numbers of particles in five size intervals are normalised to the total number, and we construct a cumulative particle number (frequency) distribution. Using equivalent meteoroid masses and cumulative particle numbers in log-log form, a linear least squares fit gives \(\beta\). But \(\alpha\) (which gives total flux) cannot be found without knowing the meteoroid exposure time of the soil. We derived \(\beta\) for 61 samples—12 surface soils and 49 from the Apollo 15 deep drill core. In all cases the linear fit explains \(> 97\%\) of the variance, thus demonstrating a strong linear dependence between log \(N\) and log \(m\).

Soils from the lunar surface should give \(\beta\) estimates near the modern flux value derived from other methods, thus offering an independent test of the model. The present meteoroid flux in our mass range has \(\beta = -1.213\) (ref. 9). Estimates of \(\beta\) for the surface samples range from \(-1.266\) to \(-1.142\) with a mean of \(-1.213 \pm 0.039\). A one-tailed \(t\) test indicates no significant difference between the modern \(\beta\) value and our estimates from
the surface soils ($t_{esc} = 2.201 > 0.043$, d.f. = −11). That is, the model works.

Large meteoroids produce ejecta blankets of sufficient thickness and extent to survive as layers. This creates three interpretation problems: (1) inverted stratigraphy may appear in the record; (2) old agglutinates may survive excavation from an earlier layer; and (3) the soil accumulation rate is nonlinear.13

First, inverted stratigraphic sequences of small thickness will not destroy regular trends in the data, but will increase deviations about the trend. The range in $β$ values is not affected. Second, Lindsay18 investigated agglutinate survival under reworking and found most pre-existing agglutinates are destroyed in excavation by layer-forming events (that is, crushed to sizes ≤ 15 μm, below our range). Third, soil accumulation rates are nonlinear13-19, but modelling the growth requires assumptions of the meteoric flux history, so it is best to model linear accumulation. The age of the substrate14 and total soil thickness at the Apollo 15 site19 give an average accumulation rate of $1.35 \times 10^{-5}$ cm$^2$ yr$^{-1}$. Nonlinear soil models13,18 fortunately give similar rates for this time period. Since our sampling interval is 0.5 cm our time resolution is $\sim 4 \times 10^5$ yr.

The core samples cover a depth of 120–240 cm in known stratigraphy (Fig. 2). Estimates of $β$ for these samples range from $1.4901 \to 1.381$ with a mean of $1.278 \pm 0.060$. The data do not show a monotonically decreasing flux distribution but suggest a quasi-steady-state background level near the modern flux value, with enhancements superimposed. Below 180 cm the deviations are a series of disorder ‘spikes’; above 180 cm three regular deviations each extend over 15–20 cm of the record. Each cycle crosses several stratigraphic units, indicating that the $β$ variations have extra-lunar, time-dependent sources, rather than being determined by independent depositional processes operating on individual stratigraphic units.

Micrometeoroid experiments on the Pioneer 8, 9, 10, and 11 spacecraft18,19 show the asteroid belt is not a small particle source. Unless the particle populations and dynamics in the Solar System were quite different 1–2 eons ago, we suggest that the flux enhancements are not redistributions of matter by asteroidal collisions. We propose the enhancements record passages of the Solar System through dense interstellar clouds, plus active cometary episodes. These two sources may be manifestations of the same event: namely the passage of the Solar System through compression lanes in the arms of the Galaxy4 and the concomitant generation of comets and their subsequent mass loss to the Solar System10.

Lyttleton10,22,23 suggests that comets are “new” members of the Solar System formed by the interaction of the Sun with interstellar clouds. The Sun encounters dense clouds ($\sim 10^{-10}$ g cm$^{-2}$) in “compression lanes” of interstellar matter in the galactic spiral arms23. Mass loss from long-period comets so formed could enhance the small particle flux for $10^4$–$10^5$ yr (ref. 17).

Hartung and Störzer24 suggest the modern small particle flux is increasing due to activity by Comet Encke. A micrometeoroid detector on the Heos-2 spacecraft25 shows that Comet Kohoutek deposits small particles into the inner Solar System. Lyttleton26 suggests that particles $\lesssim 10^{-3}$ g are lost from comets due to the solar wind. Since comets have masses of $10^{-9}$–$10^{-10}$ g and lose $10^{-3}$ of this in each solar encounter20,12, one comet could increase the particulate matter density within the orbit of Jupiter by $\sim 3 \times 10^{-10}$ g cm$^{-3}$ if the debris is in the ecliptic. For matter collected by the Moon at 20 km s$^{-1}$, the surface flux would increase by $\sim 10^{-10}$ g cm$^{-2}$ yr$^{-1}$ above the present level of $1.2 \times 10^{-4}$ g cm$^{-2}$ yr$^{-1}$ in small particles11,13-24. Further flux enhancements are possible for cometary periods which are short compared with the Solar System debris retention time21. Such enhancements could explain brief flux excursions. The “peak” at $\sim 200$ cm corresponds to a small particle flux increase of $\sim 15$ times the present value.

The speed10 of the Sun through compression lanes is 5–24 km s$^{-1}$, so cloud densities as above give enhancements $5 \times 10^{-6}$ g cm$^{-2}$ yr$^{-1}$. Although interstellar clouds have variable constitution, “typical clouds” contain $\lesssim 1%$ grains by mass.10 For an encounter speed of 20 km s$^{-1}$, these particles striking the Moon would increase the small particle flux by $\sim 10^{-8}$ g cm$^{-2}$ yr$^{-1}$. So such encounters are numerically capable of producing the flux changes detected from lunar soil parameters.

From 120 to 180 cm in the core tube the $β$ variations are smooth, cyclical deviations from the present-day value. Although it is difficult to correlate depth with age exactly, the three cycles have periodicities of $1 \times 10^4$–$2 \times 10^4$ yr and comparable durations. On this basis, the cycles cover an age $2 \times 10^4$–$1.5 \times 10^7$ yr (all Precambrian), so unfortunately our data cannot be compared with known glacial epochs. McCrea1 points out that the Solar System crosses a spiral arm every $10^7$ year or so, taking $\sim 10^7$ yr to cross the compression lane and spending a total of $\sim 10^7$ yr in the arm. This agrees well with our estimates of $β$ cycles in the soil, except for their longer durations ($\sim 10^6$ yr) which may be due to mass loss to the inner Solar System by long-period comets born in such encounters.

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Jupiter's atmospheric circulation

By numerical integration of conventional meteorological equations at appropriate parameter values we have been able to reproduce most of the major characteristics of the Jovian atmosphere.

The axisymmetry and scale of the bands, the oval-shaped disturbances, the waves and the Great Red Spot are all essentially characteristics of turbulent barotropic vorticity exchanges in a rapidly rotating planetary atmosphere. They are produced by the interaction in a spherical domain of a two-dimensional (horizontal) turbulent cascade and Rossby wave propagation, a process that we shall refer to as global turbulence. This interaction occurs at a length scale \( L_0 = (2\pi u / \beta)^{1/2} \), where \( u \) is a measure of the zonal velocity and \( \beta \) is the northward gradient of the Coriolis force, that closely matches the observed size of the bands. This hypothesis has been verified by solutions obtained for a stochastically forced barotropic equation, see for example Fig. 1.

The complete Jovian thermodynamical system can be reasonably well reproduced by using a standard (that is, Phillips's) terrestrial general circulation model under Jovian parameter conditions (see Fig. 2, for example). Apart from the characteristic banded structure the solutions also reveal the existence of an intra-jet circulation or gyre in which the flow resembles that surrounding the Great Red Spot. The planet also seems to have a heat transfer (inflow) cycle with a 4 to 5-yr period that accounts for long term variability. Clouds are produced by vertical circulation cells induced by frictional Ekman pumping.

Our theoretical flows suggest that the Great Red Spot can be thought of as essentially the core of an intra-jet circulation or as an eddy of global turbulence (as defined above). Like the ovals,

Fig. 1 An example of simulated Jovian turbulence. Sphere contains stream function contours with negative values shaded by 1/4 of grid points. Profile of longitudinally averaged zonal flow has a scale of 100 m s\(^{-1}\) in right-hand side diagram. State is transient and early in atmospheric evolution to final form. Although more orderly than final state it illustrates basic elements more clearly. A cine film of this solution is available on request.

Fig. 2 The global circulation as given by a terrestrial general circulation model integrated in the Jovian parameter range. Calculations were made over a limited sector and repeated for global display. Model is not valid at the equator.

the Great Red Spot plays an important role in the energy cascade that maintains the multiple zonal currents. The persistence of the Great Red Spot is due to the fact that (1) energy cascades toward larger scales in two-dimensional turbulence and (2) under appropriate conditions large intra-jet circulations such as that forming the Great Red Spot are an integral part of this type of multiple-jet global circulation.

Thus Jupiter's atmosphere seems to have the same dynamical ingredients as the terrestrial atmosphere and ocean. The processes occur on different scales, however, and act in different proportions. As in the terrestrial and Martian systems, baroclinic instability again seems to be the primary energy conversion process. A complete description of the meteorology of Jupiter and Saturn has been submitted for publication elsewhere.

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Noble gases in an Hawaiian xenolith

The noble gas record in meteorites and lunar samples has been the subject of many investigations aimed at determining their age, the history of their exposure to cosmic rays and to the solar wind, and the early chronology of events in the Solar System (see review in ref. 1). Information on the latter is contained primarily in the isotopes of xenon, where the decay products of extinct \(^{231}\)Pb and \(^{241}\)Pu provide a record of the synthesis of elements and the early history of planetary solids (see review in ref. 2). The occurrence of radiogenic xenon in CO\(_2\) well gas from Harding County, New Mexico is the only clear evidence that extant radioactivities were present in the early history of the Earth\(^{3,4}\), but the suggestion that this radiogenic xenon had been brought near the Earth's surface in hot magmas was not confirmed by recent analyses of xenon in lava rock from this region\(^{5}\).

The present investigation of noble gases in a volcanic xenolith containing high-purity inclusions of liquid CO\(_2\) was undertaken to see if radiogenic xenon might be associated with