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FIRST IN SITU PLASMA AND NEUTRAL GAS MEASUREMENTS AT COMET HALLEY: INITIAL VEGA RESULTS

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ABSTRACT

This paper presents the first in situ observations and a description of the large scale behavior of comet P/Halley's plasma environment. The scientific objectives of the PLASMAG-1 experiment were: i) to study the change of plasma parameters and distributions as a function of cometocentric distance; ii) to investigate the existence and structure of the cometary bow shock; iii) to determine the change in chemical composition of the heavily mass loaded plasma as the spacecraft approaches the comet; and iv) to measure the neutral gas distribution along the spacecraft trajectory.

АННОТАЦИЯ

В статье приводятся результаты первых измерений "in situ",проведенных в плазменной среде кометы Галлея,и дается их интерпретация. Научной целью эксперимента ПЛАЗМАГ-1 было поставлено:i) исследование изменений параметров плазмы и распределения частиц в зависимости от расстояния от кометы; ii) исследование структуры "bow-shock" кометы; iii) исследование изменений химического состава плазмы, обогащенной тяжелыми ионами, во время сближения с кометой; iv) исследование распределения нейтрального газа вдоль траектории космического аппарата.

KIVONAT

Ez a cikk a Halley üstökös plazmakörnyezetében végzett első in situ méréseket és azok értelmezését adja. A PLASMAG-1 kisérlet tudományos célkitűzései a következők voltak: i) a plazmaparaméterek és részecskeeloszlások változásának vizsgálata az üstököstől való távolság függvényében, ii) az üstökös bow-shock-ja szerkezetének vizsgálata, iii) a nehézionokkal erősen feldusult plazma kémiai összetétele változásának meghatározása az üstökös megközelitésekor, iv) a semleges gáz eloszlásának vizsgálata az ürszonda pályája mentén.

The VEGA probes carried a plasma instrument package called PLASMAG-1 of six different sensors [1-2]. Two hemispherical electrostatic analyzers observed the energy spectra of ions arriving from the S/C-comet relative velocity direction and from the direction of the sun. These sensors will be referred to as Cometary Ram Analyzer (CRA) and Solar Direction Analyzer (SDA), respectively. Because of the three-axis stabilization of the spacecraft electrostatic lenses were installed at the entrance slit of both ion analyzers in order to widen the acceptance angle without decreasing the energy resolution. The CRA had an acceptance angle of $14^{O}x32^{O}$ and detected ions in the energy/charge range of 15-3500 eV/eQ (where Q is the charge state) in 120 logarithmically spaced intervals providing a complete coverage of this range without any gaps. The SDA had an acceptance angle of $38^{O}x30^{O}$ and measured ions in the range of 50-25000 eV/eQ in 60 logarithmically spaced energy intervals. All acceptance angle data presented refer to the 10% level. For the same level, the energy resolutions of both CRA and SDA were $\Delta E/E = 0.055$.

A cylindrical electrostatic Electron Analyzer with an acceptance angle of $7^{O}x7^{O}$ was oriented perpendicular to the ecliptic plane. It had 30 logarithmically spaced intervals with $\Delta E/E = 0.075$ in the energy range of 3-10000 eV.

The energy spectra of the ions and electrons were continuously measured at a rate of 1/second for about 4 hours, beginning 3 hours before closest approach to the nucleus. During the two days before and one day after closest approach spectra were continuously determined at a rate of 0.35/minute.

The PLASMAG-1 experiment package also included two Faraday cups. The Solar Direction Faraday Cup with an acceptance angle of $84^{O}x84^{O}$, measured the solar wind ion flux. The Ram Faraday Cup (RFC), with an acceptance angle of $25^{O}x25^{O}$, had 4 periodically changed modes of operation. Two of them provided information on the neutral particle flux from the comet, by measuring the secondary electrons produced by neutrals impacting on the metallic emitter.

An impact plasma detector, for measuring neutral particle flux, was also integrated into the PLASMAG-1 scientific package. This detector was similar to the one developed by Dr. R. Grard at ESTEC for the GIOTTO mission. These results will be published elsewhere.

Figure 1 shows a schematic overall representation of the various plasma regions observed during the comet encounters by VEGA-1 and -2. On the inbound legs both SDA's measured a relatively hot solar wind ($u \approx 580$ and 620 km/s, respectively). The first sign of the comet was detected by the CRA, which observed ions of cometary origin as far as 5×10^6 km from the nucleus.

At the spacecraft approached the bow shock region, disturbances started to appear in the solar wind plasma distributions. In *Figure 1*, thin wavy lines mark the regions where these disturbances were observed. At a distance of about $1.1 - 1.2 \times 10^6$ km from the nucleus both VEGA spacecraft encountered a broad (~ 100000 km), heavily structured bow shock region and then entered the "cometosheath". At the shock the solar plasma flow became decelerated and the proton distribution broadened significantly, so that the peak of α-particles became indistinguishable in the energy spectrum. The direction of the plasma stream was no longer antisunward as both the CRA and SDA detected proton fluxes approximately of the same energy. VEGA-2 observed some oscillations in the direction of the plasma flow. Protons sometimes disappeared from the SDA spectra and appeared in the CRA spectra and vice versa.

On the outbound leg VEGA-1 observed a broad, eroded bow shock region at a cometocentric distance of about 1.1×10^6 km before reentering the solar wind ($u \approx 380$ km/s).

Figure 2 presents 2-minute averages of the high resolution SDA spectra measured by VEGA-1 during the four hours of high speed data transmission at the encounter. At a distance of about 800000 km (0420 UT) from the nucleus a single broad peak dominates the spectra, corresponding to a shocked solar wind proton flow with a velocity of about 350-400 km/s. Closer to the nucleus a second peak appears in the SDA spectra which corresponds to a much higher energy than that of the solar wind protons. It is obvious that this second peak is produced by cometary ions (probably of the H_2O group) since solar wind ions never have such a high energy.

At a cometocentric distance of about 300000 km (0615 UT), the solar wind proton population becomes comparable to the cometary implanted ions. Based on *Figure 2* and on the VEGA-2 data, one can conclude that around 150000 km (0645 UT) from the nucleus, the original solar wind population effectively disappears from the solar direction. Here the SDA observes mainly a broad distribution of slow cometary ions. This region can be called the "heavy ion mantle" where the plasma is still slowly moving around the cometary obstacle. Shortly after this region at a cometocentric distance of about 100000 km (0700 UT), the SDA stops observing particles. On the outbound pass, the cometary ions reappear in SDA first at about 70000 km (0735 UT) from the nucleus, then the shocked solar wind protons can be observed again.

Figure 3 shows 2-minute averages of the high resolution spectra obtained by the VEGA-2 CRA starting at about 800000 km (0420 UT) from the nucleus, i.e., well downstream of the bow shock region. Between 800000 km and about 150000 km (0645 UT), the CRA observed a broad distribution of decelerated proton population. These particles are probably diverted solar wind protons with largely randomized velocities which were observed simultaneously by the SDA. In this region signatures of heavy cometary ions can be seen in the upper part of the measured energy range. Simultaneous SDA data (not shown here) indicate that at about 150000 km from the nucleus the solar wind proton population is replaced by a slowly moving layer of heavy cometary ions which has been called heavy ion mantle.

At about 100000 km (0655 UT), the spacecraft entered the cold, almost standing or only very slowly moving cometary ion region which is characterized by increasing ion fluxes in the 300-3000 eV/eQ range. This region is inhomogeneous; extended stratified zones with layers of regularly varying densities (corresponding to a characteristic length along the orbit of about

800 km) were observed. At a cometocentric distance of about 18000 km the CRA detected only cold cometary ions and it is possible to carry out a mass analysis of these heavy ions. Unfortunately, afterwards the plasma instrument became temporarily disabled by the harsh cometary environment.

A blow-up of several successive 1-second spectra as measured by CRA in the cometary plasma region is shown in *Figure 4*. The first peak is due to H^+ ions. Their energy corresponds to about 30 eV, indicating a velocity which is around the relative velocity of V_R = 76.78 km/s. This indicates that the cometary plasma is "cold", i.e., both the bulk and thermal velocities of these ions are much smaller than V_R. The peaks of the other ions then correspond to $E/Q = 30.55 \cdot M$, where M is the mass. Under the assumption that these ions are predominantly singly charged, the CRA energy spectra depicted in *Figure 4* can be used for mass spectrometry.

From *Figure 4*, H^+, C^+, $CO_2{}^+$, and Fe^+ ions can be identified with great confidence. The major peak at $14 \leqslant M/Q \leqslant 20$ most probably originates from H_2O parent molecules with some possible contribution of CH_4 and NH_3. There are two secondary peaks at M = 16-17 and M = 19, possibly corresponding to O^+, OH^+ and H_3O^+ ions, respectively. The situation is more complicated with the $24 \leq M \leq 34$ peak which probably originates from several parent molecules such as CO/CO_2, N or S-bearing molecules.

Figure 4 is based on channeltron counting rates which reach the level of about 8×10^5 counts. s^{-1} (near saturation) at the major peaks. At such rates the channeltrons which were used operate in a nonlinear regime: significant flux increases result in only small counting rate changes. This effect will be taken into account in later publications.

Figure 5 presents two typical electron spectra; one was measured deep in the cometary plasma region while the other was obtained two days later in the interplanetary space. A major difference between the two spectra is the appearance of a very energetic (few keV) electron population. These electrons might be an additional effective source of ionization in the coma.

Figure 6 presents a preliminary neutral gas density profile determined from the RFC data. When estimating the neutral density values a secondary electron yield of 0.3 was assumed for impacting neutral particles with a velocity of ~ 80 km/s.

The dashed line in *Figure 6* represents a simple fit to the data assuming an r^{-2} exp $(-r/\lambda)$ neutral density dependence on the cometocentric distance r. The ionization scale length λ was estimated to be 2×10^{6} km while a value of 1.3×10^{30} molecules/s was obtained for the total gas production rate, assuming a neutral gas velocity of 1 km/s.

Data shown in *Figure 6* were obtained during the inbound pass of VEGA-1 fly-by. On the outbound leg of VEGA-1 a more complicated neutral gas density distribution was observed indicating significant spatial/temporal deviations from a simple r^{-2} dependence. In our opinion, the uncertainty of our preliminary analysis is about a factor of 2 to 3.

As discussed above both VEGA spacecraft crossed a wide and structured bow shock region at about 1.1×10^{6} km from the nucleus. This bow shock is not the result of a dynamic compression of the solar wind at a "hard" obstacle, but it is rather produced by the continuous mass loading of the solar wind by newly created cometary ions [3-7]. It was found that the mass loaded shocked plasma flow is dynamically controlled by the solar wind between the bow shock and the "cometopause", observed at a distance of about 100000 km from the nucleus which separates the solar wind controlled cometosheath and heavy ion mantle from the magnetized [8] cometary plasma region. This magnetized cometary plasma region in effect behaves as an obstacle to the mass loaded solar wind flow. This volume, which is controlled by the comet, is much larger than theoretically predicted [3-4]. According to earlier theoretical calculations only the plasma region inside the contact surface is dynamically detached from the solar wind. The relative contributions of the magnetic field and the various plasma components to the pressure balance across the cometopause will be the subject of a follow-up study.

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FIGURE CAPTIONS

Figure 1. The plasma environment of comet P/Halley as observed by VEGA-1 and VEGA-2

Figure 2. 2-minute averages of high time resolution energy spectra of ions measured by the Solar Direction Analyzer of VEGA-1 during encounter

Figure 3. 2-minute averages of high time resolution energy spectra of ions measured by the Cometary Ram Analyzer of VEGA-2 during encounter

Figure 4. 1-second energy spectra of the Cometary Ram Analyzer of VEGA-2 measured at a distance of 18000 km from the nucleus

Figure 5. Electron energy spectra measured in the solar wind (March 11) and at a distance of 18000 km from the nucleus (March 9)

Figure 6. Neutral gas density profile determined from the Ram Faraday Cup data

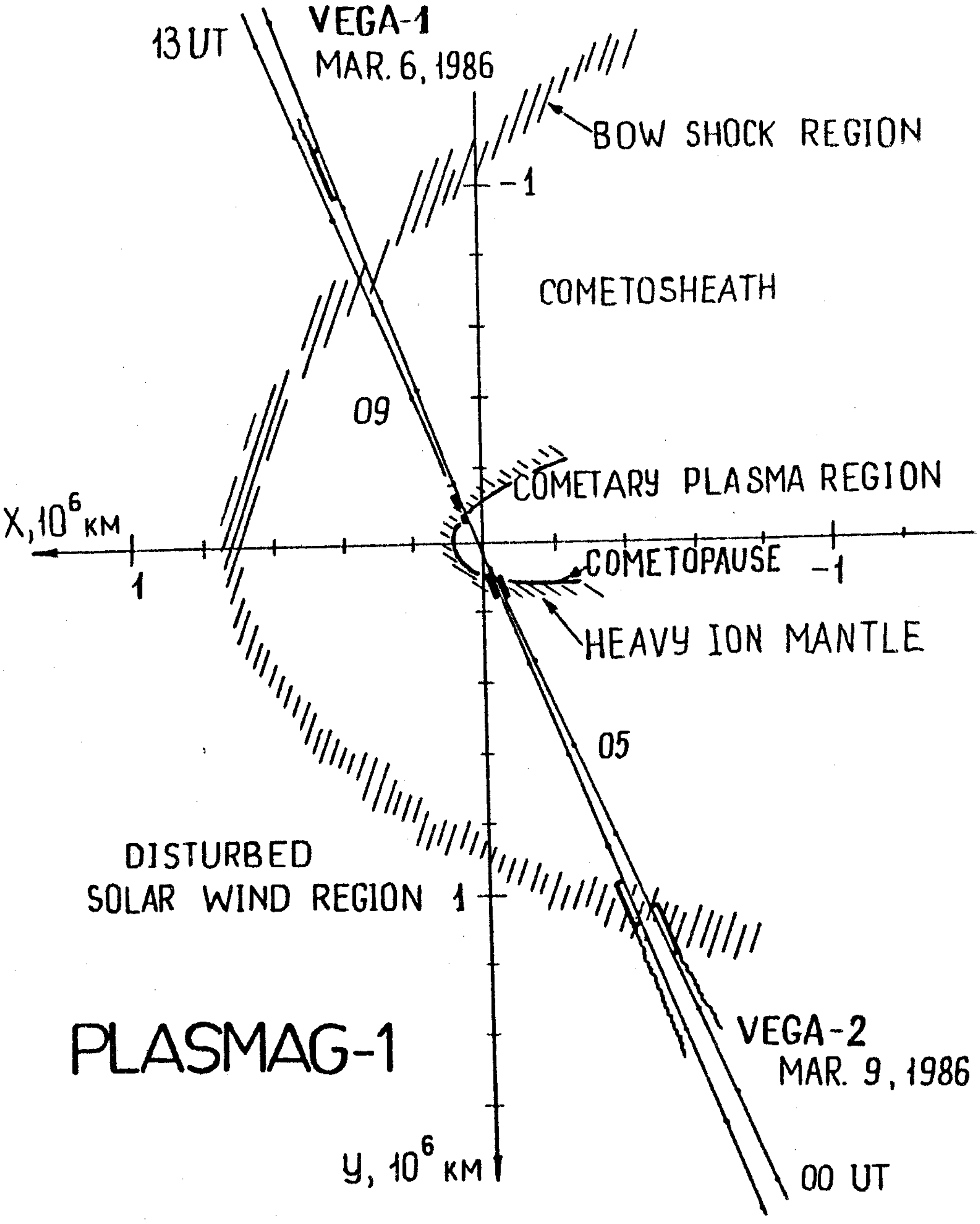
13 UT
VEGA-1
MAR. 6, 1986
BOW SHOCK REGION
-1
COMETOSHEATH
09
COMETARY PLASMA REGION
X, 10^6 KM
1
COMETOPAUSE
-1
HEAVY ION MANTLE
05
DISTURBED
SOLAR WIND REGION
1
PLASMAG-1
VEGA-2
MAR. 9, 1986
y, 10^6 KM
00 UT

Figure 1

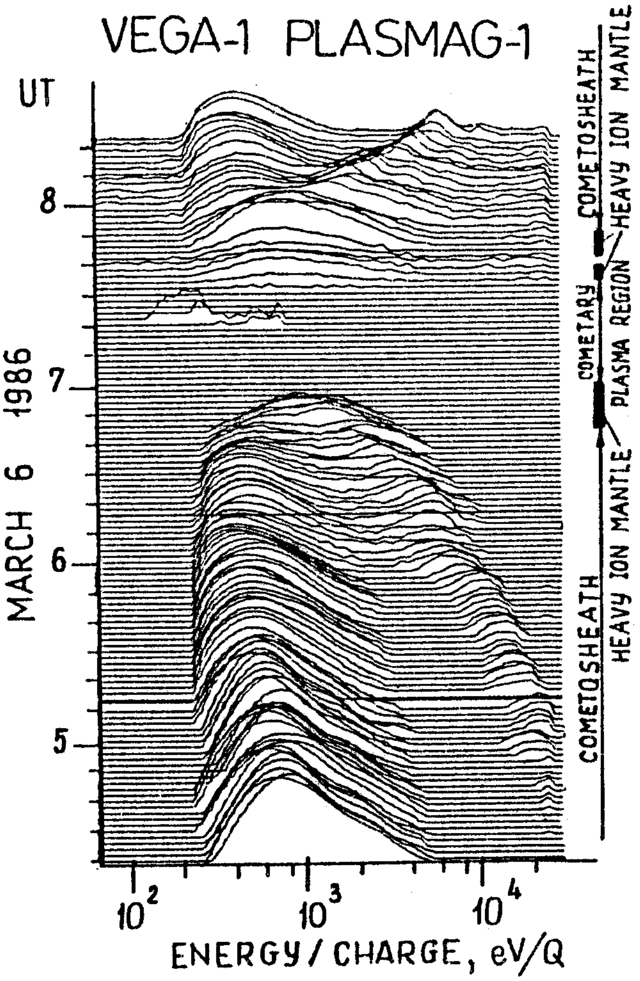
VEGA-1 PLASMAG-1
UT
8
7
6
5
MARCH 6 1986
10^2
10^3
10^4
ENERGY / CHARGE, eV/Q
COMETOSHEATH
HEAVY ION MANTLE
COMETARY
PLASMA REGION
HEAVY ION MANTLE
COMETOSHEATH

Figure 2

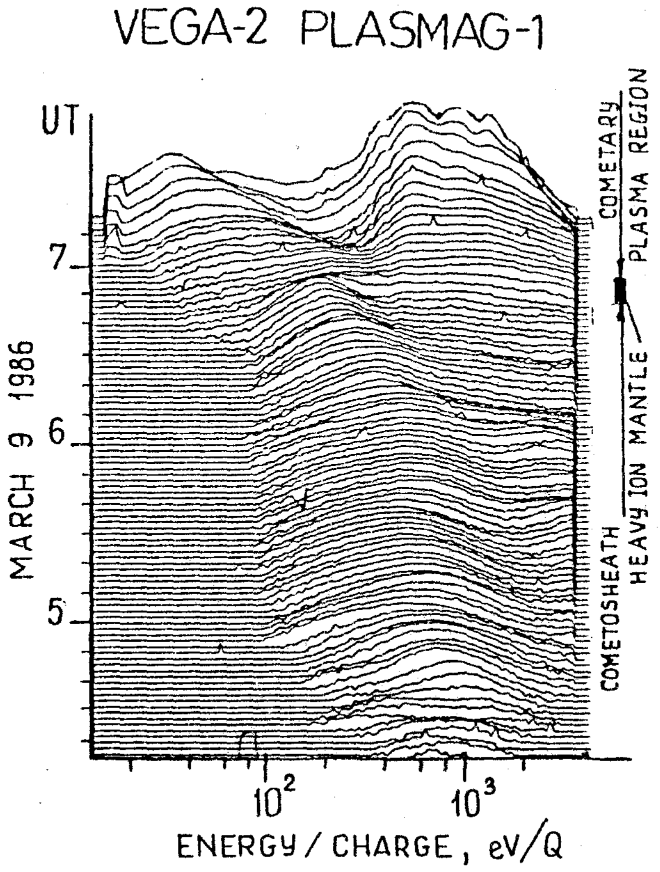
VEGA-2 PLASMAG-1
UT
7
6
5
MARCH 9 1986
10^2
10^3
ENERGY / CHARGE, eV/Q
COMETARY PLASMA REGION
HEAVY ION MANTLE
COMETOSHEATH

Figure 3

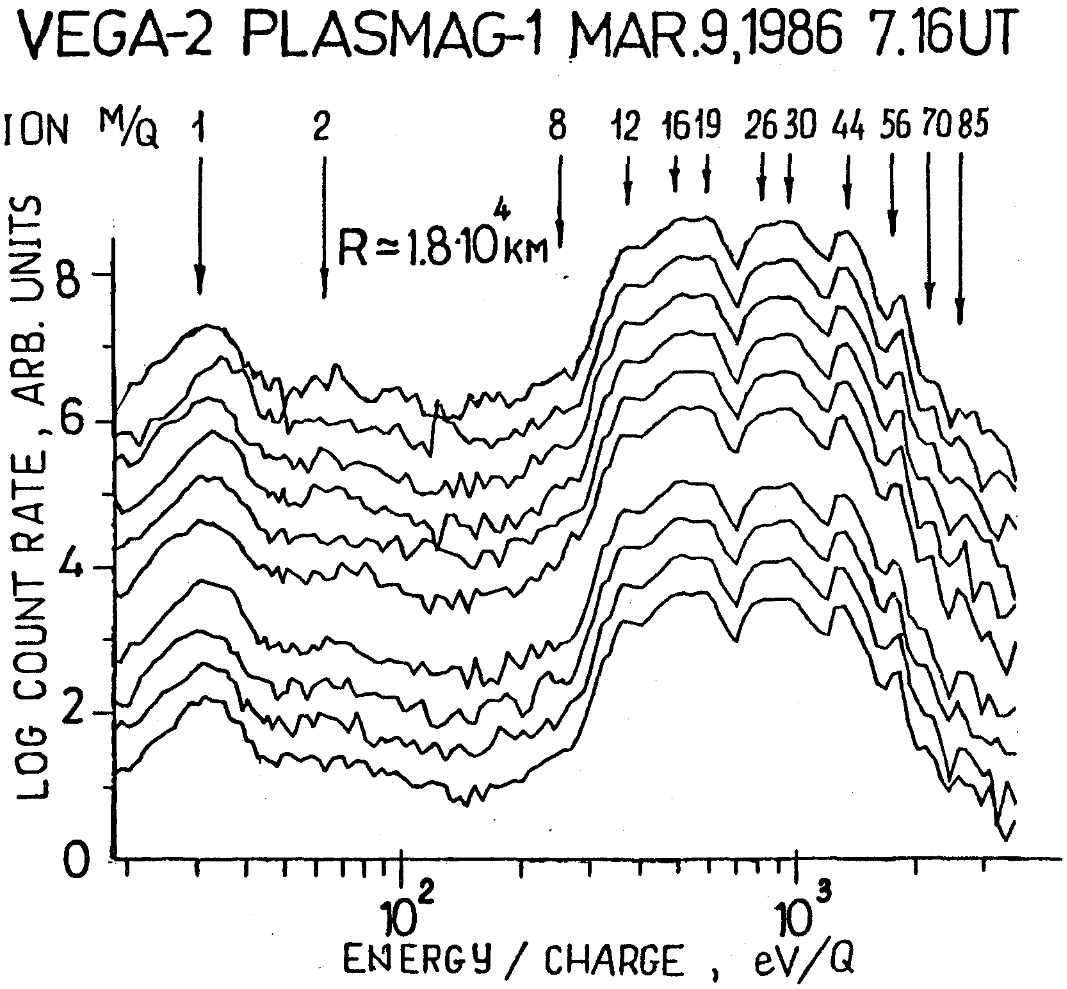
VEGA-2 PLASMAG-1 MAR.9,1986 7.16UT
ION M/Q
1
2
8
12
16
19
26
30
44
56
70
85
R ≈ 1.8·10⁴ KM
LOG COUNT RATE, ARB. UNITS
0
2
4
6
8
10²
10³
ENERGY / CHARGE , eV/Q

Figure 4

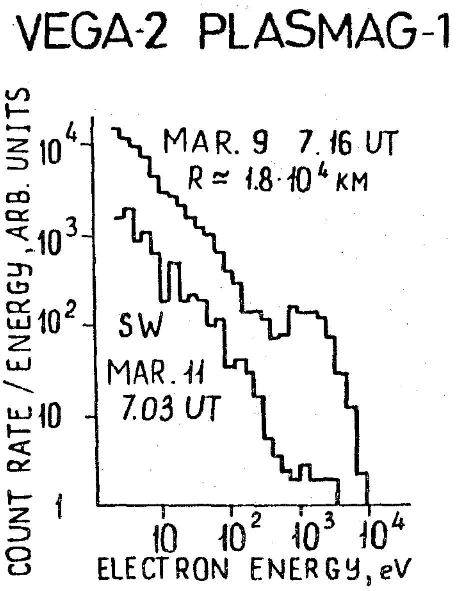
VEGA-2 PLASMAG-1
COUNT RATE / ENERGY, ARB. UNITS
10^4
10^3
10^2
10
1
MAR. 9 7.16 UT
R ≃ 1.8·10^4 KM
SW
MAR. 11
7.03 UT
10
10^2
10^3
10^4
ELECTRON ENERGY, eV

Figure 5

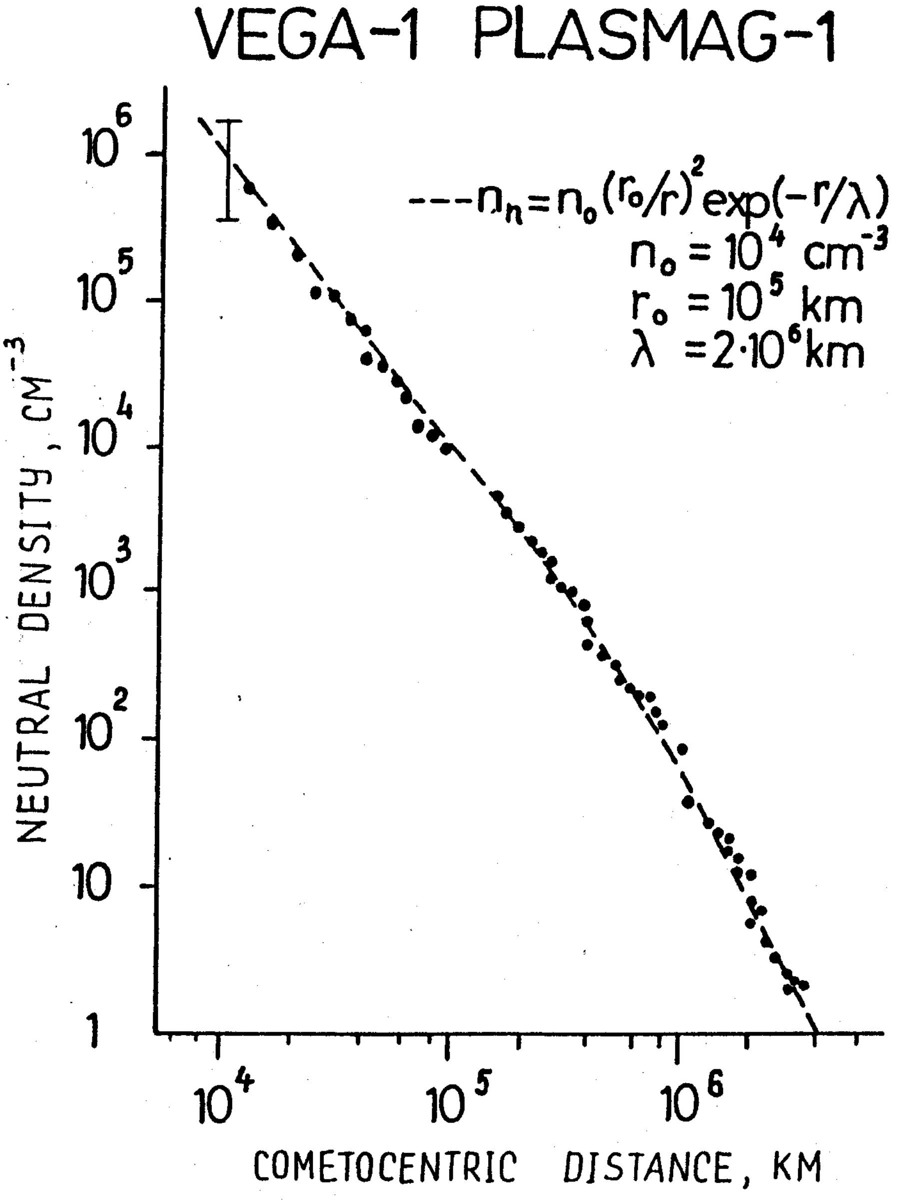
VEGA-1 PLASMAG-1
---$n_n = n_o (r_o/r)^2 \exp(-r/\lambda)$
$n_o = 10^4$ cm^{-3}
$r_o = 10^5$ km
$\lambda = 2 \cdot 10^6$ km
NEUTRAL DENSITY, CM^{-3}
10^6
10^5
10^4
10^3
10^2
10
1
10^4
10^5
10^6
COMETOCENTRIC DISTANCE, KM

Figure 6

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