Mon. Not. R. Astron. Soc. **327,** 244–248 (2001)

The 1999 Quadrantids and the lunar Na atmosphere

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Accepted 2001 June 1. Received 2001 May 21; in original form 2001 January 15

ABSTRACT

Enhancements of the Na emission and temperature from the lunar atmosphere were reported during the Leonid meteor showers of 1995, 1997 and 1998. Here we report a search for similar enhancement during the 1999 Quadrantids, which have the highest mass flux of any of the major streams. No enhancements were detected. We suggest that different chemical–physical properties of the Leonid and Quadrantid streams may be responsible for the difference.

Key words: meteors, meteoroids – Moon.

1 INTRODUCTION

Evidence of a lunar atmosphere has been sought since the dawn of the telescopic era, but none was found until *in situ* measurements by the *Apollo* missions revealed the presence of He and Ar, both of solar origin, and possibly CH_4, CO, CO_2 and N_2 (Hodges et al. 1974). Discovery from the ground of Na (Potter & Morgan 1985) and K (Potter & Morgan 1986) in Mercury's atmosphere renewed interest in observing the lunar atmosphere from Earth, since both atmospheres are believed to be generated by similar mechanisms, although at different rates. The atmospheres of Mercury and the Moon are continuously lost and repopulated under the influence of the interplanetary medium, and are known as transient atmospheres. There are four candidate source mechanisms for such atmospheres: desorption and sputtering by solar photons; chemical sputtering by the solar wind and by energetic particles from the Earth's magnetosphere; micrometeoroid impacts; and thermal desorption. The sink mechanisms are: Jeans escape; escape owing to solar radiation pressure; ionization by the solar wind; and photoionization. The latter is the dominant sink mechanism for lunar Na, with proposed lifetimes of 15 or 47 h at 1 au (cf. Cremonese et al. 1997). The expected energy distribution, characteristic temperature and spatial distribution of each source mechanism are given by Smyth & Marconi (1995).

Lunar Na and K were discovered in 1988 (Potter & Morgan 1988; Tyler, Kozlowski & Hunten 1988). Many observations using different techniques have been made to address the origin and evolution of this atmosphere, at present thought to be a combination of sputtering by solar photons and meteoroid impacts (Cremonese & Verani 1997; Sprague et al. 1998) or of chemical sputtering by solar wind ions and photosputtering (Potter & Morgan 1998). For a comprehensive overview, see Stern (1999). Similar Na atmospheres are present around Jupiter's moons Io (Brown 1974) and Europa (Brown & Hill 1996), but the source mechanism for these is believed to be sputtering by heavy ions in the Jovian magnetosphere. Na is a good tracer of such thin atmospheres because of the ease with which its strong emission can be observed.

Wide-angle imaging has shown that in the region between 1 and 10 lunar radii, about 15 per cent of the Na atmosphere is due to micrometer impacts (Flynn & Mendillo 1995). Spectroscopic observations of the inner region of the atmosphere show that meteor impacts have an effect which is spatially anisotropic, and which is variable on short time-scales (Cremonese & Verani 1997; Sprague et al. 1998). In 1991, Hunten, Kozlowski & Sprague published the results of a 3 d campaign of observations, during which the Na abundance increased by 60 per cent at 80° south, while that at the equator remained unchanged. They suggested that the cause may have been a meteor shower, undetected by radar or by other measurements, impacting near the south pole of the Moon. In 1998 Verani et al. reported a set of high-resolution spectra taken 4.5 d before the maximum of the 1995 Leonids, with the same observational technique as used for the observations reported here, as described in Cremonese & Verani (1997) and in Sprague et al. (1992). They found significant enhancements of the brightness and temperature (scaleheight) of the Na atmosphere compared with previous observations at similar lunar phase and local solar zenith angle (LSZA). Since the impact-generated component of the atmosphere has the highest expected temperature (Smyth & Marconi 1995), the measured increase in temperature may be associated with increased meteor activity during the Leonids.

A similar enhancement was detected during the maximum of the 1997 Leonids, at Mount Lemmon and Asiago observatories (Hunten et al. 1998). These measurements appear to be confirmed

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by observations taken with a different technique during the night of the 1998 Leonid maximum Smith et al. (1999). The authors reported the detection of a region of neutral Na emission in the direction of the anti-solar/lunar point in the three nights around new Moon phase (1998 November 18–20), suggesting as the most likely cause the detection of the tail of the Moon's atmosphere, i.e. its escaping component, driven outwards by solar radiation pressure. A model of these results (Wilson et al. 1999) indicates an increase of a factor of 2 or 3 in the amount of Na escaping during the peak of the Leonids.

Despite these observations, many issues remain to be resolved before one can conclude with certainty that meteor showers are responsible for the observed enhancements. In fact the lunar atmosphere shows time variations, the nature of which is not fully understood (Sprague et al. 1998; Smith et al. 2000). A measurement of enhanced Na emission from the Moon during a meteor shower other than the Leonids would strongly support the hypothesis that these showers are an important source of the transient Na atmosphere, both on the Moon and on other Solar system bodies with thin atmospheres. In terms of mass flux ($\mathrm{g\,cm^{-2}\,s^{-1}}$), the Quadrantids are the most intense meteor stream; in fact, if we compare the mass flux of the meteor streams and the mass flux of the sporadic meteoroids reported in Table 3 (see later), we can see that the micrometeoritic flux could increase by up to 30–50 per cent during the Quadrantids. From this point of view, this stream gives a good opportunity to test the impact mechanism; we therefore observed the lunar atmosphere during the 1999 Quadrantid meteor shower.

2 OBSERVATIONS

The observations were made in the early mornings of 1999 January 3 and 4 with the Utrecht Echelle Spectrograph of the William Herschel Telescope on La Palma (dispersion 0.053 Å $\mathrm{pixel^{-1}}$). Both nights were photometric. The Moon was full on January 2, at 02:49. The Sun was quiet. The diameter of the magnetotail is about 52 Earth radii at the Moon's orbit (Reiff & Reasoner 1975), which means that the Moon was inside the magnetotail on the first night of the observations (phase angle = 14°). On the second night (phase angle = 26°) the Moon was near the predicted position of the magnetopause, and thus its location with respect to the magnetotail and magnetosheath is uncertain.

The maximum of the Quadrantids was predicted on the night of January 3/4, with radiant at $\alpha = 230°$, $\delta = +49°$. The right ascensions of the Moon at 0h UT on 1999 January 3 and 4 were respectively 115° and 129°, so the shower fell on the Moon's western limb (cf. Fig. 1). The slit of the spectrograph, 150 arcsec long and 1 arcsec wide, was oriented perpendicular to the lunar limb, and observations were made at various positions along the limb (Table 1) to investigate changes in the Na emission with distance from the sub-radiant point. Exposure times were typically 500 s. The first 50 arcsec from the surface had to be discarded because of the strong scattered moonlight; the spatial coverage was then augmented by placing two fields end to end. For details of the data reduction and analysis see Cremonese et al. (1992) and Verani et al. (1998).

The full Moon prevented reliable visual measurements of the intensity of the shower at the Earth, but 50-MHz radar observations made at Toyokawa Meteor Observatory, Aichi, Japan, revealed an activity five times higher than sporadic on January 3, between 20 and 24 UT, with a maximum of 235 event $\mathrm{h^{-1}}$, in good agreement with the observations of the 1997 and 1998 showers (Suzuki 2000).

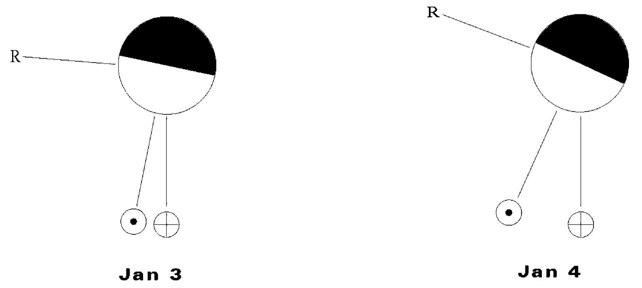

Figure 1. The Moon as seen from the north ecliptic pole at UT 0h on 1999 January 3 and 4. Shower maximum was during the latter night. The directions of the Sun, the Earth and the radiant are shown. The radiant lay about 70° above the plane of the ecliptic.

Table 1. Measurements of the lunar Na atmosphere during the Quadrantids.

Date	UT	Side	Scaleheight km	Temperature K	Brightness kR
3 Jan	3:24	equator (w)	320 ± 49	1454 ± 223	0.83 ± 0.21
	4:08	north	287 ± 41	1305 ± 187	0.86 ± 0.20
	5:06	north-west	272 ± 36	1238 ± 161	0.71 ± 0.17
4 Jan	0:36	equator (w)	300 ± 40	1365 ± 185	0.76 ± 0.18
	1:36	north	284 ± 38	1289 ± 171	0.70 ± 0.18
	2:55	north-west	305 ± 40	1388 ± 179	0.81 ± 0.19
	3:46	equator (e)	–	–	0.90 ± 0.21
	4:34	south	345 ± 54	1572 ± 249	1.02 ± 0.24
	5:36	south-east	301 ± 42	1368 ± 193	0.79 ± 0.21

The quoted errors are rms. They are larger than the intrinsic scatter between the measurements due to systematic errors in the telescope tracking of the Moon during the 500-s exposures. The calculated temperature is defined as mgH/k, where H is the real scaleheight, g is the Moon's acceleration of gravity ($1.62\ \mathrm{m\,s^{-2}}$), m is the mass of the sodium atom (3.82×10^{-23} g), and k is Boltzmann's constant. The tabulated brightnesses refer to the D2 line, and they are extrapolated to the lunar surface. Observation of the east limb on January 4 yielded no measurements of temperature and scaleheight. The lunar phase angles on the first and second nights were 14° and 26° respectively; the illuminated fractions of the Moon's disc were 0.98 and 0.95; and the local solar zenith angles were 83° and 65°. 1 Rayleigh (R) = $10^6/4\pi$ photons $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$.

In addition, the MLT Dynamics Group of the University of Wales (Howells & Middleton, private communication) used the radar station at Aberystwyth, detecting a maximum on January 4, with activity two to three times higher than the preceding and following nights. These observations suggest that the 1999 Quadrantids were at least as active as in previous years.

3 DISCUSSION

The data were interpreted using Chamberlain's model of the exosphere (Chamberlain & Hunten 1987), correcting the barometric density with an appropriately adjusted partition function for the escaping and ballistic components (cf. Sprague et al. 1992). The results of the observations are shown in Table 1. There are no significant differences between the measurements made on January 3 and 4, and none between measurements made in directions towards the radiant and in other directions. The lack of any observed difference between the first and second nights could also indicate that there were no significant changes arising from the Moon's exit from the magnetotail, if indeed that took place. While the differences between sputtering by magnetospheric and solar

Table 2. Previous measurements of Na emission from the lunar atmosphere. In the upper part are listed the results of the observations carried out during near full Moon phase. In the bottom part are listed the results of the observations taken near the polar zone (i.e. with local solar zenith angle similar to that one of our observations) during any phase angle. A mean of the results reported in this paper for the night of the Quadrantid maximum is shown in the last row as comparison.

Date	Ill. Frac. per cent	*LSZA* deg	Distance from surface (km)	Brightness kR	Temperature K	Reference
21 Feb 1989 [1]	0.99	90	50	1.25		Potter & Morgan 1991
22 Feb 1989 [1]	0.98	83	10–70	1.18		Potter & Morgan 1994
02 Dec 1990 [1]	0.99	87	10–70	0.90		Potter & Morgan 1994
04 Dec 1990 [1]	0.96	71	10–70	1.17		Potter & Morgan 1994
22 Sep 1991 [1]	0.96	71	10–70	0.17		Potter & Morgan 1994
23 Sep 1991 [1]	0.99	87	10–70	0.27		Potter & Morgan 1994
24 Sep 1991 [1]	0.99	87	10–70	0.78		Potter & Morgan 1994
20 Nov 1991 [1]	0.95	65	10–70	0.43		Potter & Morgan 1994
29 Nov 1993 [2]	1.00	90	2–12 R_{M}	0.90[a]		Mendillo & Baumgardner 1995
06 Nov 1995 [1]	1.00	90	50–180	1.38[a,b]	1538	Cremonese & Verani 1997
03 Apr 1996 [2]	1.00	90	2–12 R_{M}	0.82[a]		Mendillo et al. 1999
27 Sep 1996 [2]	1.00	90	2–12 R_{M}	1.15[a]		Mendillo et al. 1999
24 Mar 1997 [2]	1.00	90	2–12 R_{M}	1.80[a]		Mendillo et al. 1999
13 Oct 1990 [1]	0.26	81	10–170	1.40[a]	1764	Sprague et al. 1992
14 Oct 1990 [1]	0.17	83	10–170	2.20[a]	1421	Sprague et al. 1992
20 Nov 1991 [1]	0.95	90	10–70	0.30		Potter & Morgan 1994
21 Nov 1991 [1]	0.99	90	10–70	0.15		Potter & Morgan 1994
04 Dec 1990 [1]	0.96	90	10–70	0.76		Potter & Morgan 1994
05 Dec 1990 [1]	0.90	90	10–70	0.68		Potter & Morgan 1994
18 Sep 1995 [1]	0.35	88	0–1800	6.13[a]	1332	Sprague et al. 1998
19 Sep 1995 [1]	0.27	88	0–1800	1.06[a]	1451	Sprague et al. 1998
04 Jan 2000 [1]	0.95	65	50–600	0.83[a]	1396	This paper

[1] high-resolution spectroscopy; [2] wide-angle imaging; [a] value extrapolated at the surface; [b] reanalysis of the data; R_{M} (radius of the Moon) = 1736 km.

wind particles are still not fully understood, our observations are consistent with the dominant source mechanism being sputtering by solar radiation, which will be isotropic around the limb at full Moon (Mendillo & Baumgartner 1995; Mendillo, Baumgartner & Wilson 1999).

In Table 2 we compare measurements of the lunar Na atmosphere made by other authors, at full Moon phase or at similar local solar zenith angle, with those reported here during the Quadrantids. The brightness and temperature we measured during the Quadrantids are in good agreement with most of the measurements made when there was no meteor shower, i.e. the 1999 Quadrantids had no detectable effect on the lunar Na atmosphere.

These results may indicate that meteor impacts could have a significant influence on the Moon's atmosphere only under particular conditions, so that the detected difference in the effects of the two streams may be due to physical differences between the two streams. In fact, the production of gas after an impact depends on various factors, including the velocity, mass and composition of the impactors. The two streams differ in many parameters (cf. Table 3), the impact velocity being one of the greatest: the mean impact velocity of the Leonids (orbiting the Sun in the opposite direction to the Earth and Moon) is 70.7 km s^{-1}, much higher than that of the Quadrantids (41.0 km s^{-1}).

O'Keefe & Ahrens (1977) have found that the amount of gas generated by an impact is proportional to the factor $S = (\rho_{\mathrm{m}}/\rho_{\mathrm{t}})(v/c_p)^2$, where v is the impact velocity, ρ_{m} and ρ_{t} are respectively the density of the projectile and of the target, and $\mathrm{c_p}$ is the bulk sound velocity in the target. Starting from this model, Morgan, Zook & Potter (1988) calculated the amount of gas produced by impacts having impactor–target density ratios of 1 and a sound speed in the target of 7.44 km^{-1} (estimated for Mercury's regolith components). They found that a negligible amount of gas is produced at velocities below 23 km s^{-1} (less than the mass of the projectile); at progressive velocities this amount increases, becoming proportional to v^2, i.e. to the kinetic energy, for velocities higher than 44 km s^{-1} (cf. fig. 6 therein). In our case (cometary grains into lunar regolith) the density ratio is ≤ 1 (0.7–3 versus 2.3–2.7 g cm^{-3}), so the threshold velocity should be higher than the ones previously reported (up to 45 km s^{-1}). Cintala (1992), in a model of high-velocity micrometeoroid impacts in the regolith, also found that vapour production increases with impact velocity. This model suggests that a difference of a factor of 2 for the impact velocity yields a factor of almost 3 in the amount of material melted, and a factor of more than 4 in the amount of target material vaporized.

The effects of high-velocity impacts have also been investigated in the laboratory (Eichhorn 1978), using a variety of materials for the targets and for the impactors. The impact velocities ranged from 3 to 15 km s^{-1}, and the masses from 10^{-14} to 10^{-9} g with a size of few microns; both ranges are unfortunately lower than the typical ones for the Leonids and Quadrantids. This experiment shows that the temperature of the generated gas increases with the impact velocity (this could explain the enhancement of the temperature of the Na atmosphere during the Leonids). These results seem to confirm also the theoretical prediction of a low vapour production for such impact velocities, as the mass of gas produced is less than twice the mass of the impactor body. On the other hand, Schultz (1996) found that the vaporization increases with the square (or even higher power) of the velocity, even for velocities of 3–10 km s^{-1}, inconsistent with the hypothesis of a 'threshold' velocity. The mean kinetic energies delivered per unit

Table 3. Parameters at the Earth of five of the major meteor streams and of sporadic meteors (Cook 1973; Hughes & McBride 1989; Love & Brownlee 1993).

	Impact velocity [a] $\mathrm{km\,s^{-1}}$	Total mass 10^{12} kg	Mass flux $10^{-17}\,\mathrm{g\,cm^{-2}\,s^{-1}}$	$\mathrm{ZHR_{max}}$ $\#\,\mathrm{h^{-1}}$	Active period (1998) d
Quadrantids	41.0	1.3	3.3	130	4
Geminids	34.4	16	2.4	90	10
Perseids	59.4	31	0.28	85	36
Orionids	66.4	3.3	0.18	25	38
Leonids	70.7	6.7	0.3[b]	20[b]	7
Sporadic	16.9		6.3[1] 10.0[2] 15.0[3]		

[a] average impact velocity on Earth; [b] the value increased up to 3 times in 1995 and to 5 times in 1997 (Brown 1999).
[1] sum over the mass range 10^{-12} to 10^{0} g (Gault, Hörz & Hartung 1972); [2] sum over the mass range 10^{-18} to 10^{-2} g (Grün et al. 1985); [3] sum over the mass range 10^{-9} to 10^{-4} g (Vanzani, Marzari & Dotto 1997).

area and time by the Leonids (after 1994) and Quadrantids are of the same order of magnitude, so the different impact velocities of the two streams may be responsible for the observed differences only if the threshold velocity is real.

Different chemical compositions of the streams may affect the composition, e.g. the Na abundance, of the gas produced. Spectroscopic measurements of the airglow were made during the Leonid shower (Nagasawa 1978; Chu et al. 2000), suggesting a higher content of Na in Leonids with respect other meteoroids. Moreover, Borovicka, Stork & Bocek (1999) found in their spectroscopic observations of the Leonid meteors that smaller meteoroids tend to be poorer in Na than larger ones, and a similar behaviour was found for the Perseids. Šimek (1987) investigated the mass distribution of five meteor streams (Geminids, Quadrantids, Perseids, Leonids, and Giacobinids) and of the sporadics observed with the radar. In his results he found an absence of larger particles in the Quadrantids (and also in the sporadics). These results suggest that the Na content of the Quadrantids is lower than that of the Leonids. Finally, age could also play a role in depleting the content of volatiles in Quadrantid meteoroids. The Quadrantids are much older than the Leonids, being created 7500 (Babadzhanov & Obrubov 1992) or 500 yr ago (Jenniskens 1997). In addition, because the Quadrantids have a shorter orbital period (5.3 yr, versus 33 yr for the Leonids), they have passed close to the Sun more often, resulting in greater evaporation of volatile elements, such as Na, leaving the current meteoritic particles depleted in these elements.

4 CONCLUSIONS

No enhancement of the Na emission from the lunar atmosphere was detected during the Quadrantid meteor shower. This contrasts with the reported enhancements seen during at least three of the Leonid showers. As a possible explanation, we suggest the differences in the physical and chemical parameters of the two streams, as explained in detail in the previous section. To investigate this hypothesis, new measurements of hypervelocity impacts with a velocity range resembling that for the meteor showers and on a target more closely approximating the lunar regolith, or accurate modelling of such impacts, are required. Measurements of the chemical composition of the meteoroids are also required, as well as new observations of the lunar atmosphere during other major meteor streams. For these reasons we believe that is not possible at the moment to understand under which conditions the impact mechanism can generate a significant amount of gas in the lunar atmosphere.

ACKNOWLEDGMENTS

We are grateful to the referee, A. Fitzsimmons, for valuable comments and suggestions, and to J. Geiss and S. Håland for useful discussions. CB acknowledges support from ASI; MM acknowledges support from the NASA Planetary Astronomy Program. The WHT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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