20 YEARS OF OBSERVATIONS OF THE LUNAR SODIUM TAIL.

J. Baumgardner[1], C. Schmidt[1], L. Moore[1], M. Mendillo[1], M. Mayyasi[1], [1]Center for Space Physics, Boston University, Boston, MA, 02215 (jeffreyb@bu.edu)

Introduction: It has been 20 years since the discovery of a vast comet-like tail in the lunar sodium exosphere. Ground-based telescopes in the late 1980's first showed that the Moon has sodium in its thin exosphere [1] and that this gas could be readily observed out to a few lunar diameters [2]. In 1998, during an observational campaign to study the effects of the Leonid meteor shower on the terrestrial (mesospheric) sodium layer, a fortuitous discovery of a faint spot of sodium emission near the anti-Sun/Moon direction was made [3]. This spot feature was determined to be the result of sunlight scattered from sodium atoms liberated from the surface of the Moon two days earlier. Figure 1 shows an image from that discovery observation.

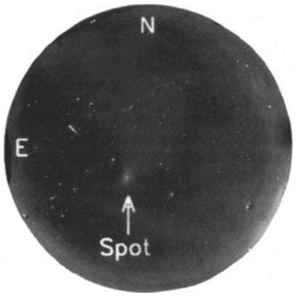

Figure 1. All-Sky image of the sodium spot from McDonald Observatory, two days after the peak of the Leonids, November 17, 1998.

The implication of this emission spot is that the exosphere is highly distorted, non-spherical in shape, and that neutral Na atoms had been accelerated by solar photon pressure to $>10^6$ km beyond the Moon. The fact that the Leonid shower in 1998 occurred 2 days before new moon meant that the anti-sunward streaming sodium atoms encountered Earth's gravity field. Bending of the trajectories of the Na atoms as they passed by the Earth resulted in the gravitational focusing of a diffuse cloud into a higher density region of significantly increased column content [4]. Fig. 2 shows a simulation of this process.

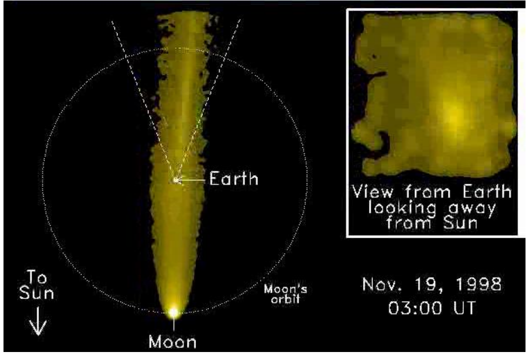

Figure 2. Model result demonstrating gravitational focusing of lunar Na by the Earth.

Boston University operates a network of all-sky imagers (ASIs) across the globe [5]. These imagers have 6 position filter wheels so that various spectral emissions from the Earth's mesosphere and thermosphere can be isolated using narrow band (~1.8 nm FWHP) filters. One such filter, centered at 589.3 nm, is used to observe wave activity in the mesospheric sodium layer. After the discovery of the gravitationally focused lunar sodium tail (hereafter referred to as the "Moon Spot"), a survey of the data archives showed that a patch (~3^o diameter) of enhanced sodium emission could be seen in almost every all-sky image within a few days of a new moon (if one knows where to look for it). This patch of emission has a typical peak brightness of ~20–30 Rayleighs (R) for the combined (D1+D2) sodium lines. Interestingly, it varies with time and location (e.g., the ecliptic latitude and lunar phase angle).

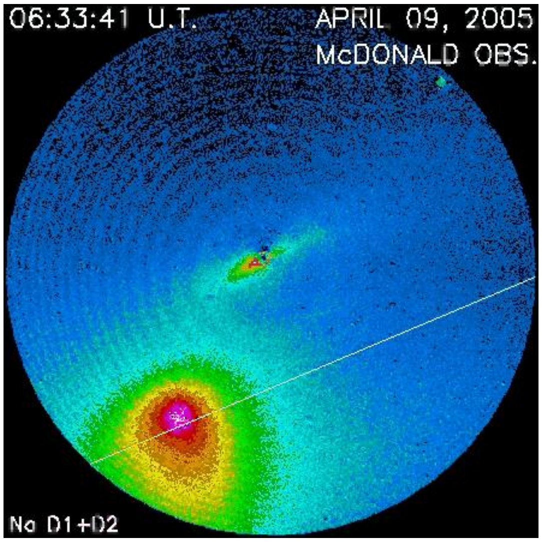

Figure 3. ~7.5° FOV image of the Moon Spot taken with a 10cm coronagraph (Jupiter is behind the central mask). The white line is the ecliptic. The sodium nebula surrounding Jupiter can also be seen (the concentric rings are an artifact due to transmission fringes in the narrowband interference filter).

Once apparitions and locations of the Moon Spot were established in a predictable way during each lunation, its spatial structure then could be resolved using narrower field instruments [6], as in Fig. 3. Additionally, Fabry-Perot instruments became a valuable new tool, since the technique could simultaneously resolve the spatial distribution and Doppler structure [7, 8]. These studies showed that the velocities in the spot are broadly and asymmetrically distributed about 12 km/s. Such velocity information offered an important new constraint for the numerical modelling. Doppler shifting relative to the deep Fraunhofer absorption lines in the solar spectrum controls the brightness of the backscattered emission. Gas velocities are hence needed to correctly interpret the column integrated brightness data. Doppler shift and absolute brightness information together enables recovery of an accurate column density, and in turn the atmospheric escape rate.

The brightness of the lunar spot has not been clearly correlated to drivers in the different sources that maintain the lunar exosphere. After correcting for geometric effects, a focused study of 2006-2008 data from the El Leoncito, Argentina ASI site, suggested minimal long term brightness variability that was generally uncorrelated with any single source (e.g., solar protons, solar UV flux, meteoritic rates), yet consistent with a multiyear period of minimal solar activity and known meteoritic fluxes [9]. A longer term study [10], used 20 observations of the Moon Spot over a 16 year time span and arrived at the same conclusion.

Analysis of more comprehensive datasets may still be able to tie atmospheric escape rates to the various drivers thought to sustain the lunar exosphere. Since our initial study, which used 3 years of data from one ASI site, 12 more years of data have been taken, and more ASIs have been added to the network. The Moon Spot can be seen from multiple sites simultaneously, allowing stereographic studies to be done (Figure 4). Moreover, with ASI sites widely spaced in longitude, continuous, 24 hour observations are now possible.

Here we report initial findings from this extended set of observations. In particular, it is clearly evident that the Moon Spot shows spatial morphology on timescales of hours. We attribute such changes to viewing parallax whereby the changing topocentric location is an important factor governing the effective line-of-sight column down the tail. Such effects are evident both from a single ASI site over the course of a night, and from the simultaneous viewing at two or more ASI sites with different latitudes, per Figure 4.

UVS results from the LADEE mission have now demonstrated that micro-meteors can significantly augment the exosphere's alkali abundance [11]. Therefore, some dependence in the atmospheric escape rates and tail spot brightness is expected as the Earth passes though seasonal and sporadic meteor showers. The sizable ASI data archive extends the characterization of meteoritic and other drivers over a long time scale relative to the LADEE mission, and previously unidentified geometric effects can be now be considered taken into account in analysis.

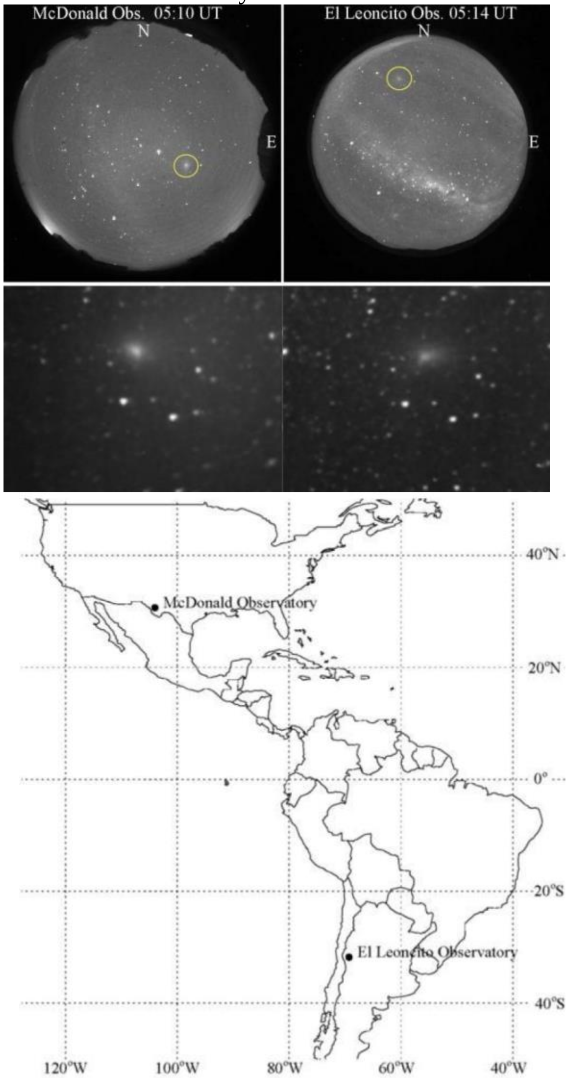

Figure 4. Sample all-sky images showing lunar sodium spots, with each zoomed-in below. Viewed with a 7000 km baseline, the shape of the spot is measurably different via parallax.

References: [1] Potter, A.E. and T. H. Morgan (1988), Science, 241, 675-680. [2] Mendillo, M., et al. (1991), GRL, 18, 2097-2100. [3] Smith, S. M., et al., (1999), GRL, 26, 1649-1652. [4] Wilson, J.K., et al. (1999), GRL, 26, 1645-1648. [5] Martinis, C., et al. (2018) Adv. Space Res., 61, 1635-1651. [6] Baumgardner, J., and Mendillo, M., (2009), Earth Moon and Planets, 105, 107-113. [7] Mierkiewicz, et al. (2006), GRL, 33. [8] Line, M.R. et al. (2012), Icarus, 219, 609-617. [9] Mayyasi, M. et al. (2009) Icarus. 204. 409-417. [10] Nishino, M.N. et al. (2016) Icarus, 280, 199-204. [11] Szalay et al. (2016) GRL 43, 6096-6102.