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# Proton cyclotron wave generation mechanisms upstream of Venus

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[1] Long-term observations of proton cyclotron waves in the upstream region of Venus raise the question of under which general solar wind conditions these waves are generated and maintained. The waves are characterized by their occurrence at the local proton cyclotron frequency and left-hand polarization, both in the spacecraft frame. Magnetometer data of the Venus Express spacecraft for two Venus years of observations are analyzed before, during, and after the occurrence of these waves. The configuration of the upstream magnetic field and the solar wind velocity is investigated, to study if the waves are generated from a ring distribution of pickup ions in velocity space or from a parallel pickup ion beam, i.e., for quasi-parallel conditions of solar wind velocity and magnetic field when the solar wind motional electric field is weak. It is found that stable and mainly quasi-parallel magnetic field conditions for up to ~20 min prior to wave observation are present, enabling sufficient ion pickup and wave growth to obtain observable waves in the magnetometer data. Persistent waves occur mainly under quasi-parallel conditions. This is in agreement with linear theory, which predicts efficient wave growth for instabilities driven by field-aligned planetary ion beams, already for low pickup ion density. The occurrence of highly coherent waves at 4 $R_V$ upstream toward the Sun implies that planetary neutral hydrogen is initially picked up at least 5 $R_V$ toward the Sun from a sufficiently dense Venus hydrogen exosphere.

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## 1. Introduction

[2] The generation mechanism of waves at the ion cyclotron frequency in the planetary frame at ionization and pickup of neutrals from planetary atmospheres is a topic of wide interest: These waves are used to prove the existence of specific ions in the neighborhood of planets and satellites and allow conclusions about the contents of their atmosphere. In general, planetary neutrals are ionized by photoionization, electron impact ionization, and charge exchange [*Zhang et al.*, 1993]. The newborn ions form an unstable secondary ion population in the solar wind, its interaction with the background plasma generates waves from different instabilities. For a pure ring distribution in velocity space of pickup ions with no parallel drift velocity (magnetic field perpendicular to the solar wind velocity), the Alfven left-hand mode is unstable [*Huddleston and Johnstone*, 1992], and for a pure field-aligned beam of pickup ions (magnetic field parallel or antiparallel to the solar wind velocity) the right-hand mode will be unstable [*Gary*, 1991]. In reality, the configuration of the magnetic field and the solar wind will be none of these extreme cases, so the general case for the ion distribution will be a ring beam, generating waves observed at the specific ion's cyclotron frequency in the spacecraft frame. The cyclotron waves can be expected in magnetic field observations at any location where ion pickup in adequate quantity from the neutral planetary atmosphere is possible.

[3] Especially upstream of a planetary bow shock the presence of ion cyclotron waves is a precursor of the approaching planet, demonstrating the existence of the specific ion in the part of the planetary atmosphere that is unprotected by an intrinsic or induced planetary magnetosphere. At Venus with no intrinsic magnetic field, upstream proton cyclotron waves were recently detected [*Delva et al.*, 2008a], showing that Venus is permanently losing hydrogen directly to the solar wind. In a comprehensive study based on magnetometer observations during the first two Venus years or 450 orbits of the Venus Express mission, the wave properties were analyzed in detail [*Delva et al.*, 2008b]. In the present paper, we use the same data set and concentrate on the interplanetary magnetic field parameters prior to, during, and after the wave occurrence, to understand which general conditions are favorable for cyclotron wave generation, as well as for maintaining the waves for at least several tens of minutes. A case study of highly coherent waves far upstream

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of Venus addresses the availability of planetary neutral hydrogen in regions toward the Sun.

## 2. Planetary Ion Pickup and Waves at the Cyclotron Frequency

[4] A planetary neutral will be nearly at rest in the planet's frame and, neglecting its small initial velocity, will have a velocity $-\boldsymbol{V}_{sw}$ in the solar wind frame, where $\boldsymbol{V}_{sw}$ denotes the solar wind velocity and here is supposed to be radially outward from the Sun. At ionization the particle is injected into the solar wind flow, drifts with a velocity $\boldsymbol{V}_{//}$ along the magnetic field $\boldsymbol{B}$ (where $V_{//} = -V_{sw}\cos(\alpha_{VB})$; $\alpha_{VB}$ is the angle between $\boldsymbol{V}_{sw}$ and $\boldsymbol{B}$), and gyrates around the magnetic field lines according to its velocity component $\boldsymbol{V}_{\perp}$ perpendicular to the magnetic field, with gyrofrequency $\Omega_i$ ($\Omega_i = q/m\ B$; mass $m$, charge $q$, magnetic field strength $B$). In the solar wind frame, the gyrating pickup ion will be in resonance with a solar wind wave of frequency $\omega$ and wave vector $\boldsymbol{k}$ if

$$\omega - \boldsymbol{k} \bullet \boldsymbol{V}_{//} \pm n\Omega_i = 0 \quad n = 1, 2, 3. \tag{1}$$

The resonant solar wind wave of frequency $\omega$ and propagating parallel to $\boldsymbol{B}$ (i.e., $\boldsymbol{k} = \boldsymbol{k}_{//}$) will be observed in the spacecraft frame with a Doppler-shifted frequency

$$\omega_{sc} = \omega + \boldsymbol{k}_{//} \bullet \boldsymbol{V}_{sw}. \tag{2}$$

Introducing the parallel velocity for planetary ions $V_{//} = -V_{sw}\cos(\alpha_{VB})$ in equation (1) and using the parallel propagation property of the waves $\boldsymbol{k}_{//}.\ \boldsymbol{V}_{sw} = k\ V_{sw}\ \cos(\alpha_{VB})$ in equation (2), a combination of both equations yields the frequency observed in the spacecraft frame

$$\omega_{sc} = \pm n\Omega_i. \tag{3}$$

Resonance occurs mainly for the fundamental mode $n = 1$ [*Brinca*, 1991]. Therefore cyclotron waves generated by planetary particles, having negligible velocity relative to the planet and to the spacecraft, will always be observed in the spacecraft frame exactly at the local proton frequency, regardless of the value of the angle $\alpha_{VB}$ between $\boldsymbol{V}_{sw}$ and $\boldsymbol{B}$. The opposite signs in expression (3) account for the inversion of the polarization of the wave in the spacecraft frame with respect to the one observed in the solar wind frame: Right-hand polarized waves at the local proton cyclotron frequency in the plasma frame will be observed in the spacecraft frame at the same frequency but with left-hand polarization [*Mazelle and Neubauer*, 1993].

[5] However, the angle between $\boldsymbol{V}_{sw}$ and $\boldsymbol{B}$ is the important variable when determining the wave generation efficiency by governing both the resonant frequency $\omega$ in the plasma rest frame (equation (1)) and the growth rate of any unstable mode. In velocity space, the pickup ions have a beam distribution for a (anti) parallel configuration of $\boldsymbol{V}_{sw}$ and $\boldsymbol{B}$, a pure ring distribution for a perpendicular configuration, or a ring beam distribution for angles in between. In case of substantial perpendicular velocity component $\boldsymbol{V}_{\perp}$ of the solar wind speed to the magnetic field, an unstable ring–beam distribution of pickup ions develops in velocity space; here the free energy of the ions in the ring acts as source for the ion cyclotron waves, e.g., at comets [see, e.g., *Coates et al.*, 1990], in the Io torus [*Huddleston et al.*, 1997], at Mars [see, e.g., *Wei and Russell*, 2006] and other planets. In cases of relatively small perpendicular component the injected ions form a beam which is nearly aligned with the local magnetic field, either parallel or antiparallel; under such conditions, the free energy is in the drift motion and ion cyclotron waves are effectively generated from the ion/ion beam instability [*Brinca*, 1991; *Gary*, 1991]. This mechanism has been discussed mainly for comets [*Lee*, 1989; *Brinca*, 1991; *Tsurutani*, 1991] but also for Mars [*Mazelle et al.*, 2004]. We here analyze the Venus Express MAG magnetometer data to see which of these mechanisms is prevailing in the upstream region of Venus.

## 3. Observations

### 3.1. Data Analysis Method

[6] Our previous comprehensive study of the proton cyclotron wave (PCW) occurrences upstream of the Venus bow shock from magnetometer data of two Venus years or 450 orbits (10 May 2006 to 10 August 2007) identified proton cyclotron waves in an automated way in the MAG data with 1 Hz resolution [*Delva et al.*, 2008b]. In the Venus Solar Orbital reference frame (VSO, centered at Venus, $x_{VSO}$ axis positive toward the Sun and opposite to $\boldsymbol{V}_{sw}$, $z_{VSO}$ axis perpendicular to Venus's orbital plane and positive to ecliptic north, $y_{VSO}$ axis completing the right-hand system) in that time interval the spacecraft orbital plane made two full rotations about the polar axis of the planet, such that uniform data coverage is given for all planetary regions. For magnetic field values $B_t$ in the range 5–20 nT, the proton cyclotron frequency is in the interval 0.075–0.3 Hz, the periods 13–4 s, respectively.

[7] For each time interval of 10 min, the local proton cyclotron frequency $f_p = \kappa\ \mu(B_t)$ and the error range $\Delta f_p = \kappa\ (\sigma(B_t) + \Delta B)$ were determined from the mean total field $\mu(B_t)$, its standard deviation $\sigma(B_t)$ and the data accuracy $\Delta B = \pm 1$ nT; $\kappa = (2\pi)^{-1}\ q/m$ with $q$ and $m$ charge and mass of the proton. Power spectra were calculated and the power per component was integrated in the frequency interval $[0.8\ (f_p - \Delta f_p), f_p + \Delta f_p]$, in order to account for power maxima just below the calculated cyclotron frequency. The following criteria on the power spectra were used to select the waves as being PCWs:

$$P_T/P_C > 1.5; \quad P_L/P_R > 1.5; \quad \text{ellipticity} < -0.5, \tag{4}$$

where $P_T$ and $P_C$ denote the transverse and compressional component of the power and $P_L$ and $P_R$ are the left-hand and right-hand polarized component of the transverse power. The ellipticity is derived from the real part of the covariance matrix and indicates the handedness of the wave in the principal axes (PA) frame ($x_{PA}$, $y_{PA}$ axes in the wave plane, $z_{PA}$ axis normal to it; ellipticity is −1 for left-hand, 0 for linear, and +1 for right-hand circular polarization) [*McPherron et al.*, 1972]. The condition of large negative ellipticity ensures that the waves are left-hand polarized in the spacecraft frame. The detection conditions (4) are required for the mean values over the whole 10 min interval; it is clear that the wave duration itself can be shorter than the full interval, such that the ellipticity determined here from the full interval is less

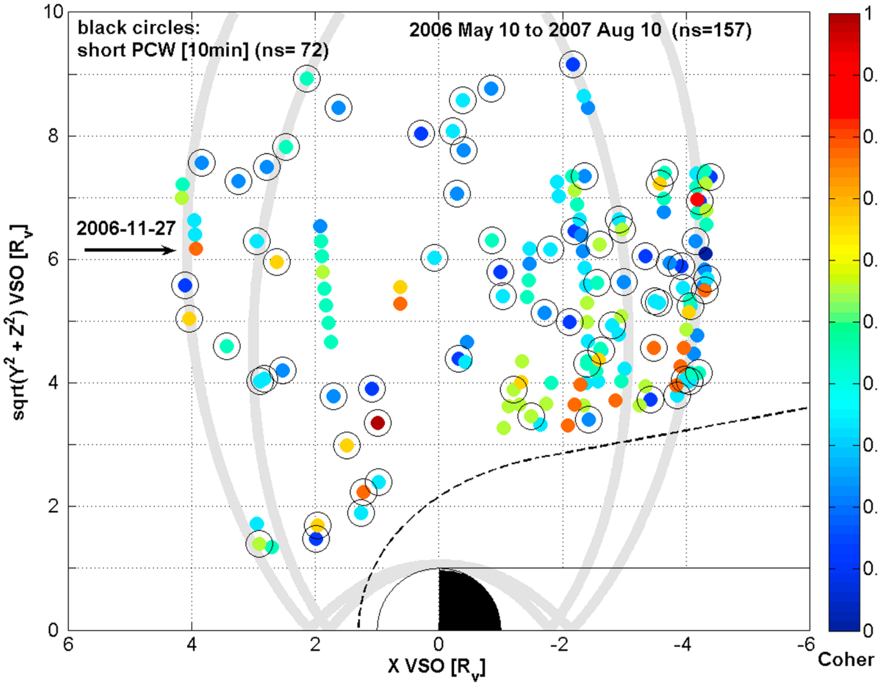


**Figure 1.** Occurrence of proton cyclotron waves (PCWs) in space, in cylindrical VSO-coordinates (*ns* = 157). Color coding is according to coherence of the waves; short occurrences of only 10 min duration are marked with black circles. Grey lines indicate the limiting orbits of the Venus Express spacecraft, regions outside of these lines were not accessed; the dashed line denotes the modeled bow shock. The arrow shows a case with highly coherent waves at large upstream distance from Venus.

explicit than if derived from a limited number of cyclotron periods within the 10 min, i.e., the actual waves may be even more circularly left-hand polarized.

[8] A static model of the bow shock as determined from the positions of the observed bow shock crossings was used [*Zhang et al.*, 2008]. From data up to 4 h before and after this modeled bow shock crossings a total number of 157 events of upstream PCW observation in single intervals of 10 min was found, corresponding to 1% of the investigated time, up to a distance of 9 Venus radii ($R_V$ = 6052 km) from the Venus-Sun line. The spatial distribution of the observation positions in cylindrical VSO coordinates is shown in Figure 1. The waves are observed mainly for inbound trajectories where the spacecraft evolves to lower distances toward Venus, into regions of higher neutral hydrogen density.

[9] We here use the same data set but organize the PCWs in continual occurrences of subsequent time intervals. This leads to 98 cases of continual PCW observations, with duration from 10 min up to 140 min at the longest. The main part of the occurrences is of short duration (72 cases of 10 min or shorter), giving the impression of a short-lived feature. Furthermore, enough longer time intervals are available (26 cases of 20 min or longer) to allow insight into the conditions for continual waves, which we analyze in the following.

### 3.2. Conditions Prior to Wave Occurrence

[10] To study the general solar wind magnetic field conditions leading to observable PCWs in the MAG data, we analyze the data of 1 h previous to each PCW occurrence and calculate mean values of several parameters in non-overlapping time steps of 10 min; if parts of this 1 h interval are overlapping with a previous PCW occurrence or are located within the modeled bow shock or closer than 10 min to the modeled bow shock crossing, the parts are not used. In the VSO reference frame, we discuss the magnetic field in terms of the total field $B_t$, the clock angle $\psi = \arctan(Bz_{VSO}/By_{VSO})$, and cone angle $\theta(-\boldsymbol{V}_{sw}, \boldsymbol{B}) = \arccos(Bx_{VSO}/B_t)$; the waves in terms of the amplitude. The evolution of the magnetic field from 1 h prior up to the start of observable continual PCWs in the MAG data in steps of 10 min is shown in Figure 2 as histograms of the mean direction (cone and clock angle) and mean total magnetic field (*ns* = 98). Sometimes, MAG data outside of the modeled bow shock are not available throughout one full hour before the PCW observation; hence the number of samples can be lower in the histograms for the earliest time intervals.

[11] We see specific characteristics in the hour of data before the occurrence of PCWs: (1) The cone angle $\theta$ evolves to values predominantly in the intervals 20°–40° and 140°–160° for 20 to 30 min before start of the wave observation; (2) the clock angle $\psi$ shows no preferred direction; and (3) the mean total magnetic field evolves to values mainly in 6–12 nT, which is the nominal range at Venus.

[12] The wave power (not shown) in the specific frequency range is generally a mixture of compressional and transverse parts, with some left- and right-hand polarized fraction present in a "wave noise" range implying small

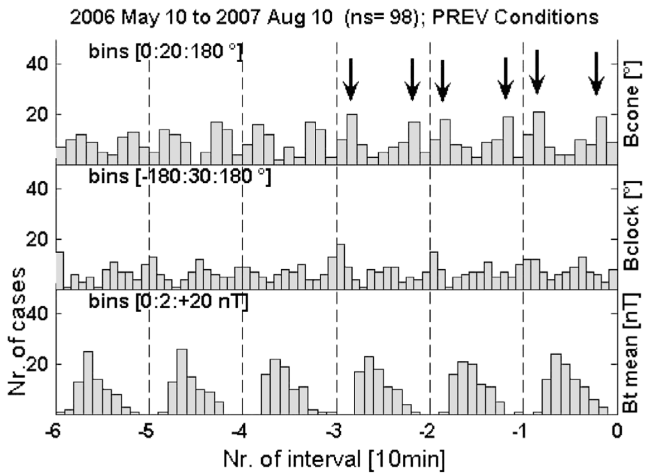


**Figure 2.** Histograms of observed mean magnetic field, 1 h prior to the continual PCW observation (*ns* = 98), in steps of 10 min intervals: cone angle, clock angle, total value of mean magnetic field; arrows indicate the predominance of specific values of the cone angle.

amplitudes (<0.25 nT). Toward the end of the 1 h interval an increase in the transverse left-hand power component is observed, whereas the right-hand power becomes negligible, such that the condition for the ellipticity <−0.5 is fulfilled; the amplitudes grow to values significantly above the wave noise level.

[13] From these findings, we can derive a scenario of necessary field conditions for PCW generation: The cone angle evolves to more and more quasi-parallel conditions before start of the wave observation, and these stable specific conditions are established during 20 to 30 min prior to the PCW observations.

### 3.3. Stability of Conditions

[14] To get better understanding of the required stability of these quasi-parallel conditions, we study the variability of the field parameters in more detail. For all 10 min intervals prior to the wave occurrence, the differences from one interval to the next are calculated and in the same way the differences for all times with PCW occurrence. To visualize the variation of the field conditions at the end of the PCW occurrence, we take the difference from the last interval with waves to the next without waves. Histograms in relative units of the respective differences are shown in Figure 3.

[15] For the full hour prior to the wave occurrence (Figure 3, left), the overall field conditions still have substantial variations, which originate from the first 30 min of that time span (see also Figure 2). For all the times with PCW occurrence (Figure 3, middle) the variation of the cone angle is within ±10° and the total field value is nearly constant (±1 nT); also, the clock angle shows mainly small variations: During the wave occurrence, very stable field conditions prevail. In contrast to this stability during PCW occurrence, the variation of the field at the end of the wave occurrence to the next interval of wave disappearance (Figure 3, right) is significant: Large differences of the cone angle and the total mean field occur, as well as large variations of the clock angle.

[16] We conclude that stable quasi-parallel field conditions need to be established to allow for observable waves and must be maintained to enable PCW observations for longer time intervals, especially a stable cone angle and stable total field. Stronger variations in the field direction with respect to the solar wind velocity immediately destroy the PCW occurrence.

[17] To enable comparison with the conditions in the pure solar wind very far from the planet, another data set was selected as follows: 100 orbits were chosen at random within the two Venus years and per orbit 1 h of data around the apocenter of the orbit (~10 $R_V$) was analyzed in the same way as for the times prior to the PCW observations. The histograms for the sample in the solar wind are shown in Figure 4; we see that the values of the cone angle are variable to a high degree and that especially values in 60°–120° generally occur, with frequency comparable to any other value. For all parameters shown, the distributions in the solar wind are similar to the first half hour in Figure 2, prior to PCW occurrence.

### 3.4. Short Versus Long Duration PCW Observations

[18] From the 98 cases of individual PCW sequences (covering 1570 min of wave observations), in 26 cases the waves are observed for a time interval longer than 10 min (covering 850 min of wave observations). For these longer cases it is important to realize that we do not observe the same wave for an extended time; the spacecraft does not track the wave on its propagation trajectory but moves across it, so a train of subsequent waves is recorded, as is always the case with observations by a single spacecraft.

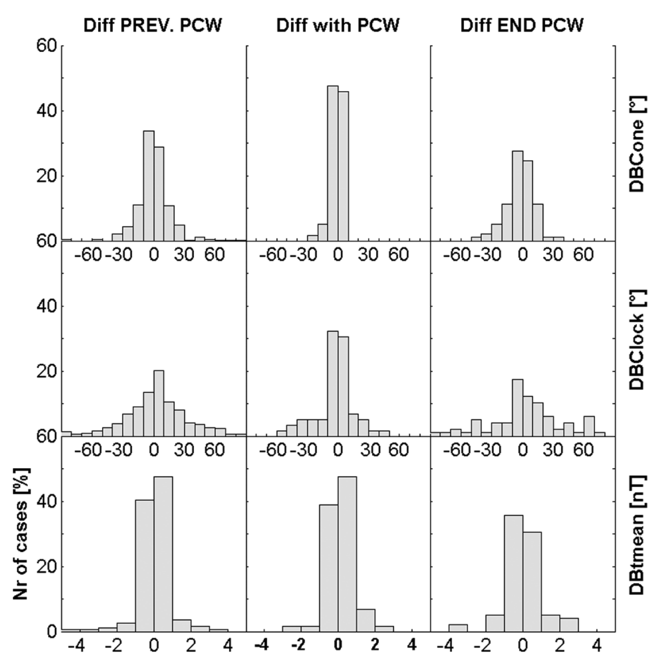


**Figure 3.** Histograms (in %) of differences (from one 10 min interval to the next) of field parameters in the time span of (left) 1 h prior to the PCW occurrence, (middle) during PCW occurrence, and (right) from last interval with PCWs to first time interval without observable waves in the MAG data, for *ns* = 98 continual cases.

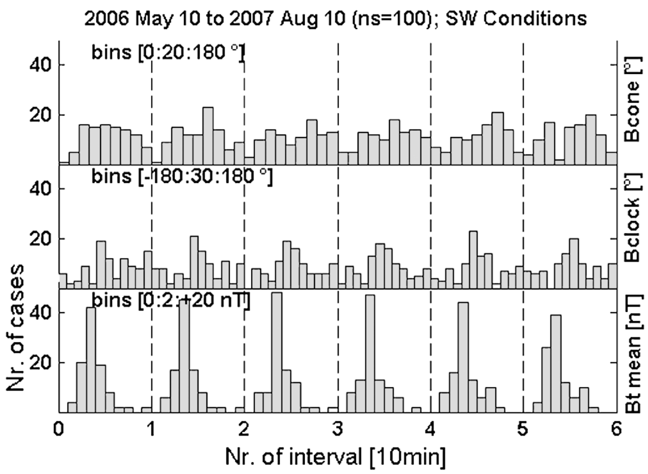


**Figure 4.** Histograms of observed mean magnetic field parameters during 1 h (in steps of 10 min intervals) in the pure solar wind around apocenter of the Venus Express orbit (~10 $R_V$), from 100 orbits selected at random within the two Venus years.

Venus Express has an elliptical polar orbit with pericenter near the north pole of the planet; for most time of the orbit, the spacecraft moves mainly from north to south (or vice versa) across the Venus equatorial plane (see Figure 1). For nominal solar wind conditions the interplanetary magnetic field direction is mainly parallel to the ($x_{VSO}$, $y_{VSO}$) plane. The PCWs propagate nearly (anti) parallel to the magnetic field and the wave propagation trajectory is also parallel to this plane. Since the spacecraft moves across the plane, it also moves across the wave propagation trajectory.

[19] Hence, in the case of longer-lasting PCWs, we in fact observe several subsequent waves over a longer spacecraft path, which means waves generated under uniform solar wind conditions but at different positions in an extended source region. Therefore the amplitude of subsequent waves in a wave train is not necessarily increasing [see *Delva et al.*, 2008b, Figure 6]. On the other hand, waves of only short occurrence duration indicate that spatial uniformity was not given and significant solar wind parameters were variable in space (and time).

[20] To get insight into the specific properties of the short (*ns* = 72) and longer (*ns* = 26) PCW occurrences, mean values for the total field, amplitude, and cone angle were determined from each 10 min interval; the longer wave duration cases contain 85 such single intervals; the specific wave parameters ellipticity, coherence, and polarization were determined from a subinterval of 10 local cyclotron periods within each 10 min interval.

[21] Histograms of these values for short and long duration cases are shown in Figure 5. For the longer-living PCWs (Figure 5a, right, and Figure 5b, right) the mean total field and the wave amplitudes are larger than for the short duration cases (Figure 5a, left, and Figure 5b, left); the longer living waves are for more quasi-parallel conditions, i.e., cone angle <45° or >135°. The wave properties ellip-

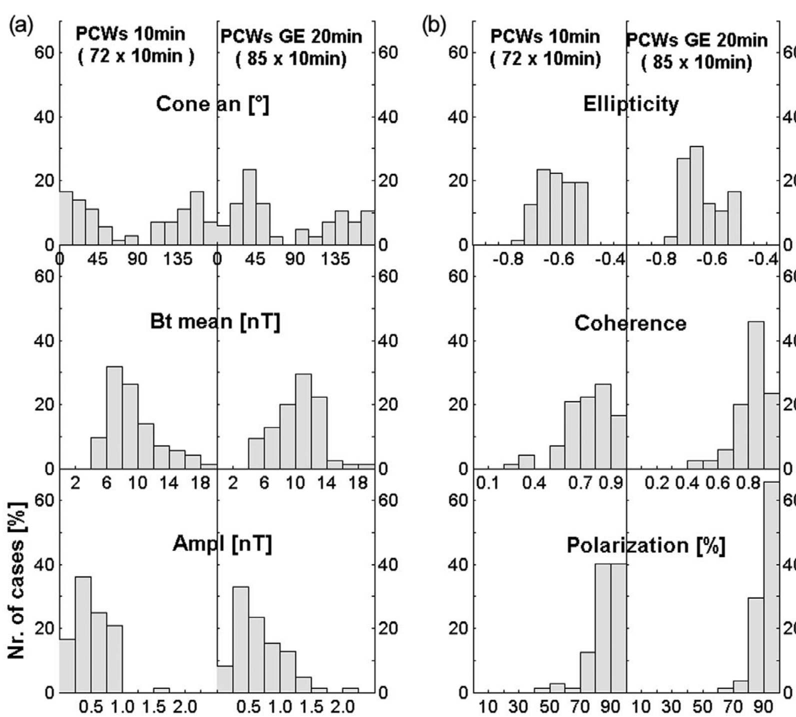


**Figure 5.** Histograms (in %) for (a) mean field parameters from 10 min PCW occurrence intervals and (b) wave parameters from 10 cyclotron periods within each 10 min interval for (left) short wave occurrences (10 min, *ns* = 72) and for (right) longer wave occurrences (≥20 min, *ns* = 85). The specific characteristics for PCWs of high ellipticity (negative for left-hand polarized waves in the spacecraft frame), strong coherence, and polarization are much more pronounced for the longer-lasting waves.

ticity (negative for left-hand polarization), polarization, and coherence have significantly larger values for the longer duration cases. This leads to a consistent picture of the difference in nature between the two cases: Persistent waves have more pronounced specific characteristics of ion cyclotron waves. It means that sufficient continual supply of pickup ions with equal dynamic properties was available from the point of initial wave generation at the source of the freshly ionized neutrals to the point of observation by MAG, such that the wave characteristics had enough time to fully develop to the values observed. In the region where most of the PCWs are seen ($-6\ R_V < z_{VSO} < -3\ R_V$) the spacecraft moves through a spatial distance of ~0.6 $R_V$ in $z_{VSO}$ in 20 min, toward the Venus equatorial plane and into regions with higher neutral planetary hydrogen density and also increasing supply of freshly ionized ions. Therefore stable field conditions must be available over a large area of space, first to enable wave generation and second over an even larger area if the waves are observed for longer time. No difference of spatial occurrence could be found between the short and longer PCW observations (see Figure 1).

## 4. Cyclotron Resonance and Wave Generation Theory

[22] Theory describes how PCWs are generated from cyclotron resonance with newborn exospheric ions. In principle, the cyclotron resonance can generate two possible modes: the first is characterized by a left-hand polarization and a second mode with a right-hand polarization, all in the plasma frame. The former mode is unstable only for cone angles ~ 90° and has low growth rate, whereas the latter is unstable for angular values in the range 0°–70° and has a large growth rate [*Brinca*, 1991]; the instability of the mode is the wave driver. So theoretically, under perpendicular conditions with a pure ring distribution of pickup protons, left-hand polarized waves (in the plasma frame) at the local proton cyclotron frequency could be generated; however, no such wave occurrences with significant ellipticity (observed as right-hand polarized in the spacecraft frame, ellipticity > + 0.5) could be detected in the investigated two full Venus years.

[23] For low cone angles, the velocity distribution for the newborn ions is a field-aligned beam of exospheric protons, with a low number density compared to the solar wind protons. For these conditions, the ion/ion resonant right-hand instability is dominant and wave growth is fast, whereas the left-hand mode cannot grow [*Gary*, 1991]. The right-hand mode represents a right-hand circular polarization in the solar wind frame and propagates in the same direction as the beam with a phase velocity smaller than the solar wind velocity. As a consequence, this mode will be perceived at the local proton cyclotron frequency with a left-hand polarization in the spacecraft frame, due to anomalous Doppler effect. Therefore under the Venus conditions of low density of the pickup planetary protons with respect to the background solar wind flow, PCW generation from field-aligned planetary ion beams is expected to be an efficient mechanism upstream of the planet, whereas for quasi-perpendicular configurations, wave growth is slow. Hybrid numerical simulations indicate the possibility that the observed waves could be produced when the pickup ion density is at least ~0.01% of the solar wind density (M. Cowee, personal communication, 2010) and also that continual supply of pickup ions under constant field conditions leads to faster wave growth and longer survival of the waves [*Cowee et al.*, 2008].

[24] Indeed, we here found predominantly wave observations for stable field conditions and cone angles with (anti) parallel configuration of the magnetic field and the solar wind flow, which is in accordance with the predictions and the simulations.

## 5. Probability of Favorable Conditions for Observable PCWs

[25] In our analysis we found that stable and specific magnetic field conditions occur for 20–30 min prior to the wave observation and in addition also during the wave observation itself, from 10 to 140 min for the longest duration of wave occurrence. In the pure solar wind, no such conditions are observed in the MAG data (see Figure 4). From solar wind studies, we know that magnetic field stability is not the general case; variations of the angle ($\boldsymbol{V}_{sw}$, $\boldsymbol{B}$) take place on short time scales, e.g., at 1 AU changes of 35°–40° in 1.5 min time are the most frequent [*Ragot*, 2006]. Furthermore, even if magnetic field conditions are stable, other solar wind parameters which have a strong influence on wave generation can be variable, e.g., the solar wind velocity and density, the ratio $\beta$ of the thermal energy density to the magnetic energy density, the load of the plasma with He ions. All these parameters are unknown over the long time span used here, and particle data from the plasma instrument ASPERA-4 aboard Venus Express are not yet available [*Barabash et al.*, 2007]; any spatial or timely change in one parameter can severely modify the conditions for wave generation and growth, eventually leading to an only short PCW occurrence even when magnetic conditions are stable.

[26] The above considerations show that stable solar wind conditions that enable observable PCWs in the magnetometer data are not frequently met; conditions for persistent wave occurrence are even more rare, which explains the prevailing observation of short occurrences. A similar difference in the ion cyclotron wave duration was observed at comets. Comet Halley was very active at its latest return, with permanently changing gas production rate and therefore unstable source of pickup ions. During the Giotto spacecraft flyby, upstream water group ion cyclotron waves (ICW) with rather low coherence were observed for several hours [*Johnstone et al.*, 1987] and also short wave packets with high coherence at the proton cyclotron frequency [*Mazelle and Neubauer*, 1993]; here the magnetic field cone angle was highly variable in a large range, 20°–160° [*Coates et al.*, 1990]. Comet Grigg-Skjellerup had a low but steady gas production rate; there upstream ICWs were observed for long times and with high coherence [*Neubauer et al.*, 1993], as well as stable cone angles in the range 45°–115° [*Coates et al.*, 1993]. For comets the difference in ion cyclotron wave occurrence duration was explained by the variability of the source of newborn ions. Furthermore, it is striking that variable field conditions correspond to only short occurrences of coherent ICWs (at comet Halley), whereas constant field conditions at comets correspond to long

observations of coherent waves (at comet Grigg-Skjellerup). This is well in accordance with the results found here for Venus.

[27] At Venus, the exospheric conditions are stable but with a neutral density much lower than in the cometary coma, such that variations in the solar wind conditions may have a stronger influence. At Mars, with a higher exospheric density than Venus, stable PCWs were observed for long time intervals and for stable conditions of the magnetic field [*Mazelle et al.*, 2004; *Bertucci et al.*, 2005]. The authors do not report a preference for parallel configuration values of the cone angle, which may indicate that there the pickup proton density with respect to the background is sufficiently high to allow PCW generation from any stable field configuration. However, recent investigation of the MGS data for significant field values ($B_t \geq 5$ nT) and well-defined field directions show more PCW occurrences under quasi-parallel configurations [*Mazelle et al.*, 2009].

## 6. Wave Occurrence and Motional Electric Field

[28] In the light of current explanations for the generation of PCWs it is important to investigate the wave occurrence as function of the motional electric field. Upstream PCWs with short and long duration in the Mars Global Surveyor (MGS) magnetometer data at Mars were reported by several authors [e.g., *Brain et al.*, 2002; *Mazelle et al.*, 2004; *Bertucci et al.*, 2005; *Wei and Russell*, 2006]; an extensive study found PCWs for long observation times of several hours and therefore for a large range of cone angle values [*Bertucci*, 2003]. In the literature the generation of PCWs is often discussed for quasi-perpendicular configurations of the magnetic field and the solar wind velocity, i.e., from a pure ring distribution of the pickup ions in velocity space. From a small set of nine of the MGS premapping orbits, the so-called AB1 phase of the mission, *Wei and Russell* [2006] suggested a mechanism for intermittent wave generation from a nonspherically symmetric but disk-shaped neutral hydrogen exosphere with asymmetry in the direction of the interplanetary electric field: At initial pickup the protons are expected to have a ring distribution with no parallel velocity in the planetary frame; reneutralization by charge exchange should happen very soon after ionization in the first part of the gyration-cycle, such that the now again neutral particles continue their paths in direction of positive motional electric field. The reneutralized hydrogen reaches larger distances from the planet and only on the side of positive electric field, thus creating an asymmetric disk of neutrals perpendicular to the magnetic field. From this disk, reionization should take place with subsequent generation of PCWs, which are observed only as MGS crosses the disk, which will be for short times only. The PCWs from this mechanism should occur mainly to the side and downstream of the planet and be intermittent.

[29] To see if such a mechanism can be at work at Venus, we study the PCW occurrences from 450 orbits in a Venus centered electromagnetic reference frame VBE ($x_{VBE}$ axis positive toward the Sun, $y_{VBE}$ axis positive in direction of the local mean magnetic field component perpendicular to Venus-Sun line, $z_{VBE}$ axis positive in direction of local motional electric field $\boldsymbol{E} = -\boldsymbol{V}_{sw} \times \boldsymbol{B}$) and as function of $B_{perp}$, the magnetic field component perpendicular to the solar wind velocity, which is a measure for the motional electric field $\boldsymbol{E}$; large $B_{perp}$ corresponds to strong electric field. In order to avoid the bias for badly defined direction of the electric field due to the data accuracy limit, i.e., for small cone angles and low total field $B_t$, we restrict this analysis to cases with well defined cone angle in the range 20°–160°.

[30] According to the proposed generation mechanism for PCWs, we should expect wave occurrences for large $B_{perp}$ preferably at large distance from the Venus-Sun line and with the larger amplitudes further out, also mainly on the side or downstream of the terminator line.

[31] Figure 6 (left) shows the distance of the wave observation positions from the Venus-Sun line as function of $B_{perp}$; the waves mainly occur within the range 3–7.5 $R_V$ from the Venus-Sun line for any value of $B_{perp}$. The largest amplitudes are observed around 3–5 $R_V$, but not further out; for weak electric field (small $B_{perp}$) waves occur at lower and also higher distances, i.e., no trend for larger distances at larger $B_{perp}$ can be detected. This means that the waves are observed at initial ionization and not after reneutralization and secondary ionization at large distance. Therefore it is not necessary that the ions have a ring distribution with no parallel velocity at initial ionization. From the analysis of the cone angles at which the waves occur, we know that mainly (anti) parallel conditions of $\boldsymbol{B}$ and $\boldsymbol{V}_{sw}$ prevail, defining large parallel velocities of the pickup ions.

[32] There is also a problem of time scales: The proposed wave generation mechanism at secondary ionization in direction of positive electric field requires a significant time span after initial ionization. Reneutralization through charge exchange takes place with a low time rate, due to the low electron density in the Venus exosphere; neutralization frequency and ionization frequency (~1.4 $10^{-7}$) are both low [*Kallio et al.*, 1997, 2006]. Secondary ionization again will take a certain time, and after that, time is needed for energy transfer from the secondary pickup ion ring distribution to the waves. In fact, in this long time scale required for the suggested mechanism, the particles will be assimilated in the solar wind and swept away into the interplanetary space behind the planet, before any wave generation can take place; also the time needed for wave growth (~10 cyclotron periods) to obtain observable PCWs is not negligible. Furthermore, the density of the secondary pickup ions will be extremely low, too low to account for the energy in the observed PCWs. Recent numerical simulations of hydrogen ion escape at Venus by *Jarvinen et al.* [2010] also show that the highest escape primary pickup proton flux is concentrated in the direction of negative motional electric field.

[33] From the above arguments we cannot support the suggested mechanism at secondary ionization; our analysis shows that the waves observed by MAG at Venus are generated at initial ionization from local neutral hydrogen and mainly under quasi-parallel conditions of the solar wind velocity and magnetic field direction.

[34] Figure 6 (right) displays the observation positions in the ($x_{VBE}$, $z_{VBE}$) plane; here the magnetic field lines are parallel to the $x$ axis and the waves travel along them with the solar wind from left to right. Some waves are observed already far upstream from the planet toward the Sun. For $B_{perp}/B_t > 0.7$ we have $B_{perp} > B_{//}$ and cone angles in the range 45°–135°. The PCW positions with such field conditions are predominantly located behind the terminator line,

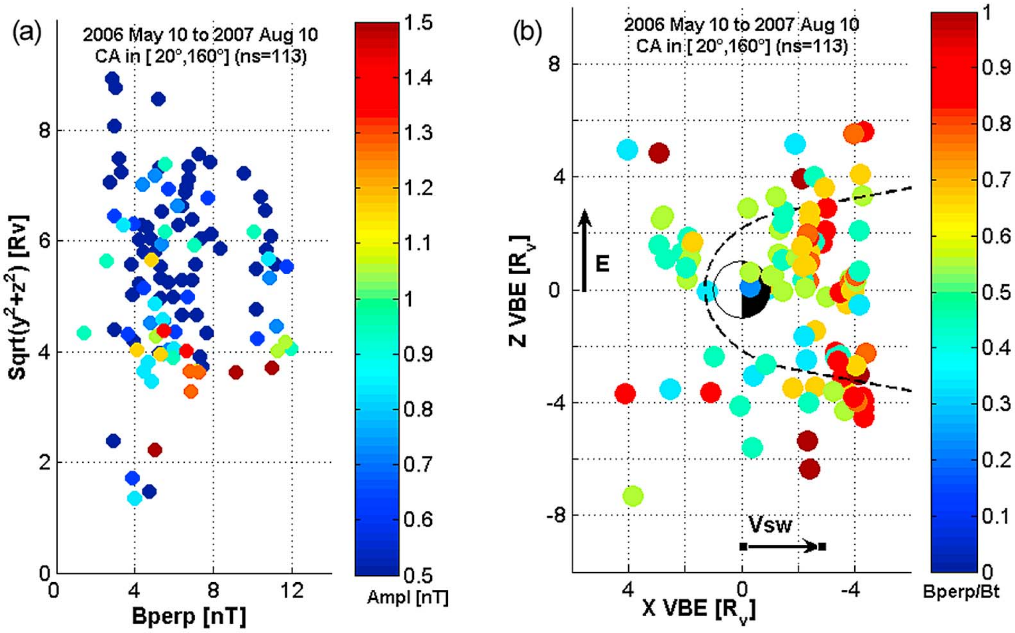


**Figure 6.** PCW observation positions as function of the field component $B_{perp}$ perpendicular to the solar wind velocity, restricted to cases with well defined motional electric field, i.e., cone angle in (20–160)°, $ns$ = 113. (a) Distance from Venus-Sun line, color coding according to wave amplitude. Also for small but well defined $B_{perp}$ or weak electric field, waves are observed up to large distances. (b) In the VBE reference frame, color coding according to $B_{perp}/B_t$ which is proportional to the electric field strength; waves are observed far into regions of negative electric field and far in direction toward the Sun; the dashed line denotes the modeled bow shock.

whereas for quasi-parallel conditions the positions occur everywhere. This can be explained by the growth rate of the waves, which depends on the cone angle: Growth rate is slower for quasi-perpendicular field conditions. If wave growth is slow, more pickup ions are required to get waves strong enough to be observable in the magnetometer data, i.e., if the wave travels through a volume of space with higher density. In the ($x_{VBE}$, $z_{VBE}$) plane the magnetic field lines are parallel to the $x$ axis, and on this path the region with highest neutral density is always on the terminator line. Therefore increased pickup occurs at the terminator line and from there the waves for large $B_{perp}/B_t$ can get strong enough to be observable in the magnetometer data.

## 7. Highly Coherent Waves Far on the Sunward Side

[35] It is especially interesting that PCWs are detected in direction to the Sun as far as the spacecraft orbit reaches toward positive $x_{VSO}$ (Figure 1). It is seen that in general the coherence of the waves increases closer the planet; however, also highly coherent waves are observed far toward the Sun and at large distance from the Venus-Sun line. We investigate the case of 30 min of PCWs (27 November 2006, 0300 to 0330 UT) at $x_{VSO}$ = 4 $R_V$ while the spacecraft was approaching the Venus-Sun line (indicated by the arrow in Figure 1); the waveform for 5 min is shown in VSO coordinates in Figure 7. Analysis of the wave properties for a short subinterval in the principal axes system yields the polarization, ellipticity, and coherence with values of 85%, −0.74, and 0.73, respectively (Figure 7b). The waves move with the solar wind toward Venus, such that sufficient wave growth has taken place already closer to the Sun than $x_{VSO}$ = 4 $R_V$; development of wave growth and high coherency is only possible if enough pickup ions are available. From this it is clear that sufficient neutral planetary hydrogen must be available up to large distances from the planet in direction to the Sun, at least at some times. When the waves are seen for 10 min (and longer), they traveled approximately 24,000 km or another 4 $R_V$ downstream. Therefore we must assume that a significant density of neutral hydrogen exists far from the planet and up to 8 $R_V$ in the solar direction. This is an additional argument for the existence of an extended neutral hydrogen exosphere around Venus, as was concluded earlier from the survey of proton cyclotron wave observations by Venus Express, where local neutral hydrogen densities significantly higher than $n_H$ = 2 cm$^{-3}$ at altitudes of 5 $R_V$ (higher than $n_H$ = 1 cm$^{-3}$ at 8 $R_V$) were derived from linear theory [*Delva et al.*, 2009].

[36] A new study [*Wei et al.*, 2010] used magnetometer data from 34 orbits of Venus Express to analyze upstream waves in a wide frequency range (0.5–1.5) $f_p$ of the local proton cyclotron frequency. The authors report that these waves have only some similarity with PCWs from local ion pickup and are mainly connected to the bow shock, and they therefore conclude that the region of exospheric proton cyclotron wave production may be restricted to the Venus magnetosheath. This is not in accordance with our findings

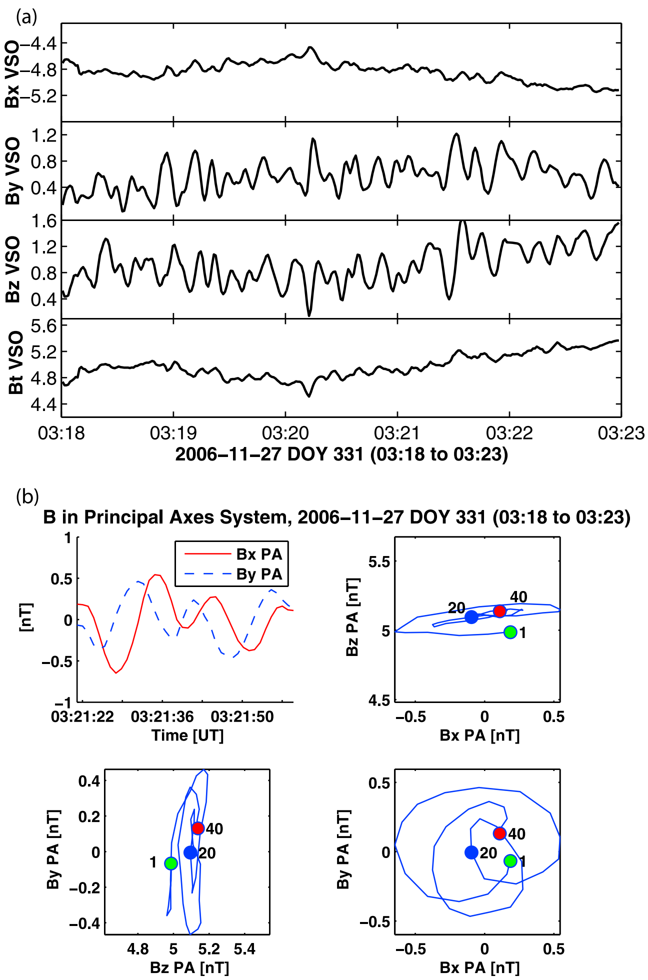


**Figure 7.** Case study for highly coherent waves at $x_{VSO}$ = −4 $R_V$ on 27 November 2006, 0318–0323 UT: (a) Wave form in VSO coordinates. (b) Wave properties in principal axes frame ($x_{PA}$, $y_{PA}$ axes in the wave plane, $z_{PA}$ axis normal to the wave plane). At the top is shown waveform in $(B_x$ and $B_y)_{PA}$ components for 40 s of time. The rest of the figure shows a hodogram in each plane of the principal axes frame for the same time of about three cycles; markers every 20 s, starting with 1 and in increasing order with time. The wave is nearly circular in ($x_{PA}$, $y_{PA}$) plane.

of 157 cases of left-hand polarized waves in the frequency range (0.8–1.0) $f_p$ from 450 orbits or two full Venus years of the same spacecraft, which are clearly proton cyclotron waves generated by pickup of planetary protons upstream of the bow shock. From the derivation of the proton cyclotron wave frequency in the spacecraft frame in equation (3), we know that the frequency is the crucial criterion for identification of PCWs generated from pickup of local hydrogen, i.e., precisely at or very close to the local proton cyclotron frequency; lower and higher frequency waves are generated by other mechanisms. The study by *Wei et al.* [2010] analyzed a much wider frequency range (only five of the cases are within the limited range (0.8–1.0) $f_p$ [see *Wei et al.*, 2010, Figure 6], so most of the there reported waves will be of other origin than from local pickup of planetary hydrogen.

## 8. Conclusions

[37] We have analyzed Venus Express magnetometer observations of waves at the local proton cyclotron frequency and left-hand polarized in the spacecraft frame from two full Venus years or 450 orbits with regard to the required magnetic field conditions for generation and maintenance of such waves. We found that before the occurrence of observable PCWs in the data, a stable magnetic field is established for at least 20 min. The stable conditions have the specific configuration of quasi-parallel magnetic field and solar wind velocity; this means that the cone angle of the field is in the interval 0°–60° for parallel and 120°–180° for antiparallel orientation. Maintenance of the PCWs during intervals longer than 10 min is observed only if the above conditions are stable for the longer time, with variations in the cone angle not larger than ±10° and in the total field not larger than ±1 nT.

[38] The findings of PCWs mainly under quasi-parallel field conditions are in accordance with the theory, which predicts efficient wave generation for parallel injection of pickup ions into the solar wind plasma with faster growth of the right-hand polarized mode in the plasma frame, which is observed as left-hand polarized in the spacecraft frame.

[39] The requirement of stable magnetic field conditions for generation and maintenance of the PCWs answers the question, why most of the wave observations are of short duration, mainly not longer than 10 min. Stable conditions in the solar wind are not frequently met at the solar distance of Venus, certainly not on longer time scales; moreover, the stable conditions have to be valid for the given restricted range of cone angles.

[40] The positions of the wave observations do not depend on the motional electric field, leading to the conclusion that the PCWs are generated at initial ionization and pickup from locally available neutral hydrogen. This is specifically confirmed by the observation of highly coherent waves at large distance from the planet toward the Sun (4 $R_V$), already at the furthest orbital limit of the spacecraft, which implies the existence of a sufficiently dense extended hydrogen exosphere at Venus.

[41] In comparison to observations of proton cyclotron waves at Mars and of ion cyclotron waves at comets, the density of the pickup ions relative to the background plasma appears to be an important parameter for possible wave generation. For high relative pickup ion density, cyclotron waves may be generated for any stable configuration of the magnetic field; for low relative density, only the most efficient mechanism under stable field conditions leads to observable waves, i.e., the ion/ion beam instability for the specific configuration of quasi-parallel magnetic field and solar wind velocity.

[42] The observation of cyclotron waves at large distances from Mars (up to 6 $R_M$), comets and here at Venus (up to 8 $R_V$) proves that the magnetic field is a very sensitive means for detecting the most rarified outer parts of exospheres, even for exospheric pickup ion densities as low as 0.01% of the background plasma, which is long before any

other instrumentation can provide evidence of the signature of the approaching celestial body.

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