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Venus tail ray observation near Earth

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Abstract. In June, 1996, Venus passed through a very close inferior conjunction with the Sun. At that time the CTOF detector of the CELIAS mass spectrometer experiment on the SOHO spacecraft near Earth's L1 Lagrangian point was measuring heavy ions in the solar wind ~4.5×10^7 km downstream of Venus. Close to the time predicted by simple geometric arguments for passage of SOHO through the Venus wake, CTOF made three encounters with unusual fluxes of O^+ and C^+ ions. Their energy distributions resembled those of tail rays originating in the Venus ionosphere or ionopause region rather than of ions produced in the corona of neutral atoms that surrounds the planet. The C^+ abundance was ≈10% of O^+. The observed O^+ speed was very close to the simultaneous solar wind speed and the O^+ temperature was a cool 5600 K/amu. The flux densities for the three events were $(2.4\text{-}4.4)\times10^3$ cm^{-2}s^{-1}.

Introduction

Because Venus has no appreciable magnetic field, the solar wind interacts directly with the planetary atmosphere and ionosphere much as with a cometary coma. In fact, several people have pointed out possible similarities of the tails of Venus and comets [e.g., *Russell et al.*, 1982; *Brace et al.*, 1987; *McComas et al.*, 1987]. The solar wind interaction can scavenge material from Venus and carry it away with the solar wind. Three different mechanisms are believed to be important: direct ionization and pickup of O^+ from Venus' corona of hot O atoms; indirect pickup through sputtering of atoms from the exobase due to bombardment by the previously picked-up O^+ ions; and removal of material from the ionosphere and ionopause region to form tail rays. While visible cometary tail rays can be preserved for tens of millions of kilometers, there is little evidence for the existence of planetary tail rays beyond a maximum of 12 Venus radii, R_V. A search for He^+ ions in the distant wake of Venus yielded negative results [*Russell and Neugebauer,* 1981]. Despite long-term coverage by several probes, among them the particularly successful Pioneer Venus Orbiter (PVO), there is large uncertainty about the composition, acceleration, and flux of ions downstream of Venus (e.g., see review by *Kar* [1996]).

A unique chance for in-situ observations as far as 45 million kilometers downstream of Venus occurred on June 10, 1996, when Venus had an extremely close inferior conjunction with the Sun, passing only ~0.5° south of the Sun center relative to the ecliptic plane. At that time, the SOHO spacecraft was on station near Earth's L1 Lagrangian point 0.01 AU sunward of Earth. In this paper, we report the detection of Venus tail rays on that occasion.

The CTOF Instrument

As part of the CELIAS package of ion mass spectrometers on SOHO [*Hovestadt et al.,* 1995], the CTOF detector was designed to measure energy (E), mass (M), and charge (q) of solar wind ions. The instrument combines a hemispherical electrostatic analyzer as an E/q filter with a time-of-flight (TOF) measurement yielding speed (v) and a silicon detector measuring total energy from which one can derive the original E/q, M/q and M. An accelerating voltage (U_{acc} ≈ 30 kV) is used to raise the ions' energy above the amplifier noise threshold (25 keV) to overcome energy losses within the TOF carbon foil and the detector front layer. The field of view is shaped by two quadrupole lenses into an almost circular cone of ~22° half-angle which ensures full integration of nominal supersonic solar wind ion distributions. During each 302-s instrument cycle, E/q sweeps down from 34.7 keV/q by 4.09% each step of 2.52 sec. Onboard reduction includes the evaluation of the solar wind speed for every cycle. Details of the instrument and calibration will be given in a future paper (H. Grünwaldt, E. Möbius, et al., in preparation) and some remarks are made here only on features of specific relevance to the data concerned.

(a) In contrast to the energy of multiply charged solar wind ions that are usually above the 25 keV detection threshold after acceleration through U_{acc}, singly charged ions picked up at Venus would typically have energies below that level. Based on this knowledge, mass identification is uniquely possible from the E/q and TOF information only. With the instrument M/q resolution (given by the energy width of the instrument transmission and by scattering in the carbon foil which add up to FWHM ≈ 1.5 amu/e around CNO^+ for the applicable input energy range) the identification of dominant CNO^+ species is only limited by their count statistics and by contamination effects.

(b) While TOF micro-channel-plate noise and UV background are negligible, the dominant contamination is contributed by abundant ions that produce noncorrelated low energy stop signals in the TOF. These "accidentals" occur when the electrostatic analyzer is set at the E/q range of their originator, and they are therefore most significant at the E/q corresponding to He^+ and the major constituents of the solar wind.

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Observations

Identification of tail ray O^+

An inferior conjunction of Venus occurred at 1600 UT, June 10 (day 162), 1996. A first prediction of the encounter of any wake or tail of Venus with SOHO must allow for the aberration angle caused by the planet's 35 km/s orbital velocity, $\tan^{-1} 35/\langle v_{sw} \rangle$, where $\langle v_{sw} \rangle$ is the average solar wind speed at Venus. A more accurate prediction makes use of the actual speed, v_{sw}, measured at SOHO. In the frame of observation the trace of any radially moving solar wind is shaped into a spiral, and the position of Venus proceeds with the synodic period of 584 days (see enhanced sketch at the inset of Figure 1 at a time between conjunction and encounter). From v_{sw}, the expected angular distance $\Delta\phi$ of Venus from the alignment with SOHO can be derived. This angle is plotted in Figure 1. The shaded band accounts for ±1.5° fluctuations in the direction of the solar wind flow vector that might be caused by waves or stream interactions. Figure 1 shows that one might expect to observe Venus ions around day 165.

From PVO observations, O^+ is expected to be by far the dominant Venus ion in the solar wind. Two distinct types of energy distributions may be encountered: we expect coronal pickup ions to be on cycloidal trajectories with speeds ranging from 0 to up to twice the solar wind speed, depending on the direction of the interplanetary magnetic field. Ion tail rays, however, would be closer to the speed and flow direction of the ambient solar wind. The process used to search for Venus ions is first to examine the O^+ channel for outstanding flux events, then to determine how many of those counts were actually caused by O^+ ions, and then to study other features such as the energy and time profiles.

The upper trace in Figure 2 is a histogram of the number of events registered in the O^+ channel in each 5-minute instrument cycle, using all data obtained during days 82-230, 1996. The most probable number of events/cycle is zero, and the distribution drops sharply to just over 20 counts/cycle. However, there were three highly exceptional cycles in which 36, 42, and 63 counts were registered, and each of those cycles occurred close to the time of the possible interception of the Venus tail.

Accidentals are primarily expected near the relative energy/charge $E/q_{rel} \approx 2$ or 4, corresponding to solar wind H^{++} or He^+, where E/q_{rel} is normalized to the energy/charge of the bulk flow of solar wind protons ($M/q \approx 1$). After correction for the accidentals by taking only those events with $E/q_{rel} > 8$ (far outside the He^{++} thermal core), the distribution is that shown in the lower (filled) histogram in Figure 2. The three events attributed to Venus ions are basically unchanged by this correction, and their exceptional nature is even more apparent than before.

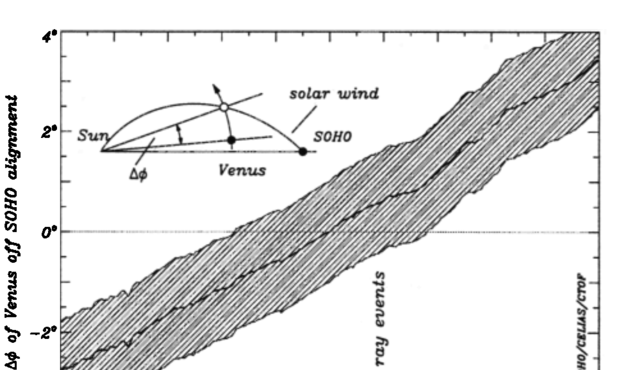

Figure 1. Venus phase angle, $\Delta\phi$, with respect to the solar wind in contact with SOHO. The times of tail ray events are marked at the bottom.

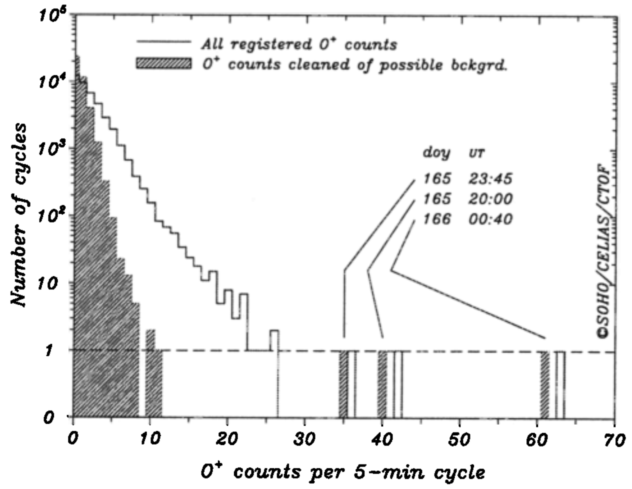

Figure 2. Distribution of O^+ counts per instrument cycle: the solid line refers to all counts in the O^+ channel while in the shaded area all background is removed. The events of days 165 and 166 appear clearly above random chance.

Figure 3 presents more evidence as to the nature of the events in the O^+ channel. The top panels show E/q_{rel} spectra during two of the exceptional events while the bottom panels show spectra near the same time, but outside the events. Running 3-channel averages were taken to smooth the data. In each of the panels the thin line shows the distribution from the He^+ channel which represents well the expected pick-up distribution; it is approximately constant above $E/q_{rel} \approx 4$, the value corresponding to the plasma bulk motion, and has a cutoff at $E/q_{rel} \approx 16$, corresponding to twice the plasma bulk speed. There is no significant variation in these distributions except statistical fluctuations. The shaded parts add spectra obtained from the O^+ channels. Only the top two panels show a well established population centered around $E/q_{rel} \approx 16$, consistent with a speed close to the solar wind speed, and a rather cool thermal distribution. There is no increase in He^+ (the only ion possibly interfering at that E/q) apparent at the times of the O^+ events, thus ruling out an increase in accidental effects.

Figure 4 presents the data in a different format that emphasizes the sharpness of the variations in time and velocity. It is a 3-dimensional plot with counts/cycle on the vertical axis, time running to the right (with each box denoting a single 5-minute cycle), and the third axis being $W = v/v_{sw}$, calculated on the basis of the M/q of O^+. Ditches in the ground plane indicate data gaps. From the second moments of the velocity distributions shown in Figure 4, kinetic temperatures near 5600 K/amu are obtained.

Each of the encounters with the Venus tail was extremely brief; the second and third events lasted no more than the instrument cycle time of 5 minutes. In fact, for those two events, the majority of the counts (40 for event 3) were collected within only one 30-second sweep of the analyzer voltage. Event 1 was broader in time with some velocity-time bins with lower but nonetheless significant counts surrounding the bin with the highest number of counts.

We conclude from this evidence that SOHO encountered an event of enhanced O^+ flux of a magnitude far beyond

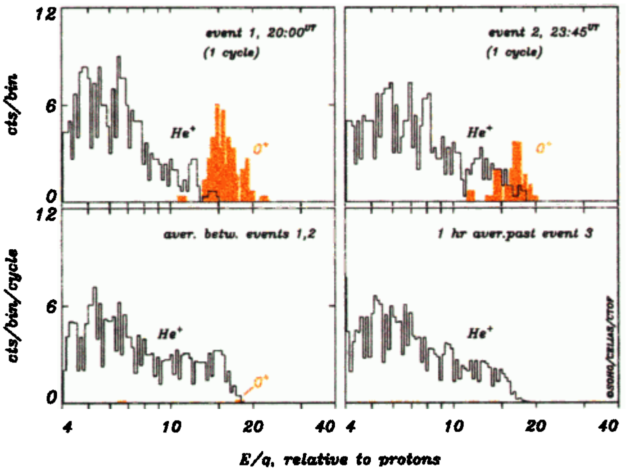

Figure 3. He$^+$ pick-up ion distribution compared to cold O$^+$: the upper panels are taken from tail ray events 1 and 2; the bottom panels are averaged over the interval between event 1 and 2 and over one hour past event 3, respectively.

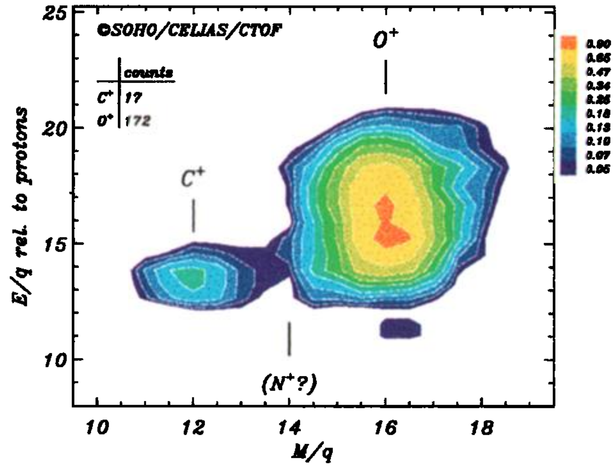

Figure 5. Contours of smoothed count rate distribution as a function of E/q and M/q around M/q values corresponding to C$^+$ and O$^+$. E/q has been normalized to the energy/charge of solar wind protons. Traces of N$^+$ may be present near M/q = 14. The speeds of C$^+$ and O$^+$ relative to the solar wind are derived from the moments parallel to the E/q axis. The total number of C$^+$ and O$^+$ counts are given in the inset.

statistical chance at a time when the spacecraft was within the projected tail of Venus. From the spectrum of those ions we conclude that they form a cool beam traveling close to the solar wind speed.

Identification of C$^+$ and other ions

Figure 5 presents a closer look at the data of the three events as two-dimensional distributions of total count rates versus the measured M/q (x-axis) and E/q_{rel} (y-axis). The distribution has been smoothed by 3-bin running averages with bin sizes of 0.5 (x) and 4.7% (y) and normalized per cycle. The range of contours is from 90% of the maximum down to 5% with logarithmic spacing as shown by the code bar; the lower limit eliminates the background determined in a comparative run using data outside these events.

The contours display two separate populations. The major peak is located around $M/q \approx 16$ and $E/q_{rel} \approx 16$ and belongs to O$^+$ as discussed above. The smaller peak is centered near $M/q \approx 12$, suggesting C$^+$ as its origin. The associated E/q_{rel} of about 13.5 is clearly distinct from the oxygen peak. Lack of a signal above the energy detector threshold is supporting evidence that the ions measured with $M/q \approx 12$ carry a charge of $q = 1$ and identifies them as C$^+$.

On the assumption of a similar link of these ions to the solar wind speed as we found for O$^+$ the central E/q_{rel} would be expected near 12. The actual value of 13.5 corresponds to a speed mismatch of about 6%. The statistical uncertainty in v is the thermal speed divided by the square root of the total number of counts, and may account for 1-2% on the basis of the better established temperature found for O$^+$. Another 2% may be caused by the width of the E/q stepping channels. Finally, there may be time aliasing of the spectrum as E/q sweeps down, but such an effect is rather unlikely since three independent events contribute to the result. Thus, however marginally, the bulk speed for this population may be higher than for O$^+$ which raises the possibility of different histories for the two ions species, O$^+$ and C$^+$.

The small table in Figure 5 lists the total counts for the two species accumulated over the three events and over the whole M/q and E/q_{rel} ranges of each distribution. The value for O$^+$ is higher than obtained by adding up counts from Figure 4 which was collected with very restrictive bandwidth. The averaged C$^+$/O$^+$ ratio is close to 0.10. We note that in Figure 5 there is also a hint of N$^+$ at $M/q \approx 14$ which was not taken into account in calculating the ratio C$^+$/O$^+$.

What about molecular ions such as O_2^+ ($M/q \approx 32$) or CO_2^+ ($M/q \approx 44$) [*Luhmann et al.*, 1995]? For the observed solar wind speed of 320 km/s, such ions would have $E/q \approx 17$ or 23.5 keV/q, respectively, which are within the 35 keV/q CTOF range. However, since the post-acceleration energies of those ions are just slightly larger than their losses in the foil, the detection efficiency and ion identification are poor. For the three tail-ray events, there is evidence for a number of counts above background associated with both candidate ions, but a more careful, quantitative analysis is postponed to a follow-up study.

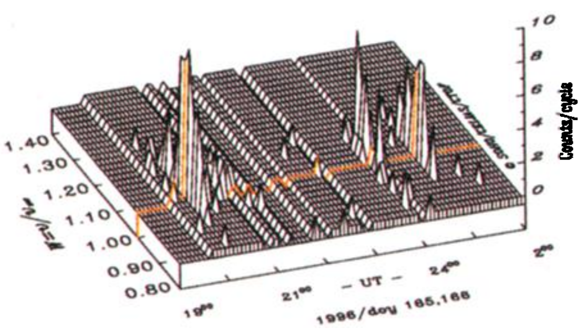

Figure 4. Tail ray observations on days 165 and 166: count rates versus time and normalized velocity $W = v/v_{sw}$. The sequence of three distinct events shows up clearly. The ditches mark data gaps.

Discussion

We believe the evidence for a cool beam of ions with mass/charge ≈ 16 amu/e traveling at close to the solar wind speed is compelling. The timing indicates that Venus was almost certainly the source of the ions. The energy distributions are consistent with the ions being tail rays rather than either direct or secondary coronal pickup ions. Although coronal pickup ions might also be present, their fluxes within the CTOF field of view are so low that more sophisticated data analysis will be required to find them.

The tail rays are probably spatially very narrow. If the rays maintained a fixed orientation with respect to Venus, a structure one Venus radius wide would pass by SOHO in 5.5 minutes, or in slightly more than one instrument cycle. In such a scenario, the observed temporal duration of ≤45 s would correspond to a spatial width $\leq 0.14\ R_V \approx 820$ km. The tail rays would not, however, be expected to remain in a fixed geometry relative to Venus because variations in the direction of the solar wind must cause the tail rays to flap around so that they could have a range of transverse velocities relative to SOHO. Thus unambiguous interpretation of the data in terms of spatial scales is not possible with observations made at only a single location in space.

From the measured high speed and thermally narrow ion distribution the assumption that instrumental integration of one snapshot has been complete over energy and directional extent seems justified. The shapes shown for O^+ in Figures 4 and 5 do not hint at any cut off by space-time effects, although none of the distributions extend much beyond the snapshot time of about 30 s within a cycle (≈ 45 s including C^+). The transformation of observed O^+ count rates into fluxes yields 4.4, 2.4, 3.1×10^3 ions/cm^2s for the three events, respectively. The calculation of the total flux within each tail ray is speculative, however, because we do not know the large scale structure SOHO was tracing through. If a tail ray is assumed to be a circular flux tube with a diameter of 820 km and a flux of $3 \times 10^3\ cm^{-2}s^{-1}$, its total flux would be 1.6×10^{19} O^+ ions s^{-1}.

The concept of comet-like tail rays extending downstream of Venus was first proposed by *Brace et al.* [1987] on the basis of data acquired within 2500 km of Venus by PVO. The observations were extended to 12 R_V by *Mihalov and Barnes* [1982] and *Intriligator* [1982; 1989]. All those studies noted the presence of O^+ ions and the filamentary or sporadic nature of the down-tail fluxes. At 1.3 R_V from the center of Venus, tail-ray widths typically varied from 600 to 3000 km [*Dubinin et al.*, 1991], with typically 1 to 3 rays observed per orbit of PVO around Venus. While at this distance the ions are just above escape speed, further downstream the speeds approach magnetosheath supersonic values. For similar phenomena at Mars, *Rosenbauer et al.* [1989] reported a systematic speed gradient across the tail up to highly supersonic values of heavy ions near the center. Many of the features of the Venus tail rays, including their very narrow structure, can be explained on the basis of a model developed by *Luhmann* [1993], and *McComas et al.* [1986] have used the observed magnetic field in the tail together with the MHD equations to model the acceleration of the tail plasma up to solar-wind speeds.

Although C^+ ions have not been previously reported in Venus tail rays, a C^+/O^+ ratio of about 0.1 has been reported in various domains of the ionosphere [*Kasprzak et al.*, 1991], in good agreement with the CTOF results.

The purpose of this short report is to point out that Venus tail rays have been identified in the solar wind some 45 million km downstream of Venus. In future papers we will report on more details of the observations, including the abundance of molecular ions, the response of the ambient solar wind to the presence of the tail rays, and comparison to different models and theories. Further analysis is also required to search for the Venus coronal pickup ions which would have broader spatial and angular distributions than the tail rays described here.

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