
Introduction: In order to observe the lunar sodium exosphere out to one-half degree around the Moon, we designed, built and installed a small robotically controlled coronagraph at the Winer Observatory in Sonora, Arizona. Details of the instrument and data reduction procedure are given in Killen et al.[1] but a brief description is given here. A lunar coronagraph was custom-designed by Claude Plymate and Roy Tucker and attached to a 101 mm refracting telescope which is operated remotely using TheSkyX™ Professional software from Software Bisque. The coronagraph is designed to carry 7 different possible occulting disks, including an open disk, designed to match the varying angular size of the Moon as seen from Earth. A 1.5 Å bandpass filter centered at 588.995 Å measures the sodium D2 line and a 1.5 Å bandpass offband filter centered 3 Å blueward of the onband filter measures the continuum. Autoguiding with TheSkyX™ autoguiding software is performed by centering the guide camera on a bright crater and locking on the image of the bright spot. Our observations were obtained from approximately 143 km off the lunar surface to about one lunar radius above the surface, 1738 km.

Results and Discussion: We report herein on observations taken during fall and spring, 2018, and spring, 2019. The observatory closes every summer due to monsoon season in Arizona. The data were reduced following procedures given in [1]. We observed on 44 nights in 2018, 33 of which were successful, and 11 nights in 2019, 8 of which were successful. Line of sight intensity (kR) at the surface as a function of latitude on the dayside is shown in Figure 1 for waning phases and Figure 2 for waxing phases. Waxing phases are those when the Moon is moving from New Moon to Full Moon, and waning from Full Moon to New Moon. A different pattern of Mare and Highlands is at the limb for each of these observations but we do not see any correlation with surface brightness due to local continuum subtraction. Our observations are shown as solid lines. A cosine latitude function, normalized to the equatorial intensity at that date, is shown as asterisks with the same color as the corresponding date of observation. This shows that the data are not strictly symmetric about the equator nor do they follow a $\cos^2 \theta$ as expected from theory (e.g.[2]) or a $\cos^3 \theta$ functional form as found by Potter and Morgan [3]. The highly N/S asymmetric sodium profile seen at many lunar phases is consistent with observations published by Potter and Morgan [4] where they report a D2 emission intensity at an altitude of 50 km of ~0.45 kR at the west limb, 1.0 kR at the north limb, 2.0 kR at the south limb and 1.5 kR at the east limb, on Feb. 21, 1989. We often see N/S asymmetries of a factor of ~2, consistent with [4]. When reduced to surface number density or column abundance the values are consistent with previous work. Because we cannot observe sodium within ~15° of full moon due to the increased light scatter off the limb, those results are not shown.

The largest column abundance was obtained on March 3, 2018, when the Moon entered the Earth’s magnetosheath and the ion fluxes measured by ARTEMIS suddenly increased. This is PA 14° at 7 AM on Figure 1, labeled CME.

![Figure 1. Dayside column abundances of lunar sodium D2 at the limb observed in 2018 are shown for waning phases. The local times at the limb are shown. The observations are shown as solid lines while the asterisks are a cosine function normalized to the observation at the equator.](image1)

![Figure 2. Dayside column abundances of lunar sodium at the limb are (solid lines) for waxing phases for 2018 data (from Full Moon to New](image2)
Mos of our measured scale heights are on the order of 800-1800 km, increasing at high latitudes. This is consistent with the data set published in [1]. Although the intensity extrapolated to the surface decreases with latitude, the scale height increases with latitude, so that the exospheric column is much more flat with latitude than a cosine function. Mendillo et al. [5] reported scale heights for the extended Na exosphere that agree with ours, particularly for waxing phases: a sodium scale height of approximately 1000 km (T=4500 K) near the equator increasing to >2000 km (T=9000 K) at the poles. We measure scale heights varying from roughly 800 to 1800 km (3600 K < T < 8100 K), consistent with [6], with larger scale heights for smaller phase angles. This means that the scale height increases as the Moon approaches Full Moon and decreases to-ward New Moon. Note that the observations are at the limb.

Conclusions: We present limb profiles from the south pole to the north pole for many lunar phases. Because we observe over the illuminated limb, the local time at the limb is a function of the lunar phase angle. Waning phase angles less than 90° are taken over the morning, whereas waxing phases greater than 90° are taken over the afternoon limb. The time of day flips for the waxing phases (from New Moon to Full Moon). Waxing phases greater than 90° show the morning limb, while waxing phases less than 90° show the after noon limb. Data taken during the 2018-2019 time frame indicate that lunar sodium column abundances vary from approximately 3x10⁸ cm⁻² to 10⁹ cm⁻². Although dayside column abundances measured for waning phases are greatest near dawn and decrease throughout the day, the opposite is true for waxing phases. Our waxing phases peak in the afternoon, but do not have a strictly monotonic variation with local time. The three observations with the largest column abundances are associated with either high speed streams or a CME. Szalay and Horanyi [7] found, based on LADEE LDEX data, that the in- impacts peak at dawn and decline with increasing time of day. Our data indicate that something associated with lunar phase is more important than local time dependence in maintaining the lunar sodium exosphere. According to Pokorny et al. [8] the anti-apex source of meteoroids, consistent with an afternoon enhancement, experiences the largest monthly variation of any meteoritic source. This is consistent with a less mono tonic variation in column abundance vs. time of day for wax ing phases. For the March 3 event the Moon is going from the magnetotail into the magnetosheath, and the ion fluxes as seen in ARTEMIS data [9] abruptly increase, along with the lunar sodium exospheric densities (PA 14 in Figure 1). The observation on Feb. 1, 2018, at PA 7° is anomalous, but uncertain ties may be 50% near full Moon [1].