Lyman Alpha Photometer (LAP) for Water Evolution Studies in Planetary Atmospheres: Instrumentation, Experimentation and Performance Aspects

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Abstract

The evolutionary history of planetary atmospheres especially of non-magnetic planets such as Mars, Venus etc depends on how well one can understand their atmospheric escape process for different gases. Owing to very mild or absence of intrinsic magnetic field, the upper atmosphere of these planets is always exposed to solar wind that triggers photo-dissociation of water by producing hydrogen (H) and deuterium (D), which are subsequently lost to space over time. Measurements of the atmospheric deuterium to hydrogen (D/H) abundance ratio are vital to understand the escape process and further aid to infer the loss process of water in the evolutionary history of planet's atmosphere. The team at '*Laboratory for Electro-Optics Systems-LEOS*' developed a light-weighed (≤ 2 kg) and low power consumption (≤ 8 Watt) ultra-violet photometer; namely, '*Lyman Alpha Photometer-LAP*' that is primarily dedicated for D/H measurements of planetary upper atmospheres. LAP has successfully qualified for space use and is one of the 5 scientific instruments flown in India's maiden mission to the planet Mars, i.e., '*Mars Orbiter Mission-MOM*'. This paper primarily shares details in brief on the instrumentation, theory, and experimental investigations; finally presents the gist on the executed operations in cruise and Martian orbit phase.

1. Introduction

The study of evolution of water in Mars has become an important topic in the investigation of the planet's atmosphere. This study has a significant role in interpreting the content of water that was available during the early history of the planet. It is also useful in investigating the possibility of existence of life-forms and organic matters. Most of the past explorations to Mars have included various kinds of scientific instruments with the objective of mapping the water content and studying its evolution. Using a set of ground based observations (at Mauna Kea observatory) Owen et. al., discovered the presence of deuterated water (HDO) in the atmosphere of Mars [1]. This led to the possibility to use the measurement of isotope ratio (D/H) as a method for investigating the evolution of water. Isotope ratio is obtained by measuring the ratio of number densities of atomic deuterium (D) and hydrogen (H). In upper atmosphere of Mars atomic D and H are produced from molecules H_2 and HD by the process of photo-dissociation caused by solar vacuum ultra-violet radiation. H_2O and HDO molecules present in the middle atmosphere are the major sources for production of H_2 and HD molecules. The measured isotope ratio can be used to estimate the enrichment in water i.e. HDO/H_2O and the fractionation i.e., $(HD/H_2)/(HDO/H_2O)$. By invoking the processes responsible for fractionation a direct relation can be established between the measured isotope ratio and the enrichment of water. The extent of enrichment essentially represents the temporal evolution of water. Observations of D/H ratio measurements of Mars have revealed only local values at certain times or average values over the planet's atmosphere ($9\pm4\times10^{-4}$ by *Owen et. al*, $7.8\pm0.3\times10^{-4}$ by *Bjoraker et. al* and 5×10^{-4} upper limit of D/H ratio by *Korablev et. al*). Analysis of the SNC meteorites which are thought to have come from Mars also provided information of the Martian D/H ratio as $8.1\pm0.3\times10^{-4}$ on the Martian surface. Owing to uncertainties observed in the measured values, the value of the pristine Martian D/H ratio is still considered to be an open question and evidently, the models required to account for the isotopic fractionation is currently a subject of research.

In order to observe the spatial distribution and time variation of D/H ratio in planetary atmospheres, imaging of hydrogen and deuterium Lyman- α coronas from spacecraft is the most effective technique, since the abundances and altitude distributions of H and D atoms can be derived on a global scale. The wavelengths of hydrogen and deuterium Lyman-α lines are 121.566 nm and 121.533 nm, respectively, and thus the separation between the two lines is quite small (0.033 nm). Therefore, a high resolution spectroscopy technique is needed to separate the two lines. A standard UV spectrometer with a diffraction grating, however, is unsuitable for spacecraft measurements because of its large size and heavy weight. Instead, hydrogen/deuterium absorption cells are superior in respect to size, weight and power consumption [2-4].

2. India's Mars Orbiter Mission (MOM) and LAP instrument

In late 2013, the first Indian mission to the red planet i.e., *Mars Orbiter Mission (MOM*) was launched successfully from Sriharikota, India using a Polar Satellite Launch Vehicle and accomplished a meticulous insertion into the Martian orbit during September 2014. The MOM spacecraft revolves around Mars in a highly elliptical orbit (~400 km x 71,000 km). Though the current mission to Mars is primarily of a technological mission, it has been configured in such a way to carry out observation of physical features of mars and execute a limited study of Martian atmosphere. The spacecraft has placed five scientific payloads in an elliptical orbit with the objective of improving our understanding of the Mars based on its morphology and mineralogy using 2 scientific instruments namely Mars Colour Camera (MCC) and Thermal Infrared Spectrometer (TIS); and upper atmospheric studies using 3 scientific payloads namely Lyman Alpha Photometer (LAP), Methane Sensor for Mars (MSM) and Martian Exospheric Neutral Composition Analyzer (MENCA).

Lyman Alpha Photometer (LAP) is essentially a compact far-ultraviolet photometer capable of providing deuterium to hydrogen (D/H) abundance ratio of Martian exosphere from spacecraft observations. LAP is developed on the absorption gas cell based photometry technique [5-6] and is the first Indian space-borne absorption gas cell photometer that operates on the principle of resonant scattering and resonance absorption. Comparison of the present and initial D/H ratio (estimated from observations of the D/H ratio in comets and asteroids, which are believed to be sources of Martian water) should allow us to calculate the amount of hydrogen and, therefore, the water that has been lost over planet's lifetime. Primary scientific objective of the LAP instrument is to determine D/H isotope ratio of Martian upper atmosphere from the ratio of measured Lyman-α intensities. The observations would enable us to *i)* generate spatial and temporal profiles of hydrogen and deuterium Lyman-α intensities, *ii)* study of deuterium-enrichment in the upper atmosphere and *iii)* estimate of the water escape/loss rate. Figure-1 depicts the LAP instrument flown in MOM spacecraft and table-1 presents salient features of the instrument.

FIG. 1: LAP instrument flown in MOM spacecraft

Table-1: Salient features of LAP instrument

Sl. No.	Parameter	Specification
1.	Operational Range	3,000 km – periapsis – 3,000 km
2.	Pointing Direction	Nadir, Limb and Exosphere
3.	Field of View	0.0016 steradians
4.	Dynamic Range	1 - 5 x 10^7 counts per second
5.	Gas Cells	Hydrogen, Deuterium
6.	Weight	1.97 Kg
7.	Power	7.2 Watt (P_{rms})
8.	Dimensions (LxWxH)	276 x 138 x 100.5 (mm)

3. Instrumentation and Challenges

The block diagram of LAP instrument with its sub-units is shown in Figure-2. As shown in the figure, LAP primarily comprises four functional units; *MHU* (Main Housing Unit), *ACU* (Absorption Cell Unit), *OU* (Optics Unit) and *DU* (Detection Unit). The MHU serves as a mounting base for all electro-optic modules of the instrument. The ACU consists of hydrogen and deuterium gas filled cells (H_2-cell, D_2-cell) with tungsten filament coils that can be electrically heated to dissociate the gases in to atoms. H_2-cell and D_2-cell are sealed and isolated from each other by means of MgF_2 windows. OU consists of an MgF_2 collection lens and a coarse Lyman-α filter. The choice of MgF_2 material for the lens as well as for cell windows is mainly due to the fact that this is the only optical material available at the wavelength of Lyman-α without deliquescence. The cylindrical baffle in front of the lens prevents stray radiation reaching the gas cells, while a coarse Lyman-α filter is used to cut-off the undesirable radiation that lies outside the wavelength range of interest. The DU consists of a UV-detector, detection and processing electronics modules. A significant aspect of this configuration is that the LAP detection unit was developed to operate in single-photon counting mode, which was best suited for the low-level incoming scattered flux from the Martian exosphere. The main sub-elements of the Detection Unit are the detector, charge sensitive pre-amplifier, pulse discriminator and time digitizer unit. Considering factors like size, quantum efficiency, speed of response and ease of use, a solar-blind side-on type UV-PMT was chosen as a detector. The resultant output current pulses from the detector are amplified and shaped. A current pulse corresponding to an incident photon is discriminated from noise pulses which have relatively low pulse heights compared to the signal pulses. The arrival time of the pulses was counted by a counter, the value of which was latched at every clock pulse and read by the processing unit.

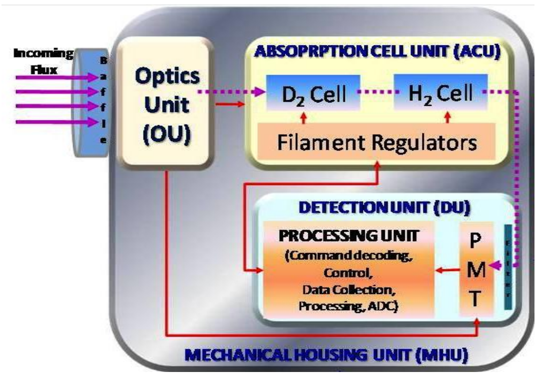

FIG. 2: A cartoon of LAP instrument configuration

The prime challenges of development are: a) realization of absorption gas cells, b) establishment of ultra-high vacuum (better than 10^{-9} Torr) baking, evacuation, gas filling and sealing techniques, c) realization of low-power consumption filament coils, d) design and realization of space-compatible high voltage electronics modules, e) realization of single photon counting detection and processing technique and f) calibration and characterization under ultra-high vacuum environments.

4. Operational Principle and Modes of Operation

As mentioned previously, the LAP instrument works on the absorption cell technique in which power is applied to the filaments to thermally dissociate the hydrogen or deuterium molecules into atoms that absorb the incoming hydrogen or deuterium Lyman-α radiation passing through cells. When the filament in the H_2-gas cell is turned on, the electrons emitted by the hot filament dissociate the hydrogen molecules to produce H atoms. These H atoms resonantly absorb a part of the incoming hydrogen Lyman-α radiation and transmit the remaining part. Similarly, when the filament in the D_2-gas cell is turned on, the electrons emitted by the hot filament dissociate the deuterium molecules to produce D atoms. These D atoms resonantly absorb the incoming deuterium Lyman-α radiation. Thus by turning on the filament of H_2 and D_2 gas cells alternately in a cyclic manner, the ratio of intensities (I_D/I_H) can be measured. The measured intensity ratio can then be used to estimate the isotope ratio i.e., D/H ratio. Figure-3 illustrates the concept of alternately turning on the tungsten filaments for measurement of D/H ratio.

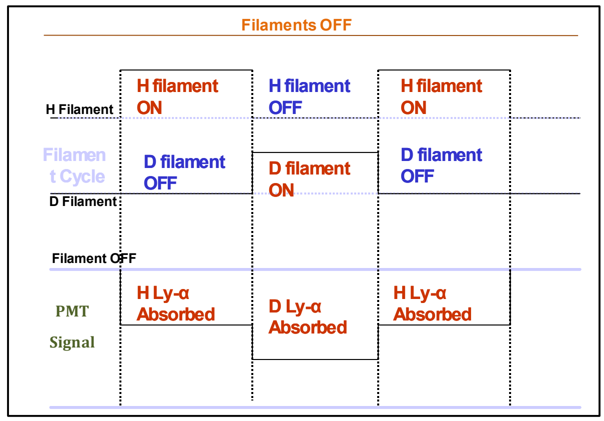

Fig. 3: The concept of alternately turning on/off the tungsten filaments of gas cells for measurement of D/H ratio

LAP can function in two modes i.e., *i) Photometer mode* in which the incoming line-of-sight photon flux within the spectral bandwidth of the Lyman alpha filter is measured without activating the filaments in gas cells. This mode of operation is useful to assess the hydrogen distribution as a function of altitude, *ii) Absorption cell mode* in which, filaments of deuterium and hydrogen gas cells are activated in a cyclic manner to record the relative signal contribution, from which the D/H ratio can be estimated employing the calibration and normalization factors derived from ground based experiments.

5. Experimentation and Performance Aspects

To validate the LAP design and to ensure its operation in Martian orbit, several system-level integration and interface tests are devised and performed. Prior to the instrument level testing and qualification, various kinds of calibration and characterization experiments are carried out in vacuum environment (pressure better than 10^{-5} Torr) at sub-system level. The major test activities were: i) filament stability and survivability along with its characterization in gaseous environment and ii) gas cell spectral absorption investigations. These tests helped to verify the filaments life for the expected on-board operational schedule and yielded calibration factors that to be employed during on-board data processing. Figure-4 shows such a photo-absorption profile of experimental D2-gas cell during its spectral calibration activity. Photo-absorption phenomena as a dip at 121.53 nm can be seen clearly from the gas cell when the set filament current was 465 mA.

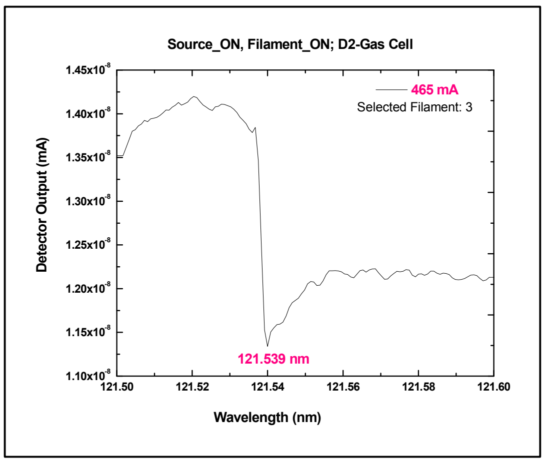

Fig. 4: Registered photo-absorption event in D2-gas cell

Gas cell photo- Cell calibration studies were carried out employing a 1.33 meter vacuum ultraviolet Czerny-Turner configuration based spectrometer that provides a spectral resolution of 0.004 nm. The input radiation source is deuterium lamp. Similar kinds of profiles were recorded during H2-gas cell photo-absorption investigations. These tests are attested the absorption signatures H2 and D2-gas cell at their respective Lyman-alpha wavelengths upon their filament turn_ON. In addition to the retrieval of calibration factors, optimization of filament current required during Martian orbit operations for LAP in 'absorption-cell mode' is devised by these experiments. Figure-5 shows the D2-gas cell calibration setup in the sample chamber of a UV-spectrometer.

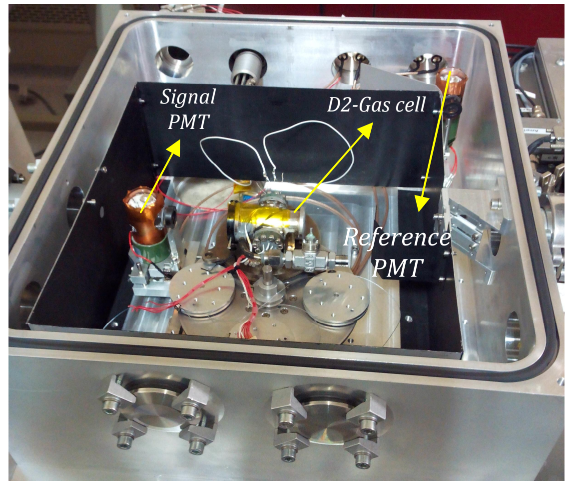

Fig. 5: D2-gas cell in the sample chamber of UV-Spectrometer

Upon the successful testing of sub-modules, all are integrated to the MHU of LAP instrument and is subjected for system level testing. LAP testing include functional (namely initial bench electrical tests), environmental (temperature vacuum cycling test, thermal soak test, vibration test) and end-to-end testing both at the instrument as well as spacecraft levels. Figure-6 shows the LAP instrument on vibration shaker during its acceptance level test subjecting to the frequency levels as defined by the mission (these vibration levels are equivalent to the expected levels experienced by the launch vehicle during launch). Instruments performance is verified by placing it in a thermo vacuum chamber and operated over several thermal cycles between temperatures (-10^0C to$+45^0$ C). To prevent corona and to ensure reliable operation, the instrument was soaked in vacuum before it was powered. After completion of functional, environmental and end-to-end tests, LAP instrument was integrated to the spacecraft and was tested successfully for its interface, functional and performance checks at various spacecraft-level tests.

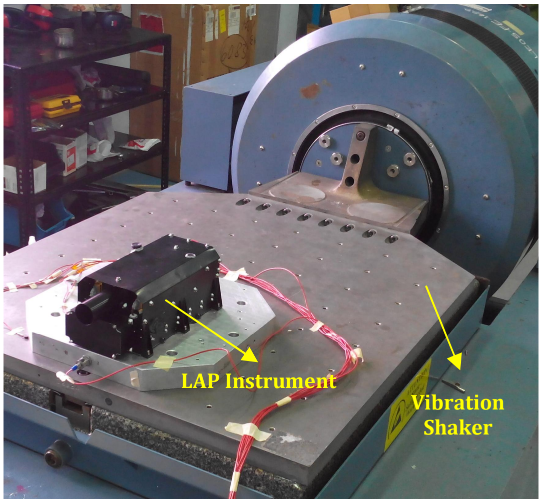

Fig. 6: LAP instrument on Vibration Shaker during it Qualification

6. Retrieval Scheme of Calibration Factors and D/H Ratio Estimation

As explained in previous sections, the hydrogen isotope ratio n_D/n_H can be directly estimated from the ratio of incident fluxes I_D/I_H (intensities received by LAP) of D-L_α and H-L_α. This ratio in principle is determined by measuring the ratio of absorbed intensities $I_{Abs,D}/I_{Abs,H}$. Here, $I_{Abs,D}$ and $I_{Abs,H}$ are the intensities absorbed by D2 and H2 gas cells respectively. The absorbed intensities are related to the respective optical depths τ_D and τ_H by the following relationships (Beer-Lambert law).

By mathematical simplification these relationships can be re-written as,

$$I_{Abs,D} = I_D\left[\tau_D - \frac{\tau_D^2}{2} + \frac{\tau_D^3}{6}\right]$$

$$I_{Abs,H} = I_H\left[\tau_H - \frac{\tau_H^2}{2} + \frac{\tau_H^3}{6}\right]$$

$$\frac{I_D}{I_H} = \xi\,\frac{I_{Abs,D}}{I_{Abs,H}}$$

$$\xi = \left[\frac{I_{Abs,H}}{I_H}\right] \Big/ \left[\frac{I_{Abs,D}}{I_D}\right]$$

Here, where ξ is defined as

$$\xi = \left[\tau_H - \frac{\tau_H^2}{2} + \frac{\tau_H^3}{6}\right] \Big/ \left[\tau_D - \frac{\tau_D^2}{2} + \frac{\tau_D^3}{6}\right]$$

Implying $\xi = \left[\frac{I_{Abs,H}}{I_H}\right] \Big/ \left[\frac{I_{Abs,D}}{I_D}\right]$

that i.e ξ is the ratio of absorption factors, that means, here

ξ = (H Absorption factor) / (D Absorption factor).

The quantity ξ is the calibration factor for the LAP instrument and is determined by recording the absorption factors of H2 and D2 gas cell during their photo-absorption investigations. The 'ξ' is employed in the estimation of Martian atmospheric D/H ratio from the recorded counts by the instrument employing following equation.

$$\mathbf{n_D / n_H = \xi\,(I_{abs,D} / I_{abs,H})}$$

The isotope Ratio is obtained from ratio of absorbed intensities, where

$I_{abs,D}$ (Intensity absorbed by D2- cell) =
I (H-cell off, D-cell-off) - I (H-cell,off, D-cell-on

$I_{abs,H}$ (Intensity absorbed by H2- cell) =
I (H-cell off, D-cell-off) - I (H-cell,on, D-cell-off

7. Summary of LAP Operations in Cruise and Mars Orbit Phase

LAP instrument is planned to be operated in tras-mars orbit and Martian orbit phases. As per schedule, the first on-board operation of LAP in trans-mars orbit phase was carried out on 6^{th} February, 2014 when MOM spacecraft was at a distance of approximately 1,57,04,605 kilometers from the Earth. Functionality checks and health parameters that were monitored during this operational phase attested good health condition of LAP instrument. After the successful insertion of MOM spacecraft in to the desired orbit, LAP instrument has been performing on-orbit investigations flawlessly. Useful scientific data sets are received and are currently under analysis. Analyzed data so far revealed successful registration of the Hydrogen Lyman-alpha brightness as well as clear Lyman-alpha flux absorption signatures of Martian atmosphere. Special operations are in progress to enhance the science yield. Analysis of all such data sets would be utilized in estimating the global average value of D/H ratio of Martian exosphere.

8. Conclusions

LAP kind of instrument is best suited to determine the D/H ratio of a planet's atmosphere, because hydrogen and deuterium gas cell acts as a perfect narrow-band rejection filter at their respective Lyman-alpha wavelengths upon the filament activation. From ISRO's perspective, this kind of instrument development is entirely novel. The performance of the realized instrument matched the desired specifications in all aspects and well within the allowable tolerance limits. LAP instrument is found to be in good health from its first on-board operations. The D/H ratio would be determined from the measured intensity ratio of deuterium to hydrogen during the Martian orbit observations. The determined D/H ratio would be employed further in assessment of the water escape rate.

9. Acknowledgements

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