# LUNAM 2000 (LUNAR ATMOSPHERE MISSION)

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**Abstract.** LUNAM 2000 is a small mission dedicated to the coronagraphic imaging in the Na yellow doublet and to UV spectroscopy in the range 2800–3400 Å of the lunar atmosphere. These studies are possible only from Space. The scientific return of LUNAM 2000 has a wider appeal for the study of transient atmospheres of other celestial bodies, in particular of Mercury. The mission is in low Earth-orbit (about 350 km); a sun-synchronous or other orbits are under investigation. The payload has very small weight, dimensions and power requests, and is essentially made with off-the-shelf components. It can be built and launched in less than 3 years from the approval. This time frame nicely overlaps that of the European technological Mission SMART 1 and can greatly add to its scientific return. Furthermore, LUNAM 2000 can give very important information to define a mission to Mercury such as Bepi Colombo.

## 1. Introduction

The Moon, long believed a celestial body lacking an atmosphere, is actually surrounded by a tenuous and transient envelope of gases released from its surface. The chemical composition of this lunar atmosphere, one that has a surface density of about $10^5$ atoms/cm$^3$, is poorly known. Indeed, from Earth we can observe directly only the alkaline component of Na and K, in addition to He and Ar detected by the Apollo era instruments (assumed to be of solar origin). There should also be more abundant species, such as Al, Mg and OH. The latter is a fascinating possibility in that it would come from photodissociation of water, according to the evidence presented by the missions Clementine and Lunar Prospector. This atmosphere is produced, lost and regenerated on time scales of the order of hours or days, thus providing an ideal laboratory where we can investigate how the transient envelopes

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of other celestial bodies are generated by such diverse processes as solar wind, solar photons, and meteoritic impacts. Those mechanisms, whose efficiency is still largely undetermined, and possibly others essentially unknown today, are at work not only on the Moon but also on Mercury, on comets and asteroids, on the moons of the giant planets. Actually, the study of the lunar sodium played a decisive part in shaping our more general line of research of the diffuse Na in the Solar System. For the Italian team, that started essentially with the Asiago data on the Io's Na cloud around 1994; indeed, using the same techniques and filters, Cremonese discovered the "third" Na tail of comet Hale-Bopp, and this discovery has greatly modified even the basic understanding of the Na atomic life times under fluorescence (Cremonese et al., 1997).

We are convinced that instrumentation for coronagraphic imaging in the Na doublet and of spectroscopy in the near UV from 2800 to 3400 Å of the lunar atmosphere (LUNAM), operating in circumterrestrial space at an altitude of some 350 km (e.g., in a sun-synchronous orbit), can acquire decisive information for the understanding of the mechanisms at work on the lunar surface and for the quantitative determination of its chemical abundance. LUNAM 2000 is therefore a highly focussed mission, but its results will have a profound impact on space science, in particular for all those missions that intend to study the processes responsible for the formation, maintenance and destruction of the transient atmospheres of planets, of moons and of small bodies of the Solar System. We believe that this understanding will be crucial also for the comprehension of the atmospheres of the known extra-solar system planets, whose orbits are so different from those of Jupiter and Saturn.

The required effort for LUNAM 2000 is indeed very modest if compared with the expected scientific return. Ideally, after an appropriate engineering debugging phase, just one month of continuous observations, covering all phases of the lunar cycle would provide exceptional information (from circumterrestrial Space, continuous observations are possible except for the 3 days when the Moon is too close to the Sun, whilst from Earth only some 10 days are available each month, except that weather conditions seldom make this possible). Lunar experts are not convinced that the Na doublet indeed traces the spatial distribution of all other gases, and hence the need for a spectrograph that will search for other gases with its slit just above the lunar limb. In order to have a good statistical coverage of several meteoritic showers we propose to extend the mission from 3 months (minimum) to 12 months (best effort goal). During the space mission, parallel coordinated observations from several telescopes on the ground (such as the Asiago echelle spectrograph, two small coronagraphic telescope in Texas, the high resolution spectrographs at the Roque de los Muchachos, etc.) will be organized in order to observe the regions closer to the lunar surface, to extend as much as possible the time coverage and to intercalibrate the great amount of data previously obtained on the ground with the new ones obtained from Space. We have already ample experience with this type of coordinated campaign (e.g., Sprague et al., 1998);

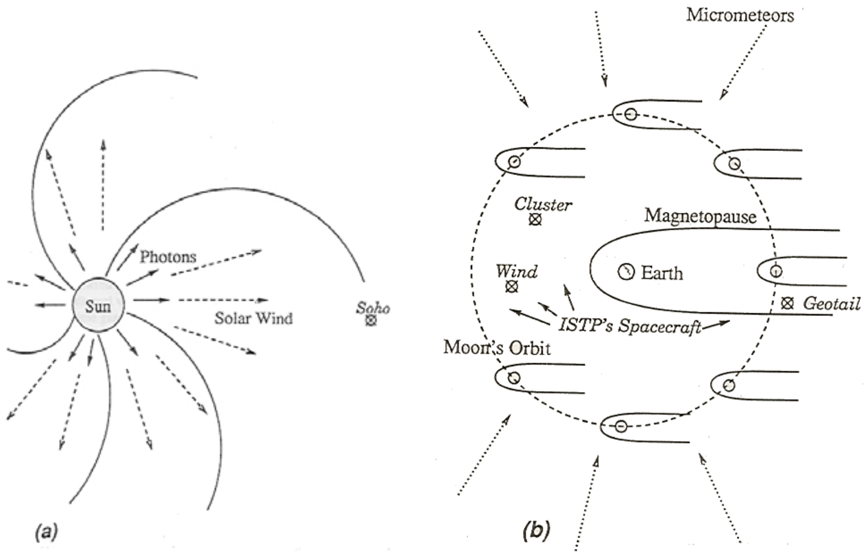


*Figure 1.* The main processes affecting the lunar atmosphere; the position of SoHO and ISTP's spacecraft is indicated.

we wish to recall that using the William Herschel Telescope we have provided the first evidence of the meteoritic impacts importance for an hitherto unknown, strongly anistropic and time dependent source of lunar gases (e.g., Cremonese and Verani, 1997; Verani et al., 1998; Hunten et al., 1998). In turn, the lunar Na varying intensity provides new data on the spatial structure of the meteoritic shower. We have recently equipped the high-resolution spectrograph SARG of the Telescopio Nazionale Galileo with that same filter, in order to exploit the superb optical quality of this telescope to obtain data from regions very close to the lunar surface.

The technology for LUNAM 2000 is largely available, and the operation is typical of a small mission that can be built, flown and achieve scientific closure in less than 5 years time, provided a highly innovative structure of cooperation between Universities, Research Institutes, and Industry is adopted. Equally important will be the influence of LUNAM 2000 on education and professional development of young researchers, and on the important need for more general public outreach.

## 2. Scientific Objectives

The complex interactions of the solid or liquid surfaces of planets and moons or of their gaseous atmospheres with photons and particles of solar origin, as well as the effects of the infall of micro- and macro- meteorites, are frontier areas of research in the Solar System. The magnetic fields, either in the body or carried by the solar wind, play a crucial role in modulating several plasma-surface-interaction

TABLE I
Sources of the extended lunar atmosphere

| Source | Characteristics | Stability and modulation |
|---|---|---|
| Vaporization of micrometeorites | Isotropic component plus an anisotropic one from showers | Always present but with strong augmentation on particular dates |
| Solar photons sputtering | Depends on the solar zenith distance from the particular lunar site | Continuous, but depends on solar activity, with flares |
| Radiation pressure (acceleration mechanism) | Extended tail in the anti-solar direction | Depends on relative Sun–Moon velocity |
| Solar wind (ionic sputtering) | Depends on the solar zenith distance from the particular lunar site | Present 25 days a month; modulated by CMEs, magnetic sectors |
| Sputtering from Earth magnetospheric energetic particles | Unknown | Geomagnetic storms? |

phenomena. Each body has its own peculiarity: at the position of Mercury (0.4 AU), the photonic sputtering of gases from the surface takes place at its maximum level; but also the vaporization of micrometeorites is important, whilst the role of the magnetic field is essentially unknown. At the distance of Jupiter (5 AU), solar photons are a minority agent, and at the position of Io, well inside the planet's magnetosphere, there are no impacts of the solar wind: therefore sputtering from charged particles trapped inside the magnetosphere plays a dominant role in producing the observed neutral Na atmosphere (we have contributed greatly to the study of these clouds with ground based and space observations). At 1 AU, the Earth-Moon system provides unique possibilities to study such interactions in a well known environment (SoHO and CLUSTER 2 are right now providing novel data), and under conditions largely controllable by the experimenter.

Table I gives a list of what are currently considered the main sources of lunar atmosphere, although from LUNAM 2000 we expect a profound revision of this scenario. Figure 1 gives a graphic account of the situation:

- Solar photons and particles impinge on the illuminated face of the Moon freeing several gases (Na is a minority component but an excellent tracer for sputtering);
- an essentially isotropic flux of micro-meteoroids vaporizes the surface regolith with spherical symmetry;

- according to our findings, anisotropic emission can occur following strong meteoritic showers;
- the solar radiation pressure carries the gases in a cometary-type tail in the anti-solar direction;
- when the Moon enters the terrestrial magnetosphere, the ionic sputtering source is suppressed.

Figure 2 shows the observability of the lunar atmosphere from the proposed orbit at 350 km: except during the 3 days of minimum angular distance from the Sun, LUNAM 2000 can continuously obtain atmospheric images with a quality impossible from the ground, thanks to the lack of Rayleigh scattering, of terrestrial Na and of atmospheric seeing. Indeed, the space observations will have a much higher sensitivity that will allow the study of much fainter lunar Na structures. And of course the UV is inaccessible from the ground. The UV must show important emission lines; in addition to atomic lines from Al and Mg, we can expect to observe a molecular transition from OH coming from the dissociation of water, whose presence has been at least suggested by Clementine and Lunar Prospector. Our data could provide important further measurements of $H_2O$ abundance and localization, useful for future applications such as the human exploration of the Moon. Figure 3 shows the calculated spectrum according to a recent model (Morgan and Killen, 1997). With the sensitivity level of the spectroscopic facility of LUNAM 2000, in a few orbits we should be able to detect Al, Mg and OH. This possibility is suddenly more interesting now that Bida et al. (2000) have detected the presence of Ca in the atmosphere of Mercury in addition to the usual Na and K. This finding demonstrates that elements less volatile than the alkalines can nevertheless be freed form the surface, pointing to a revision of the mechanism of Table I, or at least of their relative efficiency. This UV region has been observed only once with HST (Stern et al., 1997), for a very short total integration time (820 seconds), and the null result is still consistent with the model of Morgan and Killen. We can safely conclude that the Moon is no longer a target suitable for HST after its recent change of instruments, and thus a simple, dedicated payload as LUNAM 2000 is able to provide data of unique value. Regarding SMART 1, this mission will not provide data about the atmosphere, but nevertheless it will be very important to compare the LUNAM 2000 information with the soil composition determined by the SIR (near IR) instrument. Finally, the anisotropic component of meteors is better studied in specific periods of the years; this fact would allow to launch on several particular dates in order to minimize the lifetime of the satellite. For instance, a launch in early July would give ample time for engineering commissioning before the strong Perseid shower impinges on the Earth–Moon system in August; a launch in October would precede the Leonid shower in November, and so on. However these considerations do not constrain the launch date in any way; there are enough meteoritic showers distributed around the year to find at any moment a good candidate. It is therefore wise to suggest a lifetime of the satellite and of its components of the order of 1 year for a truly comprehensive mission. In conclusion, LUNAM 2000

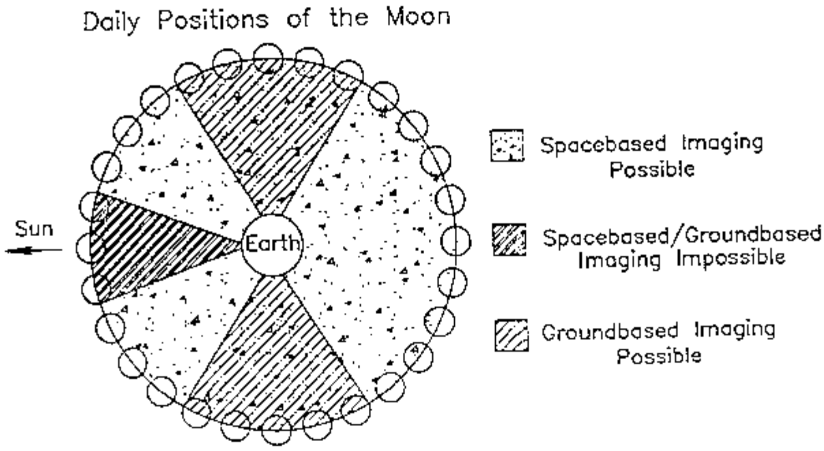


*Figure 2.* Observability of the Moon from a circumterrestrial orbit.

gives a temporal and spatial coverage and a spectral purity absolutely impossible from ground observations, at a very modest cost.

## 3. The Need for Space-Based Coverage

While it is true that groundbased studies can be conducted using sodium emission, it must be stressed that after a decade of such work the international Na observing community has essentially conducted all possible experiments. As shown in Figure 2, one cannot use coronagraphic techniques with a crescent moon due to bright sky backgrounds and high air masses (i.e., long slanted ray-paths through the Earth's troposphere). One cannot use a coronagraphic system during gibbous and full moon phases due to the extremely high levels of scattered light at such times (limitations recently discussed in Potter et al., 2000). But the major observational obstruction to progress is really the crucial need for continuity of observations. As described in Mendillo et al. (1993) and Potter and Morgan (1998), the requirement to image the extended atmosphere of the Moon (as opposed to detecting it with a photometer or spectrometer) requires exceptionally clear and photometric skies. Various lunar observing teams that are experts in imaging science all report that, if lucky, one gets 1 good night out of 5 otherwise called "photometric" for other (non-coronagraphic imaging) uses. The issues that currently dominate the lunar atmosphere community are time-dependent questions, such as:

1. How does the spatial distribution of sodium (vs. latitude or solar zenith angle) change from night to night? This is an issue linked to proposed source mechanisms that have latitude or solar zenith angle dependence.
2. How does the lunar coma change during the six day span from being outside the magnetosphere, to immersion in it (= 4 days), to its exit? This is an issue

linked to a possible relaxation of solar wind "gardening" of regolith and thus its susceptibility to photo-desorption.

3. How does the lunar tail change during the three days following a meteor shower? This is an issue linked to the ejection speeds generated by meteoritic impacts, and thus to their exospheric escape times and susceptibility to solar radiation acceleration.
4. Do solar flares or Coronal Mass Ejections (CMEs) create a transient lunar atmosphere enhancement in the same way as meteor impacts do? This most fundamental question in lunar science has never been addressed because of the lack of predictability of such events and the need to have observations underway at a site with near perfect photometric conditions. Clearly, LUNAM 2000, with its orbit-by-orbit, day-to-day coverage would be the only observatory capable of observing such events and thus produce the scientific closure needed on these outstanding solar system problems.

## 4. Proposed SMART 1 Synergistic Activities

The opportunity to have LUNAM 2000 operational during the SMART 1 mission offers an extraordinary possibility for coordinated space studies of the Moon and its environment. SMART 1 is dedicated to remote sensing measurements of the lunar surface and local, in situ, parameters. The fact that the lunar atmosphere is derived directly from the regolith merges the scientific goals of these two programs in ways not envisioned when either of them was conceived. The specific area of joint study would be during meteor stream impact. The atmosphere of the Moon is a so-called surface-boundary-exosphere (SBE), meaning that the gases at high altitudes come directly from the sputtering of the surface, i.e., there are no collisions to delay or confuse the high altitude signatures with the surface events. Thus, with known meteor showers, the direction of the incoming stream is known well in advance and both spacecraft can be optimized to record the resulting signatures in space and time. In addition to studying the temporal patterns of ejection and entry into the atmosphere, and comparision with model prediction for these events, there is the goal of using the UV instrument on LUNAM 2000 to search for species other than sodium, whether from the vaporization of the incoming meteoritic material or from "gardening" of the existing regolith. This would be a major demonstration of ESA-ASI collaboration, in addition to that of the scientists and engineers involved in the technical issues of exploratory lunar science.

## 5. Main Characteristics of LUNAM 2000

This chapter gives a summary of the main technical characteristics of LUNAM 2000.

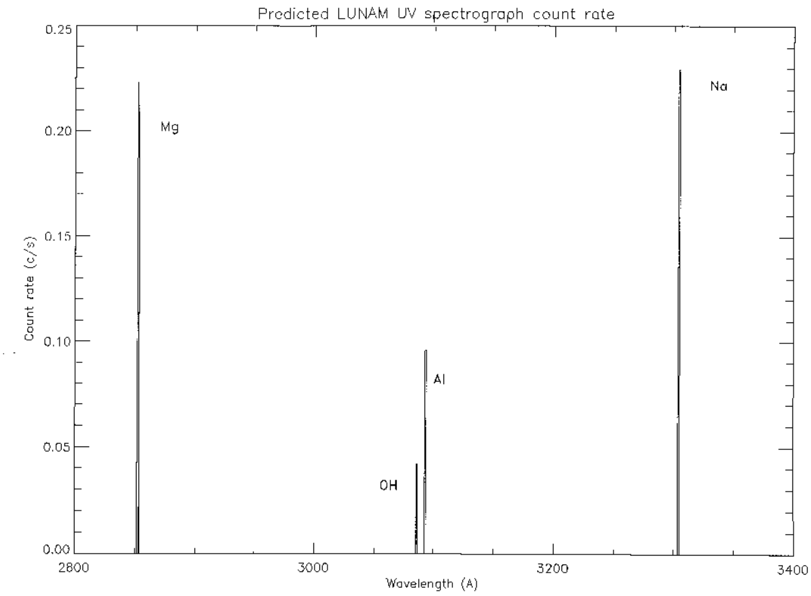


*Figure 3.* Expected lunar emission spectrum from the modeling study of Morgan and Killen (1997) convolved with the spectrograph sensitivity.

1. Definition of the payload:
   – Coronagraphic telescope for lunar atmospheric Na imaging, refractor of 125 mm diameter, detector CCD 512 × 512 px, 27 $\mu$m/px, commercially available, S/N > 20 for 10 Rayleigh of surface brightness with 1 image built of 30 exposures of 1 min each (namely 1 image = 1/3 of orbit), spatial resolution of 0.3 mrad/px (1 arcmin/px, 1/15 RM), coronagraphic mask with diameter of 13 mrad;
   – near UV spectrograph (2800-3400 Å), aimed just outside of the lunar limb, with primary mirror, holographic grating of 1200 g/mm, 2D microchannel plate wedge and strip detector, Cs2Te photocatode, slit having extension of about 2 degrees.
2. Concept of the mission:
   – Minimum operating period: 3 months (already the first month after engineering debugging will provide useful data), target 11 months;
   – coronagraphic images of the lunar Na from 1.5 to 6 lunar radii (field of view 6 degrees);
   – orbit definition: sun-sinchronous, from dawn to dusk, elevation 350 km, inclination 97° (TBV);

– launcher: any launcher capable of delivering 150 kg to 350 km, launch at any date (with scientific preferences but no strong constraints), to be selected in conjunction with ASI;
– ground operations: two PCs connected to the control center are sufficient;
– analysis and archivial of data: One workstation of average configuration, connected to the Web. Data available to scientific community with little delay.

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