MENCA onboard the Indian Mars Orbiter Mission

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Abstract

The MENCA (Mars Exospheric Neutral Composition Analyser) is one of the science instruments onboard the Mars Orbiter Mission, India's first mission to Mars. MENCA is a quadrupole mass spectrometer, and is also equipped with a Bayard Alpert gauge for total pressure measurements. The quadrupole mass spectrometer is being used to measure the exospheric composition of Mars. In this article, the theory of quadruple mass spectrometery is briefly discussed followed by description of the MENCA instrument. The various processes involved in the characterization and calibration of this mass spectrometer are also described.

1 Introduction

India's first interplanetary mission and the first Indian mission to Mars-the Mars Orbiter Mission (MOM, also known as Mangalyaan) was launched on 5 November 2013 by Polar Satellite Launch Vehicle in its 25^{th} launch (PSLV-C25). MOM escaped from Earth's sphere of influence on 5 December 2013 and after travelling for 10 months in Heliocentric orbit, was inserted into the Martian orbit on 24 September 2014, making India the first country to successfully inject a spacecraft into the Martian orbit in the first attempt. The MOM has successfully completed the planned mission lifetime of 6 months, and it is now continuing in the extended mission phase. Though the primary objective of this mission was technology demonstration, aiming to develop and demostrate the technologies for operations of an interplanetary mission including deep spae communication and incorporation of autonomous features, the satellite carried 5 science instruments to observe the red planet and its atmosphere. These instruments are: (1) Mars Color Camera (MCC) for obtaining images in the visible range, (2) Thermal Infrared Spectrometer (TIS) for mapping the surface composition and Minerology, (3) Lyman Alpha Photometer (LAP) to measure H-Lyman Alpha and the realtive abundances of D and H, (4) Methane Sensor for Mars (MSM) for detecting Methane in the atmosphere of Mars, and (5) Mars Exospheric Neutral Composition Analyser (MENCA) for the measurement of the exospheric neutral composition of Mars. In this article, we will focus on the MENCA instrument.

The MENCA is a quadrupole mass spectrometer-based instrument. In the context of MENCA, the physics of the quadrupole Mass Spectrometry is discussed in detail in section 2. In section 3, the specific feaures of the MENCA instrument are described along with some details about the characterisation and calibration of the mass spectrometer, which enables one to derive the absolute abudances from the observed mass spectra.

2 Mass Spectromety

Basically, mass spectrometers are ion optical devices that can transport, disperse and focus ions which are emitted by an ion source [1]. Mass spectrometers work on the principle that ions get deflected and gain or lose energy/charge (E/q) in electric fields and get deflected in magnetic fields by an amount proportional to their momentum per charge[1]. Basically, a mass spectrometer has three components, viz: *ion source*, *mass analyser*, and *ion detector*. The ion source ionizes the molecules and they are then accelerated to the mass analyser where they are separated according to their mass per unit charge (m/q), and some times according to energy also, by electric and/or magnetic fields. Finally, they are collected by the detector, and the output is an electrical current, which is amplified and detected. There are different methods for realizing a mass spectrometer. Some of these are as follows.

Quadrupole Mass Spectrometers: They are path stability spectrometers as they separate ions of different m/q by selecting only those ions which have stable trajectories in quasi-static electric fields (i.e., $\nabla^2\Phi = 0$, where Φ is the potential).

Ion Trap Mass Spectrometers: In Ion trap mass spectrometers ions are trapped by two end electrodes applied with DC and AC voltages making the ions oscillate in stable orbits. They are selectively thrown out of the cavity with respect to their mass-to-charge ratios and are subsequently detected.

Magnetic Mass Spectrometers: In these spectrometers, combinations of static electric and magnetic fields are used to focus ions of a particular m/q. A special configuration called *Double Focusing* is often used, where ions arriving from the ion source are first directed through an entrance slit and then they are focused in angle and dispersed in E/q using an electrostatic field. Then the ions enter a magnetic field, where they are dispersed according to momentum/charge and focused in energy and angle. Neutral gas is first ionized and then deflected first through an electrostatic filter and then a magnetic filter to a detector, and this double focusing gives a high mass resolution, for instance, it can sepearate N_2 from CO [2].

Time-of-flight Mass Spectrometers: In these spectrometeres, ions leaving the source are accelerated before entering the spectrometer and during their travel through the spectrometer, and they are dispersed in time according to m/q and then focused in time at the detector. The accurate measurement of the time of arrival yields a spectrum with mass discrimination according to m/q.

Mass Spectrometry has been a very useful experimental technique with wide range of applications. Among these instruments described above, quadrupole mass spectrometers gained popularity for space research (which requires rugged construction, high reliablity and high optimization in terms of weight and power), because of their compactness, mechanical simplicity, lightweight, absence of a cumbersome magnet, the linear mass scale, high speed scanning and relatively simple trading off between sensitivity and resolution. They are only limited by their moderate resolution and limited energy range. It may be noted that the usable energy range for the quadrupole spectrometer can be utilized for measurement of thermal paricles and hence sufficient for many planetary science applications, including upper atmospheric and exospheric compositon measurements.

The idea of using quadrupole fields for mass spectrometery was first proposed by Paul and Steinwedel at the University of Bonn, in the early 1950s. This work culminated in a paper on the quadrupole mass filter by Paul et al [3] followed by the construction of a 5.8 m long high resolution mass filter.

A quadrupole mass spectrometer consists of four rods with adjacent electrodes oppositely charged (Figure 1). The applied potential has two components, U and V, where U is the direct current (DC) component, and V is the radio frequency (RF) component, of the form V$cos(\omega t)$. The general form of the equation

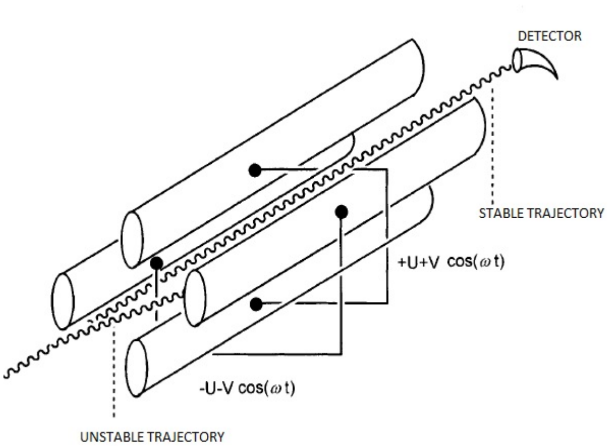

Figure 1: . Quadrupole rod system

of motion can be written as,

$$\frac{d^2u}{d\xi^2} + (a_u - 2q_u cos2\xi)u = 0$$

where

$$a_u = a_x = -a_y = \frac{4eU}{m\omega^2 r_0^2}$$

$$q_u = q_x = -q_y = \frac{2eV}{m\omega^2 r_0^2}$$

In this, u is the coordinate parameter and ξ is the time expressed in terms of $\omega t/2$.

This is the **Mathieu Equation** in the canonical form [4]. The solutions to this equation reveal that the nature of ion motion depends on a and q and not on the initial conditions. All ions with the same a and q values have the same periodicity of motion.

Furthermore, the solutions can be stable or unstable depending on a and q. For a given quadrupole geometry, r_0 is constant and ω is maintained constant. U and V are the variables. In principle, ω can also be varied keeping U and V constant, but frequency sweeping over extended range is very difficult to realize and is seldom used. For an ion of any mass, x and y can be determined during a time span as functions of U and V. Ions that are resonant with a given field will oscillate close to the z axis and are transmitted through en exit aperture located on the Z-axis. Non resonant ions will undergo unstable oscillations and will eventually strike the quadrupole rods or exit laterally, without entering the detector. The mass number corresponding to the stable trajectory can be changed by varying the magnitudes of U and V, and thus the mass scan can be realized. The mass spectrum thus obtained gives information about the relative abundances of various consituents in the ambience.

As mentioned earlier, mass spectrometers have been used extensively for studying the planetary atmospheres. Some of the early planetary explorations which included mass spectrometery experiments are the Apollo mission to Moon, Viking Mission to Mars and the Pioneer Venus mission. The Apollo-17 mission had a mass spectrometer, the Lunar Atmosphere Composition Experiment (LACE), which was physically deployed by the astronauts on the lunar surface which confirmed the existence of Helium and Argon in the lunar atmosphere [5]. Much of our knowledge about the ioonsphere of Venus was provided by the Ion Mass Spectrometer aboard the Pioneer mission [6]. The Viking landers carried Upper Atmospheric Composition Explorer mass spectrometers which provided data about the composition of the Martian upper atmosphere from 200 km to 120 km altitude [7]. The ChACE (Chandra's Altitidunal Composition Experiment) onboard the MIP (Moon Impact Probe) of India's Chandrayaan-1 mission had brought out several new aspects about the tenous surface bounded exosphere of Moon [8, 9]. Missions like the Cassini to Saturn and Rosetta to comet 67P/Churyumov-Gerasimenkoalso had sophisticated mass spectrometers [2, 10, 11]. The LADEE mission to Moon had a quadrupole neutral mass spectrometer which provided the first global characterization of He, Ar along with first observations of the diurnal variation of Ne in the lunar exosphere [12]. The ongoing MAVEN mission to Mars also carries a similar mass spectrometer [13], which is expeced to provide data on the upper atmosphere and exosphere of Mars, along with the MENCA aboard the Indian Mars Orbiter Mission [14].

3 MENCA

MENCA is a quadrupole mass spectrometer based instrument. The MENCA instrument consists of two major parts, viz. the sensor probe and the electronics. Figure 2 shows the MENCA instrument in its flight configuration. The mass range is 1-300 amu (programmable through telecommand) with unit mass resolution. Apart from having a quadrupole mass analyser, MENCA has a Bayard Alpert (BA) gauge to measure the total pressure, so that the absolute abundances

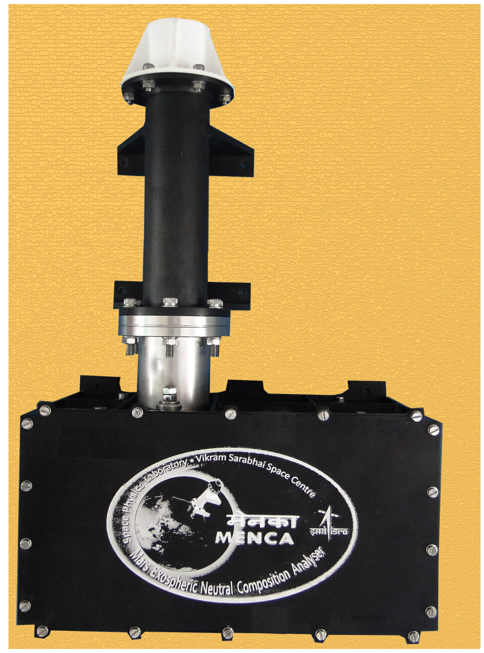

Figure 2: MENCA experiment aboard the Mars Orbiter Mission of India.

of the consituents can be derived from the observations. The BA gauge is operated at pressures below 10^{-4} Torr. The ambient neutrals are ionized by the energetic (typically 70 eV) electrons emanating from a pair of thoria coated iridium filaments operating in hot redundancy.

Within the ionizer region, there is a cylindrical region enclosed by a mesh of wires, known as source grid, which is maintained at a positive potential in order to repel the ions in the medium. The ions which are formed within the source grid region, are accelerated electrostatically along the axial direction by focus grids and enter the quadrupole mass analyser system. The mass discrimination takes place in the quadrupole system, as described in the previous section. The ions entering the detector generate a current which is proportional to the abundance of a partcular species. The MENCA has two types of detectors, viz. Faraday Cup and the Channel Electron Multiplier (CEM). The CEM detector is invoked for pressures lesser than 10^{-7} Torr since it has intrinsic current gain ($\sim 10^5$ for a bias voltage of 2000 V) to amplify the low currents corresponding to the trace constituents. This provides extremely low noise level, enhances the sensitivity in terms of detection of trace species and also facilitates faster mass scans. With both Faraday Cup and CEM, the dynamic range of the instriment is 10^{10}. In addition to Mass Scan mode, MENCA can be operated in Trend (of selected species) Mode wherein the instrument locks in to a set of preselected species and tracks their abundances.

The ionized neutrals which move outside the source grid are collected by a thin wire (BA collector) that is biased negatively to collect the ions situated in a well defined volume and the current is directly proportional to the pressure of the ambient gas. This gives the total pressure in the medium.

The main instrument parameters are as follows.

Emission current : The emission current is a measure of the flux of the thermionically emitted electrons from the filament, which is a part of the built in ion source.

Electron energy : The thermionic electrons are accelerated to 70 eV in order to ionize the ambient neutrals. The instrument has options to operate at other electron energies as well.

Ion energy: The positive ions that are created in the source grid region are directed axially through the quadrupole mass filter region to reach the detector with a potential applied axially.

During operations, several health check parameters are also monitored including power supply voltages, different internal temperatures as well as several digital telemetry parameters.

Several laboratory experiments under High Vaccum conditions (at Space Physics Laboratory, Vikram Sarabhai Space Centre) and Ultra High Vaccum conditions of 2×10^{-11} Torr (at the UHV division, RRCAT, Indore) were conducted in order to characterize and calibrate MENCA. In addition to the calibration under the residual gas enviornments, gas insertion tests were conducted using He, Ar, N_2 and CO_2 gases. Figure 3 shows a mass spectrum the prominent constituents in a residual gas environment and their dissociation products.

The Martian Orbit Insertion (MOI) was on 24 September 2014 and the MENCA instrument was commissioned in the Martian orbit on 29 September 2014. The high voltage commissioning was conducted in phased manner, which was completed on 8 October 2014. Prior to this, MENCA was operated in the Earth-bound phase and in the heliocentric phase for health check. MENCA has been operational in the Mars phase both near

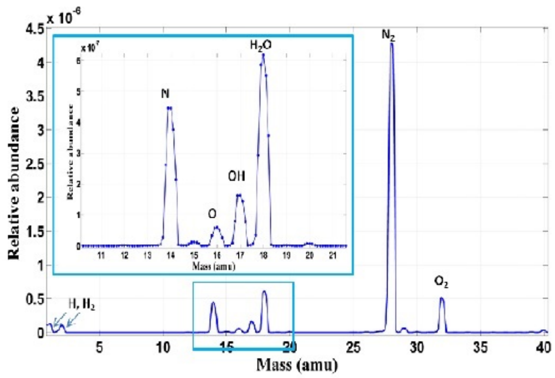

Figure 3: Mass spectrum of the prominent constituents in a residual gas environment and their dissociation products.

the periapsis and near the apoapsis, and the House Keeping (HK) parameters (temperatures, voltages) of the instrument are within the allowable ranges. Currently, the analysis of the MENCA data is in progress, and it is expected that the data would provide useful information about the exospheric consitutents of Mars and their variations.

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