HIGH RESOLUTION OBSERVATIONS OF THE SODIUM EMISSION FROM THE MOON

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ABSTRACT

High resolution spectroscopy of the Moon's atmosphere allows to analyze the closest layers to the lunar surface giving the possibility to get information on the source and the evolution of the atmospheric atoms and their distribution with respect to the latitude. The sodium emission, that is one of the main components of the atmosphere, is easier to study thanks to the good efficiency of the solar resonant scattering.

A long term program of observations of the Moon's sodium atmosphere has

been performed at the 182cm telescope of the Astronomical Observatory of Padova, using an echelle spectrograph, allowing to get spectra in different periods of the year and lunar phases and at different latitudes. The slit was placed parallel to the lunar equator, with a spatial coverage of 150 km few tens of km above the surface, at the east and west sides (bright and dark limbs) and perpendicular to the equator at the north and south sides. In this way it has been studied the behaviour of the column densities, the scale heights and temperatures with respect to the latitude and the lunar phase. We report also one spectrum obtained during the total eclipse of April 1996. Moreover it has been possible to get spectra using the WHT-IAC Canarian telescope with a very high resolution spectrograph and a larger spatial coverage in order to discriminate better the thermal and suprathermal components assumed to characterize the sodium distribution in the atmosphere.

INTRODUCTION

The high resolution spectroscopy is an important method to study the planetary atmospheres if we are looking at the emission lines with the necessary intensity above the continuum to reach a good signal to noise ratio. However we have very often to search for a compromise between the signal to noise ratio and the spectral resolution we need to analyze the velocity distribution of the atoms or molecules involved and to discriminate the different contri-

butions to the same wavelength. At the same time we clash with several difficulties to reduce the data, above all for a tenuous atmosphere as for the Moon, as it will be discussed in the next section.

With an high resolution spectrograph we can put the slit very close to the lunar surface, if we adopt a good algorithm to subtract the strong contribution coming from the diffuse light due to the surface, instead of an imaging system that is more sensitive to the diffuse light problem. Therefore in the first case we can start to collect data at a tangent altitude of few kilometers from the surface while in the second one the minimum tangent altitude reached has been 1430 km by Mendillo et al. (1991). These two approaches allow for different study of the atmosphere looking from different view points.

In the present work we report the high resolution spectra obtained with two different telescopes at full Moon and around the last quarter. Then we were able to take one spectrum during the total lunar eclipse occurred the 4th of April 1996.

Even using the two component fit, we didn't find any evidence of the thermal component, both because the local solar zenith angles at observing dates were different from 0° , and because we observed too far from the lunar limb. Only in some cases we probably were very close to a boundary between the two components, if we compare our results with those reported by Sprague et al. (1992, hereafter S92). We used then a single term fit of the data to analyze only the suprathermal component. We find some evidence for the

competing release mechanisms suggested by S92, in fact the source fluxes could be consistent with the values reported in literature while the temperatures appear to point out another mechanism. In recent papers (Cintala, 1992; Smith and Marconi, 1995) we found that the meteoritic impact vaporization should provide a minor contribution to the source flux we calculated, but the temperature, obtained from the spectrum of the 13th of November 1995, indicates just this mechanism. It is interesting to note that this data has been collected with a geometric configuration very similar to some reported by S92: around the last quarter, same slit position, similar spatial coverage and small difference in the local solar zenith angle. However the atmospheric parameters obtained are different as it will be discussed in the next sections. Moreover, during the night of the 7th of November 1995 we collected one spectrum for each cardinal point on the Moon and we found an anomalous high value at the east position that could suggest a meteor stream on the Moon, as it has been discussed by Hunten et al. (1991). We didn't find a value as high as that reported from these authors, but it is difficult to explain such an event considering other mechanisms. We think that this paper leaves still open questions such as the meteoritic impact vaporization because there are not enough data, since the sodium has been discovered on the Moon's atmosphere, to define how rare is a meteor shower and to find a periodicity correlated to the zodiacal cloud and to the dust released from the comets. This work doesn't want to emphasize such a mechanism but to

bring to the attention a behaviour not so common occurred at present and in the past without receiving an exhaustive answer.

OBSERVATIONS

Most of the observations discussed in the present paper have been acquired using a Reosc echelle spectrograph mounted at the Cassegrain focus of the 1.82m F/9 telescope of the Astronomical Observatory of Padova, at Cima Ekar Asiago. Then it was possible to get two spectra with the 4.2m William Herschel Telescope (WHT), at La Palma (Canary Islands), using the Utrecht Echelle Spectrograph at the F/10.94 Nasmyth focus. The descriptions of the two equipments are summarized in table 1.

The data reduction was based on procedures written in IDL and extensively described in the previous papers (Cremonese, et al., 1992, Contarini, et al., 1996). We have to underline that the spectra have been reduced using the same method, ensuring the homogeneity necessary to a confident long term analysis. During the reduction phase great care has been paid to perform the background subtraction as it represented the most critical point due to the scattered light coming from the Moon's surface, the Earth's atmosphere and the spectrograph itself. Some of the data shown here have been obtained with a less than optimal sky and with correspondingly larger errors. Another point we had to pay attention was the determination of the distances from

the surface used for the calculations. We took into account three main contributions: the motion of the Moon on the slit (guiding problems), how far was the slit from the lunar surface and the seeing conditions. We solved the first problem, for most of the nights, modifying the tracking of the telescope along the right ascension, in this way we fixed the Moon on one direction guiding only in declination, and consequently we were confident to get a good estimate of the slit positioning with respect to the surface. The last contribution was due to the seeing conditions during the observing runs, that at the Asiago telescope was quite poor and it increased the errors on the determination of the distances from the lunar surface. The night in La Palma have had a seeing much better and we assumed that the error was lower than the uncertainty on the slit positioning with respect to the lunar surface. This consideration reflected on the rebinning along the spatial direction of the spectra and then on the scale heights obtained. The errors reported for the distances and the scale heights take into account these contributions.

DISCUSSION

The main goals of the spectra analysis are to infer the scale height, the temperature and the number density for each one. Unfortunately it was not possible to get the parameters for all the data because of the background subtraction troubles that turned out in few very noisy spectra due to the

Table 1: Instrument configuration used for the observations

	Asiago	La Palma
Telescope diameter	1.8 m	4.2 m
CCD	1100×1100 pixel ²	2220×1280 pixel ²
pixel size	19 μm	22.5 μm
filter transmission band (FWHM)	–	12 $\text{\AA}$
echelle dispersion	0.19 $\text{\AA pixel}^{-1}$	0.053 $\text{\AA pxl}^{-1}$
slit width	150 μm	250 μm
slit length	6 mm	46 mm
angular scale on focal plane	12.56 arcsec mm ⁻¹	4.43 arcsec mm ⁻¹
angular scale on detector plane	29.47 arcsec mm ⁻¹	0.33 arcsec pxl ⁻¹

poor sky and seeing conditions. It occurred to the three spectra obtained the 10th of August 1995 that allowed for only an estimate of the emission rate with an error on the absolute calibration of 0.9 kR. We still decided to report this estimate just to make a rough comparison with other results, as it referred to the same lunar phase, the full Moon. Table 2 reports the dates and the selenographic coordinates of the slit for each spectrum.

The absolute calibration has been performed by using the center of Jupiter’s disk, assumed to have a surface brightness of $5.5 \text{ MR}\text{\AA}^{-1}$ (Brown and Schneider, 1981), for the spectra obtained in July 1993, while we used standard stars (αLyr , Hiltner 600, θVir , respectively) for the rest of the data. To perform the absolute calibration of the spectrum obtained during the lunar

Table 2: Observation parameters

Date	UT hr min	Selenographic latitude	Selenographic Longitude	Exposure time
8 July 1993	00 02	+2°	−83°	600
8 July 1993	00 55	+2°	−83°	600
8 July 1993	01 44	+2°	−83°	600
10 August 1995	21 52	+14°	−84°	600
10 August 1995	22 09	−8°	+96°	900
10 August 1995	23 32	+76°	+96°	600
6 November 1995	22 10	+2°	−86°	600
6 November 1995	22 33	−2°	+94°	600
7 November 1995	00 41	+88°	−94°	600
7 November 1995	00 58	−88°	+86°	600
13 November 1995	04 41	+2°	−84°	500
13 November 1995	04 53	+2°	−84°	500
4 April 1996	00 10	+1°	+95°	600

total eclipse was difficult because we could not use the *g-factor* adopted for the previous data; there was not the usual photon flux on the lunar surface. We compared two spectra obtained, before and during the eclipse, with the slit on the *Mare Crisium*. In this way we maintained very similar albedo conditions and it was possible to apply the ratio between the intensities to the *g-factors*. Then the bidimensional spectra have been rebinned along the spatial direction over the whole range, according to the level of the noise and looking for the best compromise between the number of points and the signal to noise ratio. In so doing the number of bins adopted is not equal for all the

spectra: each bin corresponds to 11 km for the data obtained in July 1993 and April 1996, 16 km for the 7th of November and 9.6 km for the 13th of November.

The following step was the selection between the one or two component models. At the beginning we tried to apply the two component fit to each spectrum, but it was not possible to fit the data. A major effort was spent for the spectra obtained with the WHT telescope for two main reasons: they had small errors thanks to the very good quality of the data and the lowest tangent altitude (140 km) could stay on the boundary between the thermal and suprathermal regions. S92 reported a limit of 150 km for the maximum thermal component extension at a local solar zenith angle of 0° . The WHT spectra have been taken at a local solar zenith angle of 19° . After several attempts to apply the two components fit we didn't find a meaningful result, therefore a single term model was applied also to these data finding a much higher temperature.

Table 3 shows a comparison between our spectrum obtained the 13th of November 1995, and that reported by S92 taken the 13th of October 1990.

We wanted to make this comparison because they have a small difference of 10° , as solar zenith angle, and they could give similar results. The spatial coverage of our spectrum includes also the last part of the S92 one. Furthermore they have been obtained around the last quarter.

After having considered the geometric conditions we found that the temper-

Table 3: Comparison between our spectrum and one spectrum taken by Sprague et al. (1992)

Date	Local solar zenith angle (degrees)	Tangent Height (geop.) (km)	Chamberlain Temperature (K)	Number density (cm ⁻³)
13 Oct. 1990	29	0-170	1924 $\pm$ 250	20
13 Nov. 1995	19	140-490	2804 $\pm$ 236	36

atures and above all the number densities were very different. If we take into account the photodesorption as the already dominant mechanism, as suggested by S92 at these solar zenith angles, we can have an high temperature, but looking at the comparison it is still not enough. To explain this marked difference we could consider two main hypothesis, the first one taking into account a major contribution by the meteoritic impacts and the second one assumes the suprathermal component, due to the photodesorption and the solar wind sputtering, becoming more energetic with the solar zenith angle decreasing. Such an high temperature could be due to one of the solution suggested or both at the same time. Of course we cannot give a precise answer with only two spectra.

Table 4 reports the slit position parameters for each spectrum considered on this work. The spectra obtained the 10th of August and the 7th of November, during the full Moon, showed an emission rate much higher than that

reported by Potter and Morgan (1995) for all the cardinal points. Our data appear to claim that the solar wind sputtering doesn't play a major role or the plasma sheet, that occupied the central part of the Earth magnetotail, was characterized by higher energy particles. Such an event should have occurred on both the periods considered. These results agree with Potter and Morgan (1991). That means we have to take into account other mechanisms as the photodesorption and the meteoritic impacts, ruling out the thermal desorption for the high temperature involved. An additional point to the discussion is represented from the spectrum taken on the east side, the 7th of November, that shows an emission rate higher than the other measurements made during the same night at different positions. We think that the most likely explanation of such an increase is an asymmetric sodium source as a meteor shower suggested by Hunten et al. (1991) or the meteoritic flux hitting the lunar surface with a little anisotropy. However the photodesorption process should be still important and we suggest a competing release mechanism.

The last spectrum we obtained was during the lunar total eclipse, the 4th of April, with poor sky conditions, but it was still possible to get a standard star to perform a quite good absolute calibration. The main problem was represented by the very low signal to noise ratio because of the very low number density of the sodium atoms. It is the first time that the result of a spectrum taken during a lunar total eclipse is published and only in this

case we should rule out the solar wind sputtering and the photodesorption as main mechanisms. The meteoritic impacts should be the main source of the very high temperature and the very low number density we obtained.

Table 4: Parameters on the slit position

Date	Emission rate (R)	Lunar phase	Distance from the surface (km)	Local solar zenith angle
8 July 1993	3310	0.84	50-130	46°
8 July 1993	3320	0.84	50-130	46°
8 July 1993	3500	0.84	50-130	46°
10 August 1995	3000	0.99	0-166	89°
10 August 1995	3000	0.99	0-166	90°
10 August 1995	3000	0.99	0-166	90°
6 November 1995	2580	1.00	50-178	90°
6 November 1995	2066	1.00	50-178	86°
7 November 1995	2239	1.00	50-178	89°
7 November 1995	2190	1.00	50-178	90°
13 November 1995	3312	0.73	143-480	19°
13 November 1995	3259	0.73	143-480	19°
4 April 1995	8	1.00	13-169	90°

CONCLUSIONS

The results reported in this work seem to increase the number of doubts on the answers given till now to the sodium observations of the Moon tenuous

Table 5: Atmospheric parameters calculated

Date	Cardinal point	Temperature	Scale height	Number density
8 July 1993	East	1004 ± 242	224 ± 54	58.4 ± 12.7
8 July 1993	East	1403 ± 273	313 ± 61	44.7 ± 6.9
8 July 1993	East	1117 ± 301	249 ± 67	57.4 ± 13.5
6 November 1995	East	1949 ± 434	428 ± 95	9.54 ± 0.67
6 November 1995	West	1465 ± 334	322 ± 73	8.95 ± 0.59
7 November 1995	North	1528 ± 329	336 ± 72	8.85 ± 0.47
7 November 1995	South	1323 ± 306	291 ± 67	8.74 ± 0.46
13 November 1995	East	2804 ± 236	626 ± 52	36.1 ± 2.3
13 November 1995	East	2703 ± 297	621 ± 65	32.3 ± 2.5
4 April 1996	West	4026 ± 1271	885 ± 279	3.5 ± 2.1

atmosphere. The spectra obtained during the full Moon showed an emission rate much higher than that suggested by Potter and Morgan (1995) and it means that the solar wind sputtering doesn't have always a major role, but we have to take into account other mechanisms. For sure we have to pay attention at the high energy particles that could hit the lunar surface also when the Moon should be shielded by the Earth; some authors report a quite high uncertainty on the solar wind interaction with the Moon during its full phase. If we assume that some solar particles could escape the terrestrial atmosphere hitting the Moon, it occurred both in August and November 1995 and in any case we don't believe they can explain the high emission rate measured. Furthermore the spectra obtained the 7th of November showed a

quite high temperature and a stronger emission in the east side. The difference between the measurements at east and the other cardinal points were much lower than that reported by Hunten et al. (1991) and it could mean not due to a meteor shower, but only to a low anisotropy of the micrometeoritic flux hitting the Moon. We think we should pay more attention at a possible periodicity and anisotropy of the meteoritic flux considering that is due to different sources not all completely analyzed as it has been recently reported by Taylor et al. (1996). All these considerations point out a major role of the micrometeoritic impacts and we cannot rule out the photodesorption, so we infer a competing release mechanism.

The results turned out the 13th of November showed a much higher temperature than the values suggested for the solar wind and the photodesorption mechanisms and also in this case we have to take into account the micrometeoritic impacts and therefore a competing release mechanism.

The final consideration is devoted to the spectrum obtained during the total eclipse the night between the 3rd and the 4th of April. The uncertainties due to the absolute calibration and the not so good sky conditions are high, but the emission rate we measured is very low also if we take into account a factor 10 or higher as an error bar. It means that the photodesorption and the solar wind sputtering mechanisms were not important if we assume the Moon completely shielded from the Earth, while the micrometeoritic impacts could be the only responsible of the so low emission. This last hypotheses can be

interpreted in conflict with the previous considerations, but we didn't have spectra for all the cardinal points, so we cannot say if there was an higher emission on one side, and it could confirm a periodicity on this mechanism.

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