

A POSSIBLE METEOR SHOWER ON THE MOON

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Abstract Over the 3-day period from 12 to 14 October, 1990, the sodium abundance in the lunar atmosphere at 80° South increased by 60%, while interspersed measurements at the equator showed no substantial change. The source is suggested to be an unknown meteor shower with a radiant near the south ecliptic pole. A low relative velocity of ~ 20 km/sec, combined with small particle masses, would keep the shower below the detectability threshold of radar. The stream could evolve from a reasonable asteroidal or cometary orbit with perihelion somewhat greater than 1 astronomical unit (AU) and a major axis of a few AU. The short residence time of lunar sodium makes it much more favorable than the terrestrial sodium layer for detection of such an event.

Introduction

In the course of studying a body of data on lunar sodium and potassium acquired since 1988 [cf. Tyler *et al.*, 1988; Kozłowski *et al.*, 1990], we noticed a remarkable increase of the sodium abundance at 80°S latitude during a 3-day period. Much more detail is given in a paper submitted to *Icarus* [A.L. Sprague, R.W.H. Kozłowski, D.M. Hunten, W.K. Wells, and F.A. Grosse, "Sodium and potassium atmosphere of the Moon and its interaction with the surface"]. Although 34 nights were spent at the telescope, the sodium data set is limited to 12 profiles obtained on 7 nights. The only contiguous data are for the period 12–14 October 1990, and we concentrate here on this period. The results, along with one measurement taken 2 months earlier, are shown in Table 1 and Figure 1. During the three days, the abundance (integrated column density) at the equator remained within a range of $\pm 9\%$ and consistent with earlier results, while the amount near the south pole increased a factor of 2. One measurement near the other pole agreed with the initial southern value. We believe that the stability of the calibration is $\pm 10\%$; the absolute uncertainty, not an issue for the present purpose, is probably $\pm 20\%$. These estimates are consistent with the stability of the equatorial results shown, which undoubtedly also reflect a certain amount of real variability.

Observations

Observations were made at the 153 cm Catalina telescope of the University of Arizona Observatories, with

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Table 1. MEASUREMENTS OF LUNAR SODIUM ABUNDANCE

Date (1990)	Location	D2 Intensity R	Abundance 10^8 cm^{-2}
29 Aug	equator	3700	9.9
12 Oct	equator	3400	11
13 Oct	equator	3700	12
14 Oct	equator	2800	10
12 Oct	80 S	1000	4.4, 3.8†
13 Oct	80 S	1400	4.9
14 Oct	80 S	2200	6.5
13 Oct	80 N	1000	4.3

†The two values shown for 12 Oct, 80S, represent different assumed scale heights.

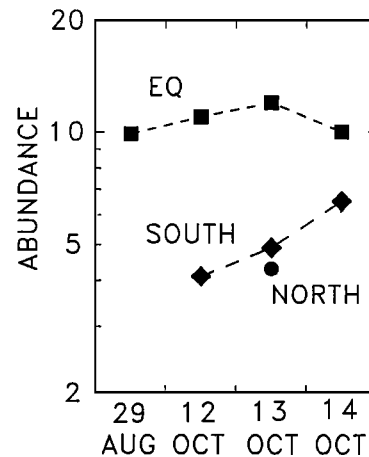


Fig. 1. Sodium abundances during October 1990; a measurement from August is included to indicate the stability of the photometry and of the equatorial (E) atmosphere. Units are 10^8 atoms cm^{-2} referred to the local vertical. Over three days, the southern (S) abundance doubled, and on the middle day the northern (N) abundance was still low. A logarithmic scale is used to emphasize relative changes. The 2σ error limits are estimated to be $\pm 10\%$ for each point, although the absolute calibrations may be somewhat more uncertain.

a Cassegrain échelle spectrograph [Cunningham *et al.*, 1988; Hunten *et al.*, 1991] and CCD detector; the resolving power $\lambda/\Delta\lambda$, where $\Delta\lambda$ is the line width, was about 10^5 and the spatial coverage along the slit about 140 km at the distance of the Moon. For the results discussed here, the instrument was rotated so that the slit was at right angles to the local lunar limb, and the image of the limb was placed at the end of the slit. The rest of the slit probed the atmosphere to the 140 km height

mentioned above. This geometry enhances the observed intensity by a long, horizontal path length. Data processing was done with the program IRAF running on Sun and Solbourne computers. Intensity calibrations were taken from Jupiter's North Tropical Zone, assumed to have an intensity of 5.3 Megarayleighs per Angstrom. Each exposure must have a background subtracted and be ratioed to a flat field. A reference spectrum from the lunar disk is then normalized and subtracted to leave the atmospheric emission lines. The intensities shown in Table 1 are observed just above the limb of the Moon. A scale height is derived from the data at higher altitudes and is then used to convert the intensities to the vertical column abundances. Because these scale heights vary somewhat, there is not an exact one-to-one correspondence between the horizontal intensity and the vertical abundance.

Discussion

The principal source of sodium is believed to be vaporization from the regolith by impact of small meteoroids [Morgan *et al.*, 1989]. An important sink is photoionization followed by rapid acceleration in the motional electric field of the solar wind. The ions are either swept away into interplanetary space or rammed back into the surface. Other sinks are less well established and will not be considered here. On release from the dayside surface, an atmospheric atom executes ballistic orbits with a typical hop time of 20 min. and is likely to be adsorbed when it reaches the surface. After spending a variable time (seconds to minutes) on the surface it is desorbed by a solar photon and undergoes another hop; there is also significant thermal desorption near the subsolar point, but it is not important for the data discussed here. The mean lifetime against photoionization is 14 hours; the mean number of hops is therefore 42, which may be reduced by the escape of atoms in the high-energy tail. Not all workers in the field agree on these details, but most of them do not affect the present discussion.

In this scenario, the obvious latitude variation of abundance is caused by variable partitioning between atoms in the atmosphere and adsorbed on the surface; the meteoroidal source is assumed to be isotropic. At 80° latitude, the projected solar flux is 17% of the value at the subsolar point; for the equatorial points, this percentage varies between 95 and 75% over the three-day period. The fraction of the total inventory lying on the surface is therefore much larger in the polar regions. We assume that the normal abundance at 80° is 4.1×10^8 atoms cm^{-2} , the average of the single northern point and the first southern one, and that the increase of abundance in the south is the result of a special event, namely an enhanced meteoroid flux. There is no way to test these assumptions without further data, which we do not have. Acquiring enough data for a real test is likely to require at least two years, if not more. The hypothesis is presented to stimulate additional thought and observations by others.

It therefore appears that the strength of the dominant source doubled in the south polar region over a period of 2 days. If meteoritic impact is this dominant source for alkalis, the most likely explanation of an in-

crease is a meteor shower with a radiant near the south pole. The flux to the surface would fall off approximately as the cosine of the angular distance from the sub-radiant point (as long as deflection by lunar gravity is not too large), and would therefore be nearly zero at distances of 90° and greater.

Another possibility is a sporadic increase in localized degassing through the regolith [Sprague, 1990]. Apollo measurements from orbit gave evidence for regional degassing of radon [Bjorkholm *et al.*, 1973] and possibly a mixture of nitrogen and oxygen [Hodges *et al.*, 1974]. A 250-day series of argon data from the landed mass spectrometer showed a variation by a factor ~ 2 . Because the time scale of the variations was comparable to the residence time (which is much longer for argon than sodium), changes in the source strength must have been much greater [Hodges, 1975]. The largest moonquake reported by Nakamura *et al.* [1979], on March 13, 1973, was near the south pole and may have been correlated with an argon release. Other seismic events are discussed by Oberst and Nakamura [1991]. Sputtering by ions or solar photons would be concentrated near the subsolar point, and reduced by $\cos 80^\circ = 0.17$ at the observed latitude; moreover, they are expected to be steady, and the latter is better considered a recycling mechanism than a source. There was no solar proton event during the relevant period. Here we will concentrate on the meteoric source and attempt to show that it is feasible.

The comprehensive radar search from Australia by Nilsson [1964] found 7 meteor showers in October; one has a radiant on the equator, and the rest are in the northern hemisphere. Although this result is disappointing, there are almost certainly many undetected showers. As a reviewer has pointed out, there are also well-known examples of particle streams that are too young to have been dispersed all the way around the orbit; such a stream could have been missed in Nilsson's 13-month survey. Visual or radio detectability of meteors depends sensitively on the velocity and is also proportional to the mass. Hughes [1978, p. 154] concludes that "only ~ 3.5 per cent of the mass incident [on the Earth] in the $10^{-6}g < m < 10^{-2}g$ range is observed by radar"; the assumed reason is that the undetected ones "have such low geocentric velocities that they produce insufficient ionization for detection". The typical sporadic meteoroid is deduced to be around $150 \mu\text{m}$ across and to have an entry velocity only a few km/sec greater than the escape speed. Their orbits therefore must have been nearly circular and of low inclination, with a nearly isotropic geocentric velocity. These orbits match rather well the expected result of evolution through Poynting-Robertson drag, described below, as long as the initial orbits had small inclinations [Sandford, 1986]. We suggest that there may be a large number of particle streams that have not been detected by visual or radar methods because they have orbital parameters similar to the sporadic particles. Specifically, most dust streams of asteroidal origin would be expected to be in such orbits [Sandford, 1986].

As a specific example for illustration, we assume that the lunar meteoroid stream is in a circular orbit with an inclination of 37° , chosen to give a velocity relative to the Earth and Moon of 20 km/sec from a direction near

the south pole. Another equally plausible orbit reaches perihelion at 1 AU, with northward, eastward, and radial velocity components of 20, 30, and 0 km/sec; in the Earth-Moon reference frame only the northward component remains. The orbital velocity is 36 km/sec, the inclination 34° , the eccentricity 0.44, and the aphelion distance 2.57 AU. Other reasonable orbits might have smaller inclinations and impact velocities and be consistent with an asteroidal origin.

Streams of this sort would have evolved by Poynting-Robertson drag from an eccentric cometary or asteroidal orbit with the same inclination but a larger perihelion [Wyatt and Whipple, 1950; Sykes and Greenberg, 1986; Sandford, 1986]. This evolution resembles that of an Earth-orbiting satellite (Figure 2). Since the drag is concentrated near perihelion, the aphelion distance and eccentricity decrease with little change in perihelion until the orbit is nearly circular; then the orbit shrinks into the Sun. The inclination remains essentially unchanged, although the plane of the orbit does precess. The rate of evolution is proportional to the ratio of surface area to mass, and therefore varies inversely as the radius. If the radius is 0.1 mm and the density 3.0 g cm^{-3} , the time scale is up to 10^7 y, depending on the initial eccentricity. For the circular orbit suggested above, the smallest particles, with their rapid evolution, may have just reached the Earth's orbit, while larger ones are trailing behind. Both the small masses and the low velocity put the ones that reach the Earth below the radar threshold.

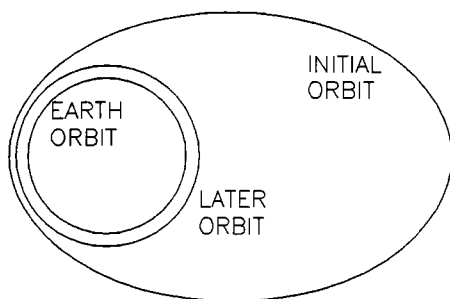


Fig. 2. Sketch of the orbital evolutionary path of debris released from a comet or asteroid with an initial semi-major axis of 2.8 astronomical units. Because the rate of evolution is inversely proportional to size, larger particles will remain essentially in the initial orbit, while orbits of the smaller ones first become circular and then rapidly shrink.

The required flux in the lunar shower may be derived by comparison with known values for the Earth. Although these are somewhat affected by gravitational focusing, most of the differences will cancel out when they are applied to the less massive Moon. According to Hughes [1974, 1978], the sporadic flux to the Earth is 44 metric tonnes per day or $10 \times 10^{-17} \text{ g cm}^{-2} \text{ sec}^{-1}$, and the peak fluxes of the Geminids, Quadrantids, and Perseids are 2.4, 3.3, and 0.28 in units of $10^{-17} \text{ g cm}^{-2} \text{ sec}^{-1}$. These streams must be relatively young, because the duration of the showers is a few days or less, and they are in eccentric orbits giving entry velocities of 35, 41, and 60 km/sec. Because of these high velocities they are a selected set, highly visible and easily detectable by radar.

Most particle streams of asteroidal origin will have direct orbits, such as the examples presented above, and must catch up to the Earth with a modest relative velocity.

It remains to show that the required flux in our postulated shower is reasonable. With their low encounter velocity, the particles can be assumed to eject sodium from the lunar surface with the same efficiency as the sporadic particles. Since the shower doubles the sodium abundance in the south polar region, its flux must be equal to the sporadic flux. Although this flux is uncertain, the estimate of Hughes [1974] shows it as exceeding that of the Quadrantids by a factor 3. Most populations in space have their mass concentrated in small particles, and this excess is very reasonable. The required factor would be reduced if the sodium originates in the meteoroids rather than the lunar soil, and if the sodium content of the shower particles is greater than in the sporadic influx.

The sodium in the layer at the Earth's mesopause has a residence time of order 10 days, and the abundance is dominated by the sporadic background, as the figures in the previous paragraph illustrate. Detection of meteor-related enhancements should be much easier on the Moon, where the residence time is only half a day; on Earth they are greatly diluted and only a handful of events have ever been reported [e.g. Kirchhoff and Takahashi, 1984].

Monitoring of the lunar atmosphere therefore has the potential of revealing meteor streams that currently cannot be detected in any other way; alternatively, it may refute the hypothesis presented here. However, such monitoring is not really feasible with the heavy, complex equipment and substantial telescope that were used for the present study. A smaller telescope with the same f/number would produce an image of the lunar atmosphere with a smaller scale and the same surface brightness. Although it could not carry our 200-kg spectrograph, a coudé feed would do the job. Another problem is the elaborate data analysis required to remove the scattered light from the bright lunar surface. The intensity of this background could be reduced by coronagraphic optics, already used successfully by Mendillo et al. [1990, 1991] for similar studies of distant Jovian and lunar sodium. Measurements just above the limb may still require a spectrograph to discriminate against the scattered light.

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