Lyman Alpha Photometer: a far-ultraviolet sensor for the study of hydrogen isotope ratio in the Martian exosphere

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The Lyman Alpha Photometer (LAP), developed for flight on the Mars Orbiter Mission (MOM) spacecraft in 2013, is primarily designed to measure deuterium to hydrogen abundance ratio of the Martian exosphere over a 6-month period from a 263 km × 71,358 km elliptical orbit around Mars. A set of ultra-pure (99.999%) hydrogen and deuterium gas-filled cells comprising tungsten filaments, a 25 mm diameter collection lens and a solar-blind photomultiplier tube together with an 8 nm bandpass Lyman alpha filter are the principal electro-optical assemblies of the instrument. This article presents scientific objectives of LAP and its performance specifications along with details of instrument design. The ground characterization techniques to assess LAP operational performance are also presented. End-to-end test results and evaluation matrix of LAP were satisfactory, well within the desired specifications. The first LAP on-board operation was carried out during the cruise phase of MOM spacecraft journey to verify its functionality and all recorded on-board health parameters were satisfactory.

Keywords: Absorption gas cell, hydrogen isotope ratio, Martian exosphere, photometer.

Introduction

THE evolutionary history of planetary atmospheres especially of non-magnetic planets such as Mars depends on how well one can understand their atmospheric escape process for different gases. The current decade saw a rejuvenated interest in the exploration of Mars[1–6]. In late 2013, the first Indian mission to the red planet, i.e. the Mars Orbiter Mission (MOM)[7] was launched successfully and accomplished a meticulous insertion into the Martian orbit during September 2014. India's Mars Orbiter has placed five scientific payloads in an elliptical orbit with the objective of improving our understanding of the planet based on its morphology and mineralogy using two scientific instruments, namely Mars Colour Camera (MCC) and Thermal Infrared Spectrometer (TIS), and upper atmospheric studies using three scientific payloads, namely Methane Sensor for Mars (MSM), Lyman Alpha Photometer (LAP) and Martian Exospheric Neutral Composition Analyzer (MENCA). Owing to mild or no intrinsic magnetic field, the upper atmosphere of Mars is always exposed to solar wind[8–12] 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 abundance ratio (D/H ratio) are vital not only to understand the escape process operating currently, but to also infer the loss process of water in the evolutionary history of planet's atmosphere. Observations of D/H ratio measurements of Mars have revealed only local values at certain times or average values over the planet's atmosphere ($9 \pm 4 \times 10^{-4}$ by Owen *et al.*[13], $7.8 \pm 0.3 \times 10^{-4}$ by Bjoraker *et al.*[14] and 5×10^{-4} upper limit of D/H ratio by Korablev *et al.*[15]). Analysis of the SNC (shergottites, nakhlites and chassingnites) meteorites which are thought to have come from Mars also provided information of the D/H ratio as $8.1 \pm 0.3 \times 10^{-4}$ on the Martian surface[16]. 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.

In order to observe the spatial distribution and time variation of D/H ratio in planetary atmospheres, imaging of hydrogen and deuterium Lyman alpha 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 alpha lines are 121.566 and 121.533 nm respectively, and thus the separation between the two lines is quite small (0.033 nm). Therefore, a high-resolution spectroscopic technique is needed to separate the two lines. A standard UV spectrometer with a diffraction grating, however, is unsuitable for spacecraft

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*For correspondence. (e-mail: mvis@leos.gov.in) measurements because of its large size and heavy weight. Instead, hydrogen/deuterium absorption cells are superior with respect to size, weight and power consumption[17–21].

One of the scientific instruments of the MOM spacecraft payload suite is the LAP[22], which is essentially a compact far-ultraviolet photometer capable of providing D/H ratio of Martian exosphere from spacecraft observations. Comparison of the present and initial D/H ratios, estimated from observations in comets and asteroids ($3.1 \pm 0.3 \times 10^{-4}$ for comet P/Halley, $2.9 \pm 1 \times 10^{-4}$ for comet Hyakutake and $1.49 \pm 0.3 \times 10^{-4}$ for Earth)[23–25], 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 the lifetime of the planet.

LAP has been developed on the absorption gas cell-based photometry technique[26,27] and is the first Indian space-borne absorption gas cell photometer that operates on the principle of resonant scattering and resonance absorption. It comprises a set of tungsten filaments furnished with ultra-pure (99.999%) hydrogen and deuterium gas cells that serve as narrow-band rejection filters at their hydrogen and deuterium Lyman alpha wavelengths respectively. System design aspects are explained in detail elsewhere[22]. LAP can function in two modes: (i) Photometer mode in which the incoming line-of-sight photon flux within the spectral bandwidth (8 nm) 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, as MOM goes through different layers of the Martian atmosphere. (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. To validate the LAP design and ensure its successful operation on-board the MOM spacecraft, several instrument-level and integration tests were devised and performed. These include an operational test sequence of LAP to verify correct ‘end-to-end’ system operation and characterization of instrument performance. The test also provided information associated with operational peculiarities of LAP and was vital for the checkout of the instrument–spacecraft interface. Figure 1 shows the flight version of LAP that was integrated with the deck of the MOM spacecraft. Table 1 summarizes the salient features of the LAP instrument.

Figure 1. Flight model of LAP instrument flown on MOM spacecraft.

Science goals

Primary scientific objective of the LAP instrument is to determine the D/H ratio of the Martian upper atmosphere from the ratio of the measured Lyman alpha intensities. The observations would enable us to (i) generate spatial and temporal profiles of hydrogen and deuterium Lyman alpha intensities, (ii) study deuterium-enrichment in the upper atmosphere, and (iii) estimate water escape/loss rate.

Operation principle

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 alpha radiation passing through the 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 (fraction n_H/n_{H_2}). These H atoms resonantly absorb a part of the (within the field-of-view of LAP as given in Table 2) incoming hydrogen Lyman alpha 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 (fraction n_D/n_{D_2}). These D atoms resonantly absorb the incoming deuterium Lyman alpha 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.

Table 1. Salient features of LAP

Parameter	Specification
Operational range	3000 km – periapsis – 3000 km
Pointing direction	Nadir, limb and exosphere
Field-of-view	0.0016 steradians
Dynamic range	1–5 × 10^7 counts per second
Data rate	64 bps
Weight	1.97 kg
Power	7.2 W (P_{rms})
Dimensions (L × W × H)	276 × 138 × 100.5 (mm)

Table 2. LAP design parameters

Element	Parameter	Value (SI units)
Gas cell	Type	Metallic – (1 for H_2 gas and 1 for D_2 gas)
	Shape/material	Cylindrical/SS 316L
	Dimensions	60 mm (length) × 25 mm (diameter)
	Heater type	Nickel pin crimped tungsten coil/no. of turns: 30
	Specifications	Wire dia and coil length: 60 μm × 5 mm
	Cell windows/% of *T*	MgF_2 windows/50% T@122 nm
	Gases/gas purity	Hydrogen, deuterium/99.999%
	Gas pressure	0.74 torr
Collection optics	Type	Lens
	Substrate material	MgF_2
	Diameter/focal length	25 mm/160 mm
Lyman alpha filter	FWHM	8 nm
	Peak wavelength	122 nm
	Percentage of T	8
	Substrate material	VUV MgF_2
Detector	Type	Solar-blind, side-on PMT
	Spectral response	115 to 195 nm
	Photocathode/QE	Cs-I /QE: 23.5% @ 121.6 nm
	Effective area	4 mm (horizontal) × 9.5 mm (vertical)
Baffle	Shape/material	Cylindrical/Al 6061
	Dimension	75 mm (length) × 31 mm (diameter)

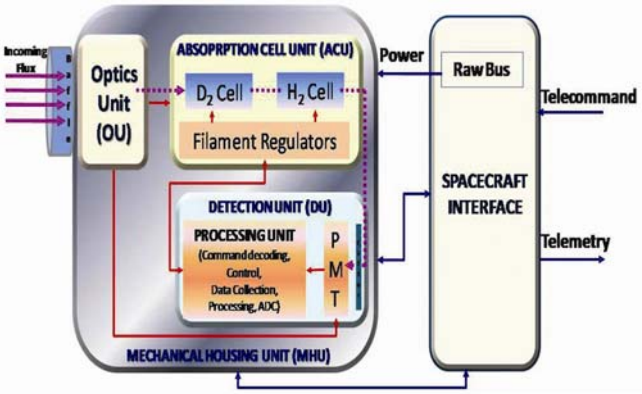

Figure 2. Block diagram of LAP with its subsystems.

System engineering and instrumentation

Instrument design and development choices were tightly constrained from the outset, principally by the schedule and spacecraft resources. Figure 2 shows the block diagram of LAP with its subsystems. The LAP payload primarily comprises of four functional units: MHU (main housing unit), ACU (absorption cell unit), OU (optics unit) and DU (detection unit). MHU is made up of black-anodized aluminum alloy (Al-6061) and serves as a mounting base for all electro-optic modules of the instrument. ACU consists of hydrogen and deuterium gas-filled cells (H_2-cell, D_2-cell) with tungsten filament heaters. OU consists of a collection lens and a coarse Lyman alpha filter, while DU consists of a photon-counting detector, and detection and processing electronics modules. The prime challenges of instrument 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) instrument calibration and characterization under ultra-high vacuum environments.

As shown in Figure 2, the incoming radiation is collected by a 25 mm diameter plano-convex lens of OU. The cylindrical baffle in front of the lens prevents stray radiation reaching the gas cells. The hydrogen and deuterium gas cells that were made up of stainless-steel alloy are resonance absorption cells filled with pure molecular hydrogen and deuterium gases (purity in the order of 99.999%) respectively, and contain nickel pin crimped tungsten filament coils that can be electrically heated to dissociate the gases into atoms. Quadruple redundancy was provided for tungsten filament coil in each gas cell and these coils were characterized and tested in vacuum as well as in gaseous environment for their performance. H_2-gas cell and D_2-gas cell were sealed and isolated from each other by means of MgF_2 windows using ultra-high vacuum single-component epoxy having low out-gassing, high peel and shear strength. The inner walls of the gas cell were coated with teflon to minimize recombination rate of the atoms with the cell walls. The choice of MgF_2 material for the lens as well as for the cell windows is mainly due to the fact that this is the only optical material available at the wavelength of Lyman alpha without deliquescence. Figure 3 *a* and *b* depicts the indigenously developed H_2-gas and D_2-gas cells. A coarse Lyman alpha filter of 8 nm bandpass with peak transmission wavelength of 122 nm was used to cut-off the undesirable

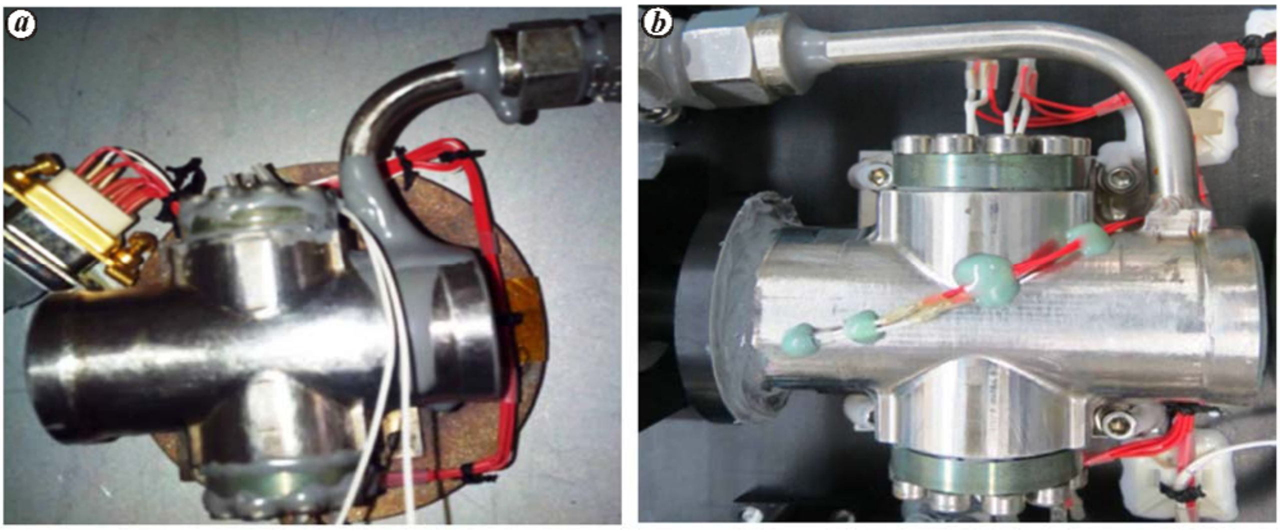

Figure 3. ***a***, Hydrogen gas cell (flight model). ***b***, Deuterium gas cell (flight model).

radiation that lies outside the wavelength range of interest. Table 2 gives the percentage of transmission (%*T*) of the filter. An ultraviolet (UV) sensitive photo multiplier tube (PMT) was used as the photon counting detector. Table 2 also presents the LAP design parameters. Following the fabrication of absorption gas cell, detection and processing electronics, integration and acceptance tests at the instrument level were taken up. The integrated LAP was subsequently tested and flight-qualified at both instrument and spacecraft levels. A significant aspect of our 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 DU 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 for LAP as a detector. The PMT detector was kept at the focus of the collection lens. The instantaneous field-of-view of the LAP instrument is 3.5°(v) × 1.5°(h). The resultant output current pulses from the PMT detector were amplified and shaped. A current pulse (≃500 mV) corresponding to an incident photon was discriminated from noise pulses (≃50 mV) which had 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. A 16-bit data command was implemented in the processing unit to cater to and control different modes and parameters of the LAP instrument during on-board operation.

Ground calibration experiments

Prior to the instrument-level testing and qualification, various kinds of calibration/characterization experiments were 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 verify the life of the filament for the expected on-board operational schedule and yielded calibration factors (from gas cell photo-absorption experiments) that need to be employed during on-board data processing. Figure 4 shows the trace of the filament life test that was carried out continuously for 120 h with a 2 sec ‘ON’ and ‘OFF’ duration in a 1.2 m vacuum chamber at a pressure level of 5×10^{-6} torr for maximum operating current of 500 mA. A small variation in filament voltage can be seen from the plot. A similar kind of test was carried out in the hydrogen/deuterium gas environment and filament was observed to withstand up to 11,000 cyclic operations continuously with a 5 sec ON and OFF interval. Figure 5 shows the filament characterization trace (i.e. filament temperature versus filament current) of H_2-gas cell that was mounted in the flight version of the LAP instrument. This characterization test provides the optimum filament current range required to accomplish effective thermal dissociation of gas present inside the cell. The inset of the figure shows the filament glow of the H_2-gas cell under test. All four filaments of the cell were characterized. The same procedure was followed for characterization of the D_2-gas cell tungsten filaments.

Gas-cell spectral calibration studies

The hydrogen and deuterium filled-gas cells were individually characterized for the photo-absorption studies with filament OFF and ON at various temperatures. The spectral characteristics were studied in the wavelength range 120–123 nm employing a vacuum UV spectrophotometer that offers a spectral resolution of less than 1 nm and reproducibility of 0.1 nm. The light source used for observations was a deuterium lamp. Figure 6 shows the typical transmission profile of D_2-gas cell captured at the best attained photo-absorption event. Cell-calibration studies were further carried out employing a 1.33 m vacuum UV Czerny–Turner configuration-based spectrometer that provides a spectral resolution of 0.004 nm. In addition to the retrieval of calibration factors, optimization of filament current required during on-board operations of LAP in ‘absorption-cell mode’ is achieved by these experiments.

LAP testing and performance analysis

LAP testing includes functional (namely initial bench test), environmental (thermal vacuum cycling test, thermal soak test, vibration test) and end-to-end testing, both at the instrument as well as spacecraft levels.

Functional testing

The functional testing and performance evaluation of integrated LAP instrument was carried out in a 1.2 m thermo-vacuum chamber. As shown in Figure 7, a RF-powered Lyman alpha source consisting of both hydrogen and deuterium emission wavelengths at equal flux levels was used as the light source. This light source was connected outside the chamber and aligned in-line to the optical axis of LP (inset, of the Figure 7 shows the worked-out test scheme of LAP at package level). LAP functionality and performance were verified for various combinations of operation, i.e. source OFF and filament

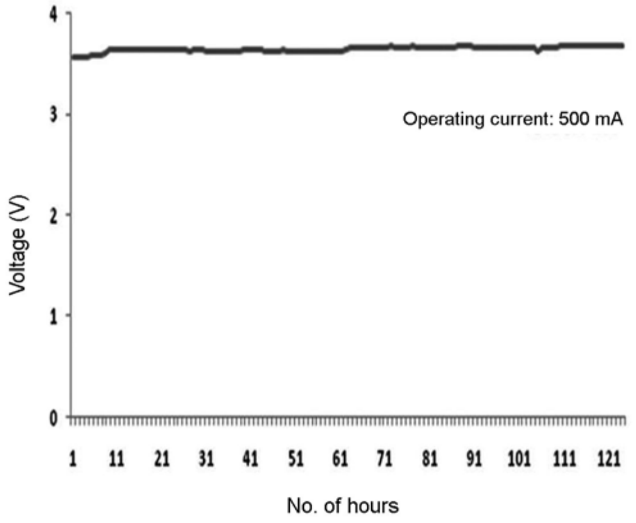

Figure 4. Life-test performance profile of tungsten filament coil in vacuum.

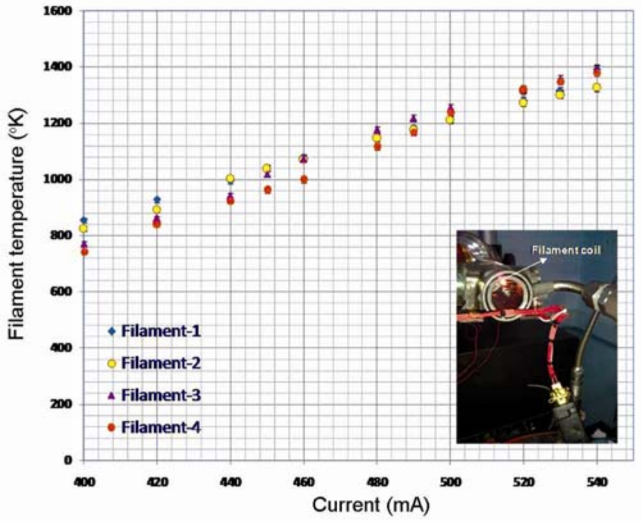

Figure 5. Characterization plots of tungsten filament coils of H_2-gas cell.

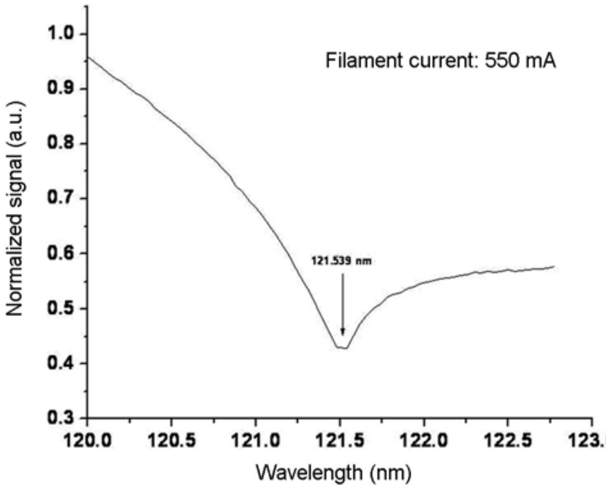

Figure 6. Spectral transmission profile of D_2-gas cell.

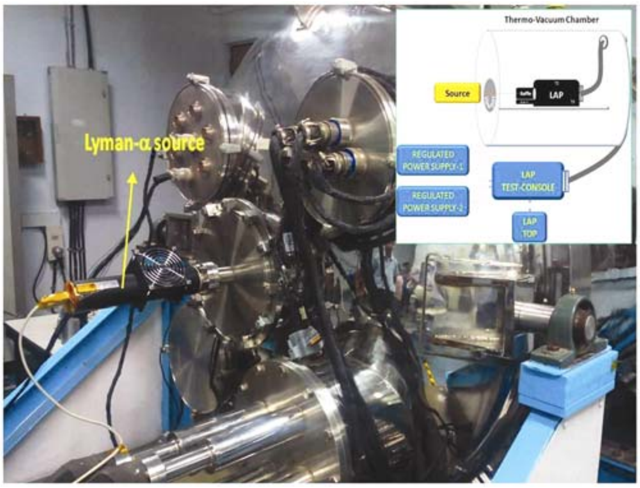

Figure 7. Test facility for LAP integrated performance checks (As shown in the inset LAP is placed inside the chamber and aligned inline to source axis).

OFF, source OFF and filament ON, source ON and filament OFF, source ON and filament ON and source heater set-point (source flux) versus response. All these activities were carried out with in-house built test console. The measured dark count was negligible or at the most 1–2 counts/sec and the LAP integrated system proved to be insensitive to the filament glow. One of the remarkable observations of the instrument at its integrated level was its dynamic range estimation (Table 1). Instrument response with respect to the incoming flux level was verified by changing the heater-set point of the light source. In addition to the above, the instrument interface with satellite subsystems like power, health checks, telecommand, telemetry, data handling, etc. was successfully carried out with in-built test console. The same test plan was followed to assess performance reliability of the instrument under various environmental conditions.

Environmental testing

LAP was subjected to rigorous environmental conditions. As mentioned above, the entire integrated instrument was placed in a thermo-vacuum chamber and operated over several thermal cycles between temperatures –10°C and +45°C. To prevent corona and ensure reliable operation, the instrument was soaked in vacuum before it was powered. All necessary instrument parameters at three temperature levels, –10°C, +25°C and +45°C were monitored. Only small thermal influence on the LAP performance was found over the entire temperature range. The instrument was then subjected to mechanical vibration test up to acceptance levels, which involved frequency-swept vibration levels, mechanically induced from 20 to 2000 Hz at a slope rate of 3 dB/octave. Filament cold resistance checks were performed during this test. Pre- and post-vibration performance tests yielded similar observations. After completion of functional, environmental and end-to-end tests, the LAP instrument was integrated to the spacecraft and tested successfully for its interface, functional and performance checks at various spacecraft-level tests.

Planned on-board operations

The LAP payload is planned to be operated in tras-Mars orbit and Martian orbit phases. According to the schedule, the first on-board operation of LAP in trans-Mars orbit phase was carried out on 6 February 2014, during the period 09:45:35 UT–10:03:02 UT, when the MOM spacecraft was at a distance of approximately 15,704,605 km from the Earth. Functionality checks and health parameters that were monitored during this operational phase attested to the good health condition of the LAP instrument. After the successful insertion of MOM spacecraft into the desired orbit, the LAP instrument has been flawlessly performing on-orbit investigations. Data downloading and processing are currenlty under progress.

Conclusions

Owning to the complexities and challenges involved, only a few space-agencies have been able to accomplish LAP-type of photometer development to study planets, e.g. Mars, Saturn and Venus. This type of photometer is best suited to determine the D/H ratio of a planet's atmosphere, because hydrogen and deuterium gas cells act as a perfect narrow-band rejection filter at their respective Lyman alpha wavelengths upon filament activation. From ISRO's perspective, this kind of instrument development is novel. The combined requirement of operating an instrument in deep space under strong design constraints contributes significantly to the complexity of instrument development. The performance of the realized instrument matches the desired specifications in all aspects and is well within the allowable tolerance limits. LAP functionality and performance have been evaluated to be normal and as expected during its qualification and integrated checks with the spacecraft. The LAP instrument was found to be in good health condition from its first on-board operation. The D/H atomic ratio can be determined from the measured intensity ratio of deuterium to hydrogen during the Martian orbit observations. The determined D/H ratio could be employed in assessment of the water escape rate.

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