THE ATMOSPHERE OF THE MOON

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Abstract. The possible existence of a lunar atmosphere has both fascinated and challenged astronomers for hundreds of years. Galileo searched for evidence of clouds, and Kepler imagined an Earth-like climate. Landings during the Apollo era brought instruments that measured a weak atmospheric pressure. Decades later, new spectrographic and imaging instruments detected sodium and potassium gas that extended to surprisingly large distances, making the Moon's gaseous environment appear as comet-like. The sources of the lunar atmosphere involve the impact of sunlight, solar wind plasma and meteors upon the surface to release atoms and perhaps molecules. Solar radiation and the gravitational influence of the Earth play dramatic roles in the subsequent evolution of the lunar atmosphere.

1. Introduction

The cosmology of the Earth–Moon system is, perhaps, the single scientific theory to withstand the test of time. That is, no significant hypothesis ever existed that suggested an alternative to geocentric motion. In all other aspects of lunar research, the traditional methods for the advancement of science have revised continuously our understanding of Earth's cosmic neighbor. A topic that typifies this evolution of lunar research is the existence of its atmosphere.

Galileo devoted considerable effort to a systematic search for a lunar atmosphere. In Siderius Nuncius (1610) he noted the absence of shadows cast by clouds in his remarkable drawings of lunar terrain (Berry, 1961). His depiction of shadows cast by mountains and within craters were consistent with the solar illumination angles at the times of his observations, thus making Earth and Moon similarly "real" places. Yet, perhaps due to his residence in a city where clouds are an everyday phenomenon, a place without clouds (implying a Moon with no atmosphere) was not the "real" world he expected the Moon to be. Thus, he persisted in additional tests defining what is now the classic method of remote detection and study of an atmosphere around another planet or moon – the stellar occultation experiment. Galileo watched the brightness of a star as the Moon approached and eventually passed in front of ("occulted") it. If the star's light dimmed gradually and then disappeared suddenly, the interpretation would be that an atmosphere absorbed (or diverted) some of the starlight prior to the edge (limb) of the solid surface physically blocking the star. Galileo saw no such near-limb effects and thus

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concluded that the Moon had no appreciable atmosphere. This finding withstood many subsequent occultation experiments using far more sophisticated equipment.

2. The Apollo Lunar Experiments

A new perspective on the rocky, dusty lunar environment began with the Apollo program of lunar exploration in the 1970s. Sensors brought to the surface of the Moon by astronauts detected a very low atmospheric pressure. As summarized recently in a comprehensive review of lunar atmospheric science by Stern (1999), the Apollo instruments measured a concentration of gases of approximately 10^7 particles/cm^3 during the day and about 10^5 particles/cm^3 at night. Such densities are still comparable to vacuum conditions in comparison to the gas content at the surface of the Earth (10^{19} particles/cm^3). Initial concerns that the instruments were merely detecting gases that evaporated off the lunar modules were ultimately dismissed in favor of accepting a weak atmosphere produced by capture of solar wind particles (such a helium) or the radioactive decay of elements in the lunar soil (such as argon from potassium). As interests turned to other areas in the solar system, the Moon's minor atmosphere received little attention for many years.

3. Remote Sensing of the Moon's Atmosphere

Starting in the mid-1980s, the use of ground-based telescopes with spectrographs to record the signals of specific chemical species signaled a new era of ground-based remote sensing of primitive bodies. Much like comets, the rocky surfaces of Mercury, the Moon and some asteroids emit gases that escape into space, providing a transient atmosphere to study. The spectroscopic technique applied to the Moon by Potter and Morgan (1988) and Tyler et al. (1988) revealed the presence of sodium and potassium gases just above the Moon's limb. The elements sodium and potassium are not particularly abundant in the solar system but are relatively easy to detect because they scatter sunlight very efficiently. They are not the major constituents of the atmospheres of the Moon (or Mercury), but they do serve as excellent "tracers" of other gases presumably there but more difficult to detect. For example, the total number of sodium plus potassium atoms detected just above the Moon's surface is barely 100 atoms/cm^3, far below the concentrations suggested for total abundances in the Apollo data.

4. Sputtering Sources

The source of the sodium gas on the Moon is a research topic very much in active debate (Stern, 1999). Liberating gases from the surface material (regolith) requires

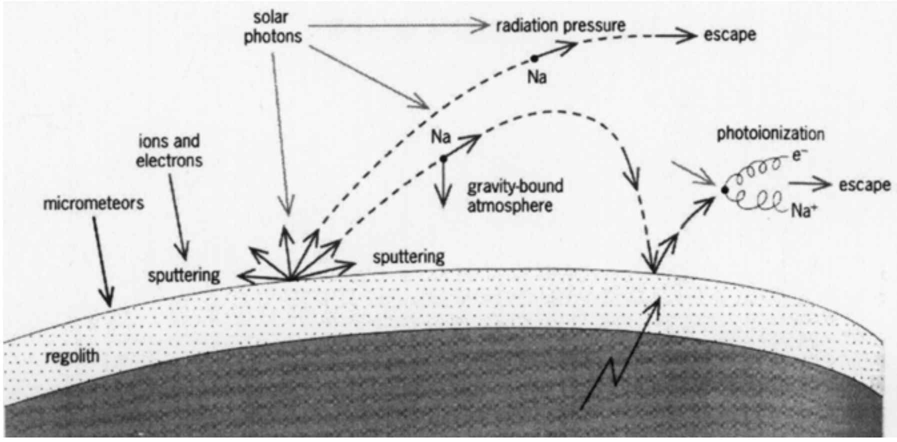

Figure 1. A schematic illustration of the processes that release and govern the subsequent motion of sodium atoms (Na) ejected from the regolith of the Moon.

the impact of micrometeors or solar wind ions and electrons, or sunlight. These are called sputtering agents, and laboratory experiments show that they indeed can free atoms and molecules from surfaces with sufficient energy to move away from the surface. Both hot and cold gaseous populations are possible from these processes, and the degree to which the thermal and superthermal components dominate close and distant regions is still under study (Sprague et al., 1992). Sputtered gases are either pulled back to the regolith by gravity, pushed away by solar radiation pressure, or lost by photoionization and removal by the magnetic field in the solar wind (see Figure 1). The term surface-boundary-exosphere (SBE) is applied to an atmosphere produced by vaporization of surface material under conditions where collisions aloft are so rare that the liberated gases can have long parabolic trajectories back to the surface, or can escape directly from it.

5. Imaging Results

The next step in understanding the sodium atmosphere of the Moon came from new low-light-level imaging techniques capable of taking a picture of the full extent of the atmosphere. Images of the sodium brightness in two dimensions show that the atmosphere extends to several times the radius of the Moon (Figure 2). If the brightness levels were very much higher, the Moon's sodium atmosphere would be visible to the naked eye as a large cloud (nebula) spanning several degrees of the night sky. This large extent suggests that sodium atoms have relatively high speeds, close to the escape speed (2.3 km/sec); yet, the pattern of brightness decreases with distance (d) as d^{-4} showing that there are slower speed sodium atoms as well. To test the mechanisms responsible for sputtering processes with the required release speed distributions, several research groups are actively making lunar observations

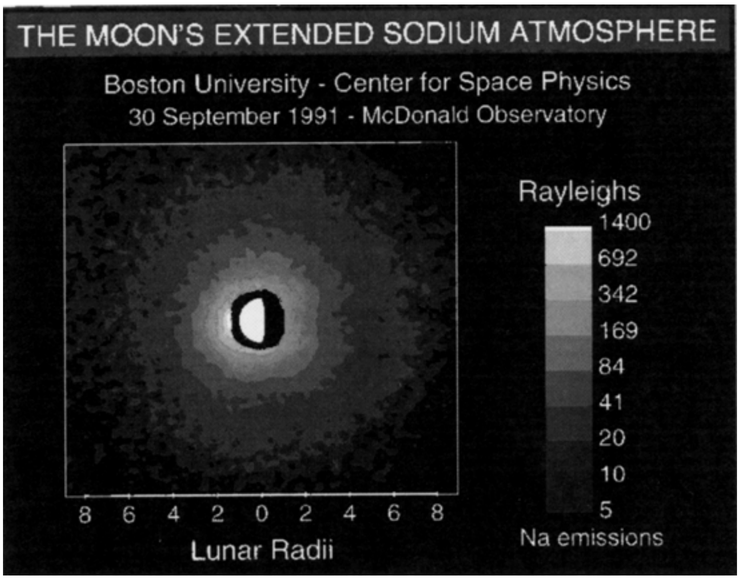

Figure 2. Image of the sodium atmosphere surrounding the Moon near quarter phase. The sodium brightness units shown are far below those capable of being seen by the unaided human eye. The Rayleigh unit is defined as $10^6/4\pi$ photons per square centimeter per second per steradian.

during meteor showers and at times when the solar wind is shielded from the surface by the Earth magnetic field.

6. Lunar Atmosphere Generated by Meteors

There have been several reports of an enhancement in the Moon's atmosphere during a meteor shower (Hunten et al., 1992; Cremonese and Verani, 1997; Verani et al., 1998). A particularly strong case occurred during the Leonids "storm" in November 1998. Using a wide-angle (180° all-sky) field of view, Smith et al. (1999) described a persistent sodium "spot" seen on the nights after the peak meteor events of 17 November 1998. The unusual aspect of their observations was that they were made near new Moon phase, i.e., when the Moon cannot be observed directly due to it location between the Earth and the Sun. Their analysis and companion computer simulations (Wilson et al., 1999) showed that sodium atoms released via the meteor-regolith impacts were accelerated away from the Moon by the radiation pressure of sunlight. In approximately two days (i.e., on 19 November), a cloud of Na gas swept past the Earth where it was focused into a beam by the Earth's gravitational field. Thus, in viewing the sky in the direction opposite from both the Moon and the Sun, the distant lunar tail was observed. Figure 3 summarizes the observational and modeling description of this effect. Subsequent observations reported by Smith et al. (2000) show that the lunar sodium spot (and

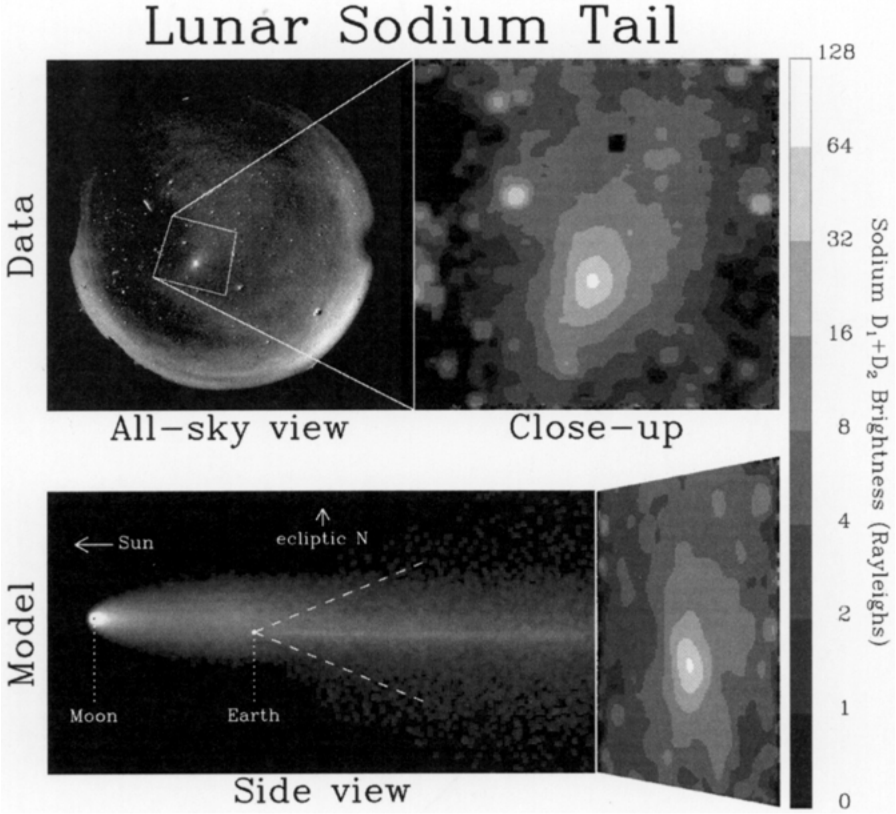

Figure 3. Top panel: (Left) all-sky image showing the sodium "spot" discovered on 19 November 1998. (Right) magnified portion of the feature. Bottom panel: (Left) computer model showing (to scale) neutral sodium originating from the Moon, accelerated by radiation pressure to the Earth where a portion is gravitationally focused into a column of enhanced sodium brightness. (Right) This simulated "spot" is shown as it would appear to a wide-angle camera system (dashed lines) on the night side of the Earth.

therefore the distant atmospheric tail) is a permanent feature of the Earth–Moon system, occasionally modulated in prominence by transient sources of sputtering.

7. Lunar Atmosphere Seen during Eclipses

For approximately four days each month, the Moon passes through the Earth's magnetic envelope (called the magnetosphere) thereby shielding its surface from solar wind plasma impact. To see if the lunar atmosphere is affected by this removal of a sputtering agent, observations of the tenuous Na gas have to be made during the nights spanning the bright full Moon. This presents a serious, if not impossible, impediment to wide-angle imaging systems. An innovative solution to this problem is to conduct such observations during the totality phase of a lunar eclipse. Under

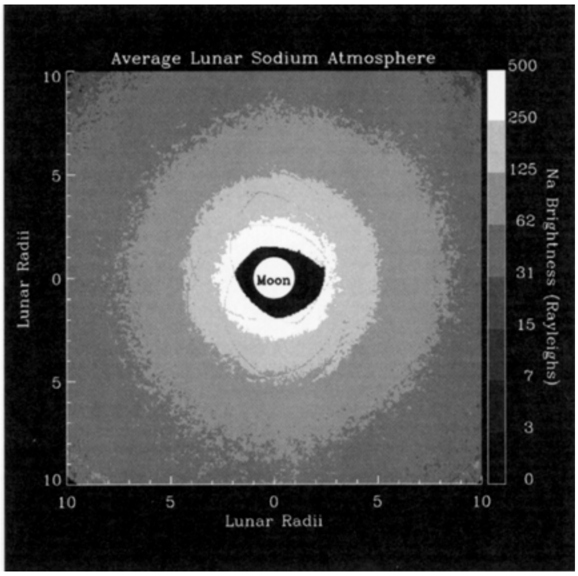

Figure 4. Average pattern of the Moon's extended sodium atmosphere at the time of full Moon as observed during four lunar eclipses. The irregularly shaped dark area near the center is the sum of the regions close to the Moon that were not observed during any of the eclipses due to geometrical differences of the events.

such conditions, the bright lunar disk (and therefore scattered light) is very much reduced, and yet sunlight beyond the penumbra is still at full strength to illuminate any distant sodium that may be present. Mendillo et al. (1999) reported on four such experiments and found that the robust, extended nature of the Moon's atmosphere is not affected in any drastic way by the absence of a solar wind sputtering source (see Figure 4). Thus, of the three proposed mechanisms for generating the extended lunar atmosphere, photon-sputtering is always present on one hemisphere and is thus considered to be the dominant source; ever-present micro-meteors are a secondary source, one certainly enhanced during meteor showers; solar wind sputtering appears to be the least significant source.

8. Summary

The history and subsequent understanding of the Moon's atmosphere is a research topic that typifies the classic evolution of scientific inquiry. The connection of its atmosphere to geocentric concepts spans the range from philosophical preferences to actual dynamical governance. The physical presence of the Earth as the Moon's dominant neighbor is revealed by the terrestrial gravitational focusing of its atmosphere at new Moon into a jet of escaping gas aligned with the Sun–Moon–Earth axis. The occasional eclipse geometry of a Sun–Earth–Moon alignment offers rare glimpses of the lunar atmosphere at full Moon (and scientific insights into the role of plasma-surface interactions). At quarter Moon, the lunar atmosphere appears comet-like, reminding us that cosmic properties and changing appearances link the celestial and the terrestrial, making the Earth–Moon connection a true laboratory-in-space that enables our search for how Nature works.

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