

LUNAR SCIENCE ON A SHOESTRING: THE ADVENTURES OF LADEE. R. C. Elphic¹, B. P. Hine¹, G. T. Delory², S. Noble³, A. Colaprete¹, M. Horanyi⁵, P. Mahaffy⁴, and the LADEE Science Team, ¹Planetary Systems Branch, NASA Ames Research Center, MS 245-3, Moffett Field, CA, 94035-1000, ²Space Sciences Laboratory, University of California, Berkeley CA 94720, ³Planetary Science Division, Science Mission Directorate, NASA, Washington, DC 20546, ⁴NASA Goddard Space Flight Center, Greenbelt, MD, 20771, ⁵Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309.

Introduction: On September 6, 2013, a near-perfect launch of the first Minotaur V rocket successfully carried NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) into a high-eccentricity geocentric orbit. The launch, from NASA's Wallops Flight Facility in Virginia, was visible from much of the eastern seaboard. Over the next 30 days, LADEE performed three phasing orbits, with near-perfect maneuvers that placed apogee at ever higher altitudes in preparation for rendezvous with the Moon. LADEE arrived at the Moon on October 6, 2013, during the government shutdown.

Objectives: LADEE's science objectives are twofold: (1) Determine the composition of the lunar atmosphere, investigate processes controlling its distribution and variability, including sources, sinks, and surface interactions; (2) Characterize the lunar exospheric dust environment, measure its spatial and temporal variability, and effects on the lunar atmosphere, if any. But the LADEE project was also required to demonstrate a number of other firsts: (1) first launch of the Minotaur V; (2) first deep-space demonstration of high-speed laser communications; (3) first use of the Ames Modular Common Spacecraft Bus; (4) first planetary launch from Wallops Flight Facility, one of only three locations permitted to launch Minotaur rockets; (5) acquire all necessary science data to achieve success in 100 days of operations.

Instruments: The LADEE science payload consisted of three instruments. A neutral mass spectrometer (NMS) sampled lunar exospheric gases and ions *in situ*, covering the 2-150 Dalton mass range. NMS drew its design from similar mass spectrometers developed at GSFC for the MSL/SAM, Cassini Orbiter, CONTOUR, and MAVEN missions. At LADEE's low operational altitudes, NMS was capable of measuring the abundance of gases such as Ar and CH₄, which could reflect internal geophysical processes at the Moon. NMS was also designed to detect refractory elements in the exosphere (Si, Al, Mg, Ca, Ti, Fe), as well as Na and K, which may be indicative of more energetic processes acting on the lunar surface such as sputtering and impact vaporization. In terms of volatiles, NMS could detect H₂O, OH and CO. There is also an ion-detection mode. Ultimate sensitivity for detection of most species is in the range of a few parti-

cles/cc. A complete instrument description is provided by Mahaffy et al., [1].

LADEE's ultraviolet/visible spectrometer (UVS) acquired spectra of atmospheric emissions and scattered light from tenuous dust. Derived from the LCROSS visible spectrometer, UVS spanned the 250-800 nm wavelength range, with <1 nm spectral resolution. UVS also performed dust extinction measurements via a separate solar viewer optic. UVS was designed to detect volatiles such as OH, K, Li, Ba, and Na, as well as more refractory elements such as Al, Ca, Si, Ti, and Mg. UVS could also detect water (H₂O) in several of its positively ionized states. A complete instrument description is provided by Colaprete et al. [2].

The Lunar Dust Experiment (LDEX) sensed dust impacts *in situ*, at LADEE orbital altitudes, via impact ionization and charge detection. The instrument's heritage included HEOS 2, Ulysses, Galileo and Cassini missions. LDEX could detect dust particles in the size range between 100 nm and 5 μm. A complete instrument description is provided by Horanyi et al., [3].

A fourth payload instrument was the Lunar Laser Communications Demonstration (LLCD), a test of high-speed optical communications capable of higher bandwidth than conventional radio frequency communications.

Science Mission: The commissioning phase was carried out at high altitudes, ~250 km. For the prime science phase, however, LADEE's periapsis and apoapsis were dropped to between 20 and 50 km, and

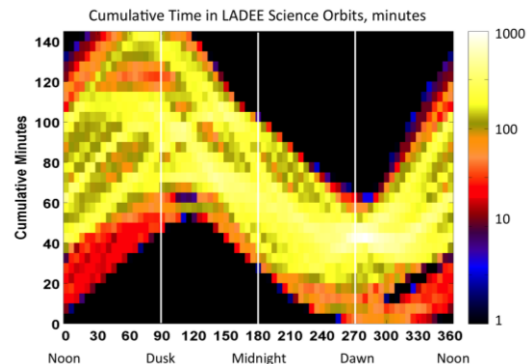


Fig. 1. LADEE's altitude vs. solar angle in lunar solar ecliptic coordinates for the prime science phase. Cumulative time scale is in minutes.

75 and 150 km, respectively. Figure 1 shows the local time versus altitude coverage of LADEE's prime science mission. Periapsis was maintained over the sunrise terminator, to investigate how exospheric species respond to the transition from the cold (<100K) nightside to warm dayside.

At that low vantage point, NMS was able to detect Argon-40 for the first time, and see its distinctive variation across the sunrise terminator. Argon-40, a noble gas, has a lower scale height than that of helium, and can condense on the cold nightside lunar surface. The rate that LDEX was sensing lunar dust at high altitudes (approximately one dust grain every few minutes) suddenly increased several-fold at 50 km.

LDEX also observed occasional bursts of dust particles, where rates increase from about one particle per minute to several hundreds of hits in under 30 seconds. These bursts may be due to LADEE flying through the dust plumes thrown up from the lunar surface when a meteoroid impacts the lunar surface near the LADEE orbit.

NMS systematically monitored helium, neon and argon during the mission. These three noble gases appear to constitute the majority of the lunar exosphere. Figure 2 shows a pie chart of these three as measured by LADEE, plus the contribution by other species.

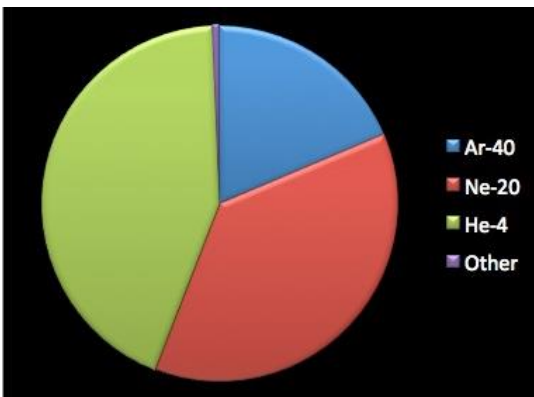


Fig. 2. Proportions of the major three gases of the Moon's exosphere, He, Ne and ⁴⁰Ar., plus the remaining minor species, which include sodium and potassium.

UVS measurements of potassium and sodium are telling us about the processes that govern these exotic species. We now know that the sodium exosphere responds to meteoroid input – when the Earth-Moon system passes through a meteor stream like the Geminids, increased micrometeoroid impact vaporization seems to increase the sodium content of the atmosphere during meteor showers.

The Moon's sodium and potassium appear to diminish as the Moon approaches Full phase. Why would they respond to phase? As the Moon approaches Full,

it leaves the solar wind and enters a more protected environment, the geomagnetic tail. Here, the solar wind sputtering ceases, and the source rate diminishes.

But after a few days, as the Moon leaves the tail, there follows a rapid rise in sodium and potassium as the incoming solar wind protons force sodium and potassium atoms off the surface.

Other possible exospheric species being studied include H₂, O, OH, CO, Mg, Al, CO₂, Ti, and water.

LADEE Data and Ongoing Studies: The operational part of the LADEE mission ended with controlled impact on the lunar farside on April 18, 2014/04:31:47 UTC at 11.840 deg latitude and -93.252 deg longitude (Moon-centered Mean Earth coordinates). As of late summer, the first delivery of LADEE science data has been made to the Planetary Data System, in time for the Lunar Data Analysis Program. The LADEE science team is still at work analyzing the natural variations in the lunar gas and dust exosphere; but LADEE data may also be useful in understanding the effects on the atmosphere introduced by spacecraft. The Chinese lunar mission Chang'e 3 landed in northern Mare Imbrium at 13:10 UTC Dec. 14, 2013. This development offered an interesting opportunity for active experimentation. Did LADEE observe any evidence of the Chang'e 3 landing? Did the arrival of a large robotic lander have a noticeable effect on the dust and gas exosphere? LADEE's propulsion system also carried out numerous orbit maintenance maneuvers, including one at low-altitude that fortuitously sprayed the lunar surface on the pre-dawn nightside with exhaust products. Careful study of these man-made effects may tell us about how known quantities of gas, of known composition, interact with the lunar regolith.

References. [1] Mahaffy, P. R., et al., The Neutral Mass Spectrometer on the Lunar Atmosphere and Dust Environment Explorer Mission, *Space Sci. Rev.* DOI 10.1007/s11214-014-0043-9; [2] Colaprete, A. et al., The Ultraviolet and Visible Spectrometer for the Lunar Atmosphere and Dust Environment Explorer, *Space Sci. Rev.*, (in review). [3] Horanyi, M., et al., The Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE), *Space Sci. Rev.*, (in review);