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Pioneer Venus Orbiter Neutral Gas Mass Spectrometer Experiment

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Abstract

The Pioneer Venus Orbiter Neutral Mass Spectrometer (ONMS) is designed to measure the vertical and horizontal density variations of the major neutral constituents in the upper atmosphere of Venus. The mass spectrometer sensor includes a retarding potential ion source, hyperbolic quadrupole rod analyzer, and electron multiplier detector. The supporting electronic system consists of hybrid integrated circuits to reduce weight and power. The ONMS instrument was launched aboard the Pioneer Venus Orbiter on May 20, 1978, and turned on in orbit around Venus year (243 earth days) and has returned data of the composition of the major constituents in the Venus atmosphere between the altitudes of 150 and 350 km.

Introduction

The Objective Of the Pioneer Venus Orbiter Neutral Mass Spectrometer (ONMS) is to measure the neutral gas composition in the upper atmosphere of Venus between the altitudes of approximately 150 km to 300 km above the surface of the planet. Particle densities are determined for all major constituents and for some isotopes, with adequate spacial resolution to determine the horizontal and vertical variations of the constituents. Measurements of these variations are important when defining the dynamical, chemical, and thermal state of the upper atmosphere. Preliminary data and their interpretation have been published [1], [2]. In this paper we describe the instrument design and the measurement techniques employed.

Measurement Techniques

A quadrupole mass spectrometer equipped with an electron impact ion source is the sensor employed for the composition measurements. The basic instrument concept is derived from similar instruments used in the upper atmosphere of the earth from orbiting satellites [3]-[5] but incorporates a number of modifications to make it more suitable for the intended purpose. For example, a new retarding potential ion source was developed to allow direct sampling (no surface collisions) of reactive gases in the Venus atmosphere.

Fig. 1. Schematic cross-sectional view of the functional elements of the ONMS sensor.

A schematic diagram of the sensor is shown in Fig. 1. The major sensor components are the ion source, the quadrupole analyzer, and a secondary electron multiplier used as an ion detector. The ion source is enclosed, but exposed directly to the ambient atmosphere through small aperture. An ion repeller grid just inside the aperture is positively biased (approximately 40 V) to reject positive ions. The neutral particles not influenced by the ion repeller potential pass through an ionization region where a fraction is ionized by electron impact either during the first pass through the region or after being reflected once or several times from the inner surfaces. The grids enclosing the ionization region are electrically biased so that all ions produced are drawn through the retarding grid and the focussing grid to the ion lens system where an ion beam is formed by the ion lens system and directed into the quadrupole analyzer field for mass separation. The ion source structure differs considerably from conventional ion source designs, consisting of a combination of an especially structured electron beam gun and grid assembly and a strong focusing ion lens system. The grid assembly also functions as a miniaturized retarding potential analyzer for analyses of the direct streaming neutral particles.

Closed Source Operation

The relationship between the ambient particle density of a nonsurface reactive species no and the measured thermalized particle density in the ionization region ni is given by

$$\frac{n_i}{\;} = \left\{ \frac{T_o}{\;} \right\}^{1/2} F(s) \qquad (1)$$

$n_0 \quad \{ T_i \}$

and

$$F(s) = \exp(-s^2) + (p)^{1/2} s [1 + \mathrm{erf}(s)] \qquad (2)$$

where s is the ratio of the normal component of the satellite velocity to the ion source orifice and the most probable thermal velocity of the ambient gas. The kinetic temperature of the ambient gas is T_o and the gas temperature in the ionization region is T_i.

The ambient density and temperature are unknown quantities. The vehicle velocity and the angle of attack are obtained from spacecraft data. The kinetic temperature of the gas inside the ionization chamber is essentially equal to the surface temperature of the source electrodes because the gas accommodates to the surface temperature after a few collisions. To eliminate the ambient temperature in the equation it is in principle necessary to make two independent measurements, e.g., at two different angles of attack. In practice, however, at angles of attack smaller than 60+ the ambient temperature has only a very weak effect on the density relation, and it does not produce a measurable error in the density determination. The relationship between the particle density in the ion source n_i and the measured ion current is obtained by laboratory calibration.

The angle of attack dependence of the particle density in the ion source predicted by (1) is shown in Fig. 2. A strong mass dependent enhancement of the source particle density over the ambient particle density occurs which is accurately predictable. The weak angle of attack dependence (cosine function) makes this mode useful for measurements at large angles of attack. It also provides a sensitivity enhancement useful for constituents with low concentration. The contributions of ions coming from direct streaming particles in the focused ion beam is negligible in this mode since surface reflected particles pass the ionization region many times before leaving through the entrance aperture and therefore increase the probability of ionization accordingly.

Open Source Operation

In the open source mode as in the closed source mode, free streaming and surface reflected particles are ionized by the electron beam in the ionization region of the source. The potentials of the electron beam enclosing grids, however, are equal, providing a field free drift space. Since the momentum of the particles is not significantly changed in the ionization process, ionized particles will continue along the path followed prior to ionization. Taking advantage of the large relative kinetic energy of the free streaming particles with respect to the probe, a retarding field caused by a positive potential applied between the retarding grid and the drift space is employed to discriminated between the surface reflected and the free streaming particles. The ions produced from thermalized surface reflected particles are rejected because their kinetic energy is too small to overcome the retarding field. The rejected ions will collide with the instrument surface

Fig. 2. The dependence of the ion source particle density on angle of attack for the closed source mode. The satellite velocity if 9.8 km/s and the ambient temperature is 300K.

and be neutralized. Ions with enough kinetic energy to overcome the retarding field are focused by the ion lens system into the quadrupole mass analyzer for exact mass selection.

The ion current, Ii, resulting from free streaming particles can be predicted using kinetic theory

$$I_i = (1/2)n_0 \left\{ 1 + \mathrm{erf} \left\{ \frac{E_{pi}^{1/2} - E^{1/2}}{E_0^{1/2}} \right\} \right\} G \qquad (3)$$

where E is the retarding energy, Ep is the average kinetic energy of the particle relative to the spacecraft motion, Eo is the thermal energy (kTo) of the ambient particles, and G is the ion source sensitivity which is determined by the electron beam current, the ionization cross section of the gas to be analyzed, and the transmission factor of the ion optics. The sensitivity is determined either by laboratory calibration using high velocity molecular beams or in flight by comparing measurements made on nonreactive species in both operating modes. The angle of attack dependence is strongly influenced by the efficiency of the ion optics. This is illustrated in Fig. 3(a) where flight data are shown for atomic oxygen measured in the open source mode over several spacecraft spin periods at periapsis. For comparison closed source data obtained for CO2 are shown for the same spin periods in Fig. 3(b).

The functional dependence of the ion current on the particle mass and the retarding energy is shown in Fig. 4. The ordinate is normalized to the ambient density, the ionizing electron beam current, and the ionization cross section. A probe velocity of 9.78 km/s normal incidence is assumed. Retarding curves for H2, He, N, O, N2, O2, Ar, and CO2 are shown in the figure. Also shown is a retarding curve (lower left hand corner) of thermal ions of 300 K kinetic temperature.

Fig. 3. (a) Atomic oxygen (mass 16) variation in the open source mode with angle of attack obtained at periapsis on orbit 186.

(b) Carbon dioxide (mass 44) variation in the closed source mode with angle of attack also obtained at the same time as the data in (a).

Fig. 4. The dependence of the normalized ion current on the retarding potential. Solid lines are normal incidence, dotted lines are at 10 deg. angle of attack.

These curves illustrate that energy discrimination can easily be maintained even for very light constituents. The retarding voltages suitable for the individual masses are indicated in the figure on the abscissa. They are programmed together with the bias potentials which affect mass selection in the quadrupole mass filter. The dotted curves illustrate the case when the angle of attack is 10+.

Instrument Description

A cross-sectional view of the sensor housing showing the arrangement of the sensor electrodes is given in Fig. 5. An exploded view indicating the mounting of the electronics boards is shown in Fig. 6, and a block diagram of the electronic system is shown in Fig. 7.

The sensor housing is thin walled stainless steel and is bakeable to 350+C for vacuum cleanup. A small getter pump is provided as part of the mass spectrometer housing which helped to maintain the mass spectrometer below 10-6 torr pressure during launch preparation and cruise. The ion source is covered by a metal-ceramic break-off cap which is removed by a pyrotechnic actuator after orbit insertion. The quadrupole mass filter consists of hyperbolically contoured rods 7.5 cm long with a field radius of 0.2 cm. The rod contours are precision ground to an accuracy of 0.0002 cm. The secondary electron multiplier is a copper beryllium 14 dynode box and grid design. The electronics is packaged around the cylindrical spectrometer tube on a concentric structure fabricated from magnesium. All low power electronic components, about 80 percent of the total, are packaged in hybrid form to save weight and space. The average power consumption of the instrument is 12 W. The instrument is mounted on the spacecraft instrument platform via a wedge shaped crate with its axis pointing 27+ off the spacecraft spin axis. This aligns the instrument axis directly with the ram direction once every spin period near periapsis. The weight of the instrument is 3.8 kg including 0.4 kg for the break-off cap assembly which was ejected after orbit insertion.

The ion source is equipped with two electron beam guns to provide redundancy in case of filament burnout. The energy of the ionizing electrons can be switched by ground command to two levels -70 eV and 27 eV. This is needed to aid in the identification of complex mass spectra by observing the fractionated mass peaks at both energy levels.

Fig. 5. Cross-sectional drawing of the mass spectrometer sensor.

Fig. 6. Exploded view of the instrument showing the mounting of the printed circuit boards and approximate size of the instrument.

The mass peaks produced by the precision hyperbolic quadrupole rod assembly have flat tops which permit stepping from mass unit to unit without requiring peak searching. Mass selection in the quadrupole mass spectrometer is achieved through application of proper combinations of ac and dc voltages to the analyzer rods which allows transmission of ions through the analyzer with a specific mass to charge ratio only. Specific masses are selected by stepping the ac and dc voltages. Resolution is determined by the ratio of the ac amplitude to the dc potential. Preselected masses are tested in sequence by stepping the analyzer potential from mass to mass so that no measurement time or telemetry bandwidth is spent on the flanks and in the valleys between the peaks. The experiment programmer driven by the spacecraft clock furnishes an amplitude command to the RF generator which corresponds tot he selected mass. The RF generator is free running and the amplitude stability is achieved by feedback control. The mass to charge ratio (mass number) can be programmed to scan individually any 8 selected mass numbers (0 to 46 amu), to scan sequentially 0 to 46 amu at unit increments (search mode) or to scan sequentially 0 to 46 7/8 amu at 1/8 amu increments (diagnostic mode). On addition, the RPA mode can

Fig. 7. Block diagram of the electronics system of the Neutral Gas Mass Spectrometer.

be set to retarding, nonretarding, or alternate for each mass number selected. Commandable options exist also to change filaments and electron energy, retarding grid potentials, tuning and resolution in the mass analyzer, secondary electron multiplier high voltage, and discriminator threshold of the pulse counter as well as to set up the various mass and RPA modes described previously.

The ions existing the analyzer are deflected into the entrance aperture of a secondary electron multiplier by a pair of electrodes. The secondary electron multiplier operates as a charge converter and amplifier and provides a large negative charge pulse at the multiplier anode for each ion impacting the first dynode of the multiplier. The charge pulses at the anode are amplified by a wide-band pulse amplifier and counted. The count rate is proportional tot he particle density in the ion source and therefore a measure of the ambient concentration of the analyzed constituent. At high signal levels where the counting system has a significant dead-time, the anode current at the multiplier is used as a measure of the ion current. The dynamic range of the instrument is greater than 106.

The basic instrument data are the pulse counter or electrometer output for a given mass and ion source mode. Auxiliary data in the form of monitors of the more important supply voltages, current etc. complete the telemetry output. the integration period of the pulse counter (and hence the number of samples per second) depends on spacecraft telemetry format (3 possible) and bit rate (12 possible) and is limited to a maximum of 0.172 s. The instrument samples at equally spaced intervals for all spacecraft spin phase angles or only within about +45+ with respect to the occurrence of velocity ram. In the latter case the sampling rate is four times the normal rate and the data are read into a 4 k bit solid state memory to be transmitted by telemetry at the normal spacecraft rate.

Calibration

Preliminary sensor testing was done with a low energy (0-25 eV) ion beam source on a high vacuum system. The source was used to evaluate the angle of attack variation and retarding characteristics in RPA mode. The ion beam test mode can be successfully used with the sensor filament off and the external ion repeller grids grounded since the ion source uses a nonmagnetically confined electron beam. After mating of the sensor and its flight electronics, operational parameters were finalized and a gas calibration performed over the pressure ranges expected. This established the overall relationship between the thermalized particle density in the ionizing region of the sensor and the electronics telemetry output. Gas calibration pressures for CO2, O2, N2, A, and He were generated with an estimated error of +2 percent in the chamber on which the sensor was mounted. Sensitivity values for CO and NO were estimated from ionization cross section.

The instrument has been in operation in orbit around Venus since December 4, 1978. It has yield the first detailed data of the neutral gas composition of the upper atmosphere of Venus. The results have shown that the dual approach of retarding potential and closed source operation is an effective measurement technique.

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