LADEE SCIENCE RESULTS AND IMPLICATIONS FOR EXPLORATION. R. C. Elphic[1], M. Horanyi[2], A. Colaprete[1], M. Benna[3], P. R. Mahaffy[3], G. T. Delory[1,7], S. K. Noble[4], J. S. Halekas[5], D. M. Hurley[6], T. J. Stubbs[3], M. Sarantos[3], S. Kempf[2], A. Poppe[7], J. Szalay[2], Z. Sternovsky[2,], A. M. Cooke[1], D. H. Wooden[1], D. Glenar[3], [1]NASA Ames Research Center, Moffett Field, CA 94035 USA, [2]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder 80309 USA, [3]Solar System Exploration Division, NASA's Goddard Space Flight Center, Greenbelt, MD 20771 USA, [4]Planetary Science Division, NASA Headquarters, Washington D.C., 20062 USA, [5]Dept. of Physics and Astronomy, University of Iowa, Iowa City, IA 52242 USA, [6]Johns Hopkins University/Applied Physics Laboratory, Laurel, Md 20723 USA, [7]Space Sciences Laboratory, UC Berkeley, Berkeley, CA 94720 USA.

Introduction: NASA's Lunar Atmosphere and Dust Environment Explorer, LADEE, concluded a fully successful investigation of the Moon's tenuous gas and dust atmosphere on April 18, 2014. LADEE hosted three science instruments to address atmospheric and dust objectives, and a technology demonstration of deep-space optical communication. The three science instruments were an ultraviolet-visible spectrometer (UVS), a neutral mass spectrometer (NMS), and a lunar dust experiment (LDEX). All data acquired by these instruments have been submitted to the Planetary Data System. A mission overview and science instrument descriptions are readily available [1,2,3,4].

LADEE inserted into a low-altitude, retrograde lunar orbit optimized for observations at the sunrise terminator, where surface temperatures rise abruptly. LADEE also carried out observations over a wide range of local times and altitudes. Here we describe some of the initial results.

Lunar Exospheric Dust: LDEX began measuring lunar dust particles even before the nominal science phase. LDEX measurements have revealed the presence of a tenuous but persistent "cloud" of small dust grains, from <0.3 to >0.7 μm in radius [5]. The number density of these grains maximizes over the morning side of the Moon, the hemisphere on the "upstream" side of the Moon's motion about the sun (Fig. 1). The cloud, with observed densities ranging between 0.4 – 4 x 10^{-3} m^{-3}, is made up of ballistic ejecta from micrometeoroidal impacts on the lunar surface. The cloud density increases as the Earth-Moon system passes through known meteoroid streams, such as the Geminids, which are derived from cometary debris trails. LDEX data show no evidence for an electrostatically-lofted dust component at densities greater than a few per m^3 [6].

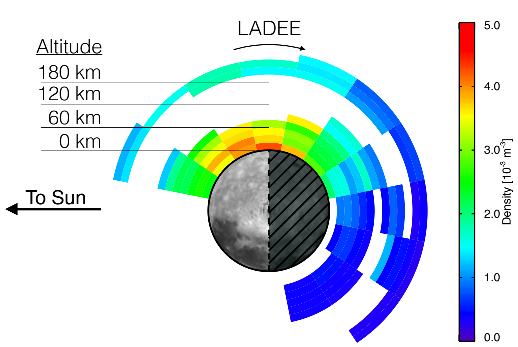

Fig. 1. LDEX dust density variation with local time and altitude. From [5].

LADEE's UVS searched for scattered light from exospheric dust. There are indications of a population of extremely small, ~10 nm-scale grains in the UV continuum, and this is still under investigation..

Lunar Exospheric Structure and Composition: LADEE's NMS instrument immediately detected helium (^{4}He) in the lunar atmosphere during high altitude commissioning. At lower altitudes it also measured neon (^{20}Ne) and argon (^{40}Ar). NMS measurements revealed systematic variations in density and scale

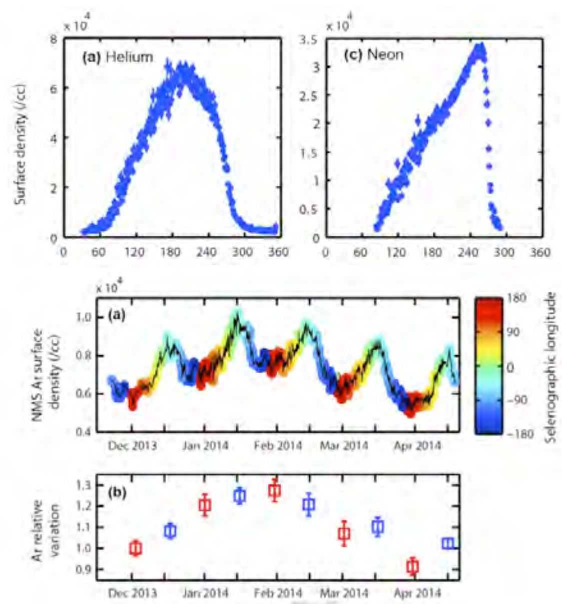

Fig. 2. (top) LADEE NMS results for ^{4}He and ^{20}Ne. Horizontal axis is solar longitude, with 0 at noon, 90 at sunset, 180 at midnight and 270 dawn. (bottom) Time variations in ^{40}Ar over the LADEE mission. Argon density maximizes over the western maria. From [7].

height for these three noble gas species [7]. Figure 2 shows the diurnal variation of helium and neon density, which are largely controlled by surface temperature as expected for non-condensible species. Helium density closely tracks the input of He^{++} from the solar wind; loss is by way of thermal escape. ^{20}Ne is a minor solar wind constituent, but it has a long lifetime at the Moon and builds up to significant densities in the lunar atmosphere. ^{4}He, ^{20}Ne and ^{40}Ar are the three most abundant species in the lunar exosphere. ^{40}Ar density maximizes over the western maria, in particular the KREEP-rich Mare Imbrium and Oceanus Procellarum areas, part of the PKT. There is also an overall, many-lunation variation in argon density, perhaps reflecting changes in the rate of release out of the subsurface, either the interior diffusive source or impacts.

NMS also ran an ion-only mode, which has revealed the presence of multiple species that are ionized by solar EUV and accelerated by the solar wind electric field, as measured in the lunar neighborhood by ARTEMIS [8]. These species include H_2^+, He^+, $^{20}Ne^+$, Na^+, K^+ and $^{40}Ar^+$, as might be expected from known

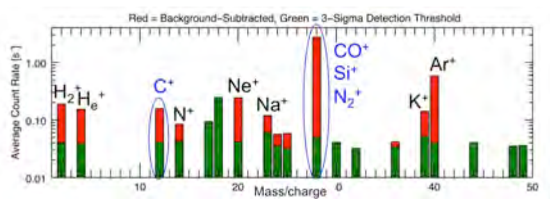

Fig. 3. Exospheric species identified by their pickup ions. Because of the very significant carbon detection, mass 28 is likely at least partly CO. From [8].

exospheric sources (Figure 3). But also seen are $^{12}C^+$, $^{14}N^+$ and mass 28, which could be Si^+, N_2^+ or CO^+. Based on the significant $^{12}C^+$ detection, the mass 28 species is likely to be mostly CO^+. While masses 17 and 18 (OH and H_2O) were also observed in ion mode, their flux did not correlate with the solar wind electric field – these are considered probable outgassing artifacts, from the local spacecraft "coma".

Remote Sensing of Na and K: Sodium and potassium are present in the lunar surface boundary exosphere, as they are at Mercury. LADEE's UVS made measurements of the sodium and potassium exospheres over several local times throughout the mission, and found evidence of a monthly variation. This variation is evidently tied to geomagnetic tail crossings and the delivery of fresh sodium inventory by, for example, the Geminid meteoroid flux. Figure 4 shows the Na and K density variations from UVS during the mission.

The sodium exosphere appears to exhibit a systematic behavior with lunar phase. It appears to peak near Full Moon, but with temporal structure in the density

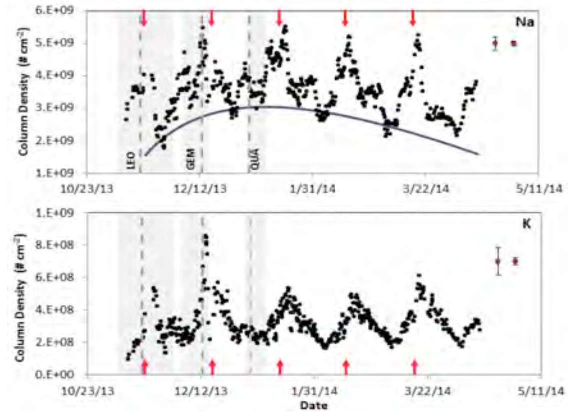

Fig. 4. LADEE UVS Na and K column densities (40 km grazing altitude) during the mission. Red arrows denote Full Moon, when the Moon is in the geomagnetic tail.

that suggests solar wind sputtering (absent in the geomagnetic tail) is an important source term. Meanwhile, mobile Na atoms that are not lost to photoionization can be trapped on the cold nightside, and recycled into the atmosphere after sunrise. As the Moon leaves the geomagnetic tail, sputtering again becomes important and the abundance rises with newly-released Na atoms. There is a long-term trend to the sodium, with an overall decline resembling that of ^{40}Ar. Its cause is not yet known, but sodium is not obviously related to interior release processes, so perhaps both have a long term response to micrometeoroid impact and vaporization. Na densities also appear to increase over the maria.

The potassium exosphere is similar to that of sodium but there is less evidence for magnetotail-related drops in density (sputtering shutoff). There are indications of regional enhancements related to surface composition, with higher values of K over the PKT.

LADEE found no evidence for a persistent, significant water or OH exosphere. Instead, these species are seen sporadically, with indications of a connection to meteoroid streams. These findings and their ramifications for future exploration will be discussed.

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