

CORONAGRAPHIC OBSERVATIONS OF THE LUNAR SODIUM EXOSPHERE. A. E. Potter¹, R. M. Killen², and T. H. Morgan², ¹National Solar Observatory, emeritus (1035 Scott Dr., Prescott, AZ 86301), ²NASA Goddard Space Flight Center, Greenbelt, MD 20771 (rosemary.killen@nasa.gov).

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 Sonoita, Arizona. Observations are obtained remotely every available clear night from Goddard Space Flight Center, Greenbelt, MD, or from Prescott, Arizona. We employ an Andover temperature-controlled 1.5 Å wide narrow-band filter centered on the sodium D₂ line, and a similar 1.5 Å filter centered blueward of the D₂ line by 3 Å. Our data encompass lunations in 2015, 2016, and 2017, thus we have a long baseline of sodium exospheric calibrated images. During the course of three years we have refined the observational sequence in many respects. Herein we present the results of the spring, 2017, observing season. We present limb profiles from the south pole to the north pole for many lunar phases. Our data do not fit any power of cosine model as a function of lunar phase or with latitude. The extended Na exosphere has a characteristic temperature of about 2250 - 6750 K, indicative of a partially escaping exosphere. The hot escaping component may be indicative of a mixture of impact vaporization and a sputtered component.

Lunar Coronagraph Description: 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. The telescope and autoguider are operated using TheSkyX™ Professional software from Software Bisque™. Remote observations are performed using two different MaximDL™ software packages separately for the science camera and guide camera. 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: 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 observed 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. 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 as expected from theory (e.g. [1]) or a \cos^3 functional form as found by Potter and Morgan [2]. The highly N/S asymmetric sodium profile seen at lunar phase 91 is consistent with observations published by Potter and Morgan [3] 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 [3]. When reduced to surface number density or column abundance the values are consistent with previous work. Because we cannot observe sodium within 25° of full moon due to the increased light scatter off the limb, those results are not shown.

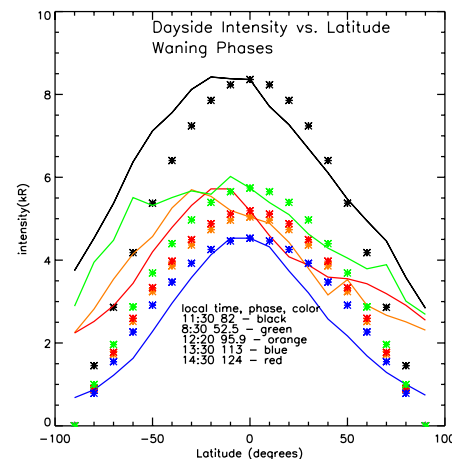


Figure 1. Intensity extrapolated to the surface of lunar sodium D₂ at the limb is shown for waning phases, from New Moon to Full Moon. The limb observations represent local time as shown. The observations are shown as solid lines while the asterisks are a cosine function normalized to the observation at the equator.

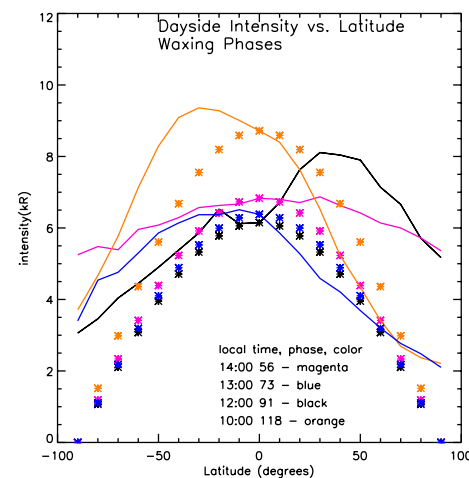


Figure 2. Intensity extrapolated to the surface of lunar sodium D₂ at the limb is shown for waxing phases, from Full Moon to New Moon. The intensity is greatest in the morning but is not linear in time. The exosphere is not symmetric north/south, consistent with [3].

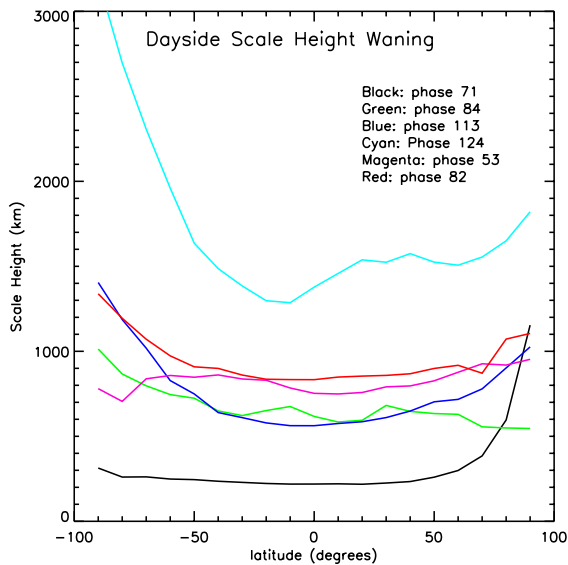


Figure 3. Scale height versus latitude for waning phases. The high phase angle data (phase 124, cyan) are probably unreliable.

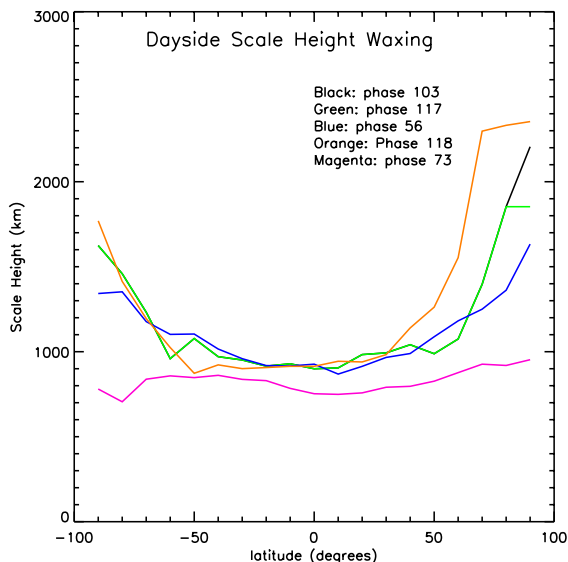


Figure 4. Scale height versus latitude for waxing phases.

Most of our measured scale heights are on the order of 500 - 1500 km, increasing at high latitudes. Although the intensity extrapolated to the surface as shown in Figures 1 and 2 decreases with latitude, the scale height increases with latitude, as shown in Figures 3 and 4, so that the exospheric column is much more flat with latitude than a cosine function. Mendillo et al. [4] 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. Stern and Flynn [5] also reported exospheric temperatures increasing with latitude, consistent with our observations. Their derived temperature was > 3000 K for 80° latitude and a mixture

of 1200 K and ~ 2500 K for low latitudes above the very low altitudes where cold Na at about 140 K was observed. Scale heights reported by Potter and Morgan [5] are somewhat smaller, 320 - 388 km for comparable phase angles. Potter and Morgan [6] reported scale heights from 44 km ($T=191$ K) at 70° N to 510 km (1736 K) at the equator measured at lunar phase 51° . Observations of the lunar sodium exosphere by Potter and Morgan [2] at a lunar phase angle of 51° were reported to decrease as \cos^3 in latitude with a characteristic temperature of about 1280 K, consistent with a photon-stimulated desorption source. Their scale heights were reported to decrease with latitude, in the opposite sense of our measured scale heights. One important difference between the observations in [2] and ours is that they used a 3 Å onband filter whereas we used a 1.5 Å bandpass; in addition they used a broad bandpass filter (50 Å) centered at 5860 Å for their off-band observation while we used a 1.5 Å bandpass filter for both onband and offband observations. Therefore our scattered light correction is much more precise. High resolution line profiles of lunar Na obtained with a Fabry-Perot spectrometer [7] indicate a range of temperatures from 2500 K to 9000 K during magnetotail passages, with a systematic increase in temperature from quarter moon to full Moon. We do measure scale heights varying from roughly 500 to 1500 km (2255 K $< T < 6765$ K), consistent with [7], but we see no trend with phase angle. Schmidt [8] presented evidence that the Na line profile observed in Mercury's exosphere increases with altitude. This may explain why some observers found a cold profile, while others concluded that the Na exosphere is hot. It is also possible that we observe the tail of an altitude profile derived from a non-thermal process.

References: [1] Sarantos M. et al. (2010) *Icarus* 205, 364-374. [2] Potter A. E. and Morgan T. H. (1998) *Journ. Geophys. Res.* 103 E4, 8581-8586. [3] Potter and Morgan (1991) *Geophys. Res. Lett.* 18 # 11, 2089-2092. [4] Mendillo M. et al. (1993) *Adv. Space Res.* 13 #10, 313-319. [5] Stern S. A. and Flynn B. (1995) *Astron. Journ.* 109, 835 - 841. [6] Potter A. E. and Morgan T. H. (1988) *Journ. Geophys. Res.* 103 #E4, 8581-8586. [7] Kurupparatchi D. C. P. et al. (2018). *Journ. Geophys. Res.*, doi:10.1029/2018JE005717. [8] Schmidt C. et al. (2018) EPSC2018, Abstract #1216.