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The bow shocks and upstream waves of Venus and Mars

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Abstract

Because they both lack measurable magnetic fields, Venus and Mars are often compared to each other in terms of their solar wind interaction. Upstream from each planet the most distant signs of this interaction occur at the bow shock, and in regions upstream from the shock where plasma waves are observed. In many respects the collisionless shocks at Venus and Mars are quite different. The Martian shock is located slightly farther from the planet (with respect to planetary size) and is more variable than the Venus shock. In addition, the position of the Martian shock is not observed to correlate strongly with solar cycle, unlike at Venus. These differences indicate that the solar wind obstacles at the two planets are somehow quite different. However, the characteristics of observed upstream waves at the two planets (and at other solar system bodies) suggest that similar processes are at work at both shocks, and that the size and shape of the shock do not play significant roles in wave generation or damping. This review compares the observations of the bow shocks and upstream waves at Venus and Mars, with reference to model predictions and observations at Mercury and Earth.

Keywords: Venus and Mars; Bow shocks; Upstream waves

1. Motivation

Bow shocks form upstream of any electromagnetic obstacle to the solar wind. Earth's obstacle to the solar wind is its global magnetic field, and we test our understanding of Earth's shock by extending our theory and models to observations at other planets possessing global magnetic fields: Mercury, Jupiter, Saturn, Neptune, and Uranus. Both Venus and Mars, however, lack appreciable global magnetic fields – the obstacle to the solar wind at both planets results primarily from currents induced in their ionospheres. Therefore, Venus and Mars present interesting laboratories for investigation of the more general nature of shocks in the solar system. Further, we do not expect the shocks at Venus and Mars to be entirely similar; Mars is located at a greater heliocentric distance than Venus and is also much smaller. The former point means that the solar wind density and embedded magnetic field strength is higher at Venus than at Mars. The latter point has two consequences: the Martian bow shock is physically smaller than the shock at Venus, and the Martian exosphere extends beyond the bow shock due to the weak Martian gravity. Finally, Mars' small size coupled with the low strength of the interplanetary magnetic field (IMF) at Mars makes the gyroradius of solar wind protons comparable to the size of the planet. Kinetic effects are therefore potentially important at Mars.

In addition to direct observations of planetary bow shocks, spacecraft observations of plasma waves upstream from the shocks also yield important information about the physical processes occurring at the shock. A variety of waves have been observed upstream from many solar system planets – similarities in the observed waves at all planets indicate that a similar set of physics operates at all bow shocks. Differences in the observed characteristics of these waves highlight differences in shock shape, solar wind parameters, charged particle characteristics, and (in the case of Mars and Venus) the role of the exosphere at the location of the shock.

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Though several spacecraft have returned observations of the bow shocks and upstream waves at Venus and Mars in the past 30 years, detailed studies of the physical processes operating at these bow shocks have been limited in the past decade by the number and type of spacecraft to visit these planets. There have been no new observations of the dayside Venus shock since the Pioneer Venus Orbiter made observations from 1978 through the 1980s. The Mariner 4, Mars 2, Mars 3, Mars 5, and Phobos 2 spacecraft returned observations of the Martian shock from 1964 to 1989 (Slavin et al., 1991). Continued analyses of the Phobos 2 observations have yielded several new results since 1997. These results have been supplemented by a large database of bow shock crossings by the Mars Global Surveyor (MGS) spacecraft from 1997 to 1998. However, MGS was equipped with no plasma instruments other than a magnetometer and electron reflectometer. Shock studies by MGS have therefore been limited to the shape, size, and variability of the Martian shock, the energy flux of electrons near the shock, and low frequency electromagnetic plasma waves near and upstream from the shock that can be resolved in magnetometer observations.

This review summarizes the current understanding of the bow shocks and upstream plasma waves at Venus and Mars. Reviews of these topics can be found in Brecht (1995); Russell et al. (1992a); Spreiter and Stahara (1995); Strangeway (1991); Russell et al. (1992b). In addition to briefly summarizing the older observations discussed in these reviews, I address more recent information published since the arrival of MGS at Mars in 1997. Additional information about plasma waves throughout the magnetic environments of Venus and Mars is available in Strangeway (2004).

2. Bow shocks

A collisionless bow shock forms upstream from a planetary obstacle to the solar wind, serving to slow the flowing solar wind plasma from supersonic to subsonic. A number of different parameters are used to classify bow shocks theoretically and observationally. The Mach number (magnetosonic Mach numbers are often used, as well as sonic and Alfvenic Mach numbers) indicates the amount of deceleration and heating that occurs at the shock (the strength of the shock). The angle that the upstream magnetic field makes with the normal vector to the shock surface ($\theta_{\mathrm{B}\hat{\mathrm{n}}}$) affects the motion of charged particles near the shock, and affects the observed shock morphology (turbulence, length-scale, etc). The size of the solar wind obstacle largely determines the size of the shock relative to the planet – both Venus and Mars have small shocks relative to planetary size, as shown in Fig. 1(a). However, the physical size of the shock (shown in Fig. 1(b) and characterized by a radius of curvature) is also relevant because it dictates length scales for physical processes operating near the shock as well as the amount of space the upstream solar wind has available to be slowed and deflected around the solar wind obstacle. Finally, in the case of Venus and Mars (where the shocks form close to the planet) the extent of the exosphere determines the composition, densities, and temperatures of different particle populations near the bow shock.

Fig. 1 summarizes the size and shape of the shocks of the terrestrial planets as determined in Slavin and Holzer (1991). It is evident from the figure that (with respect to planetary size) the shocks at Venus and Mars are quite small compared to planets with intrinsic solar wind obstacles. Further, the Martian shock is slightly larger

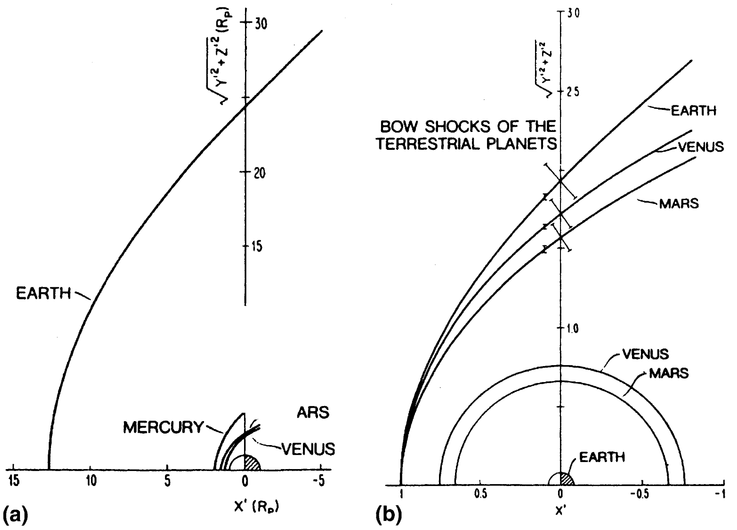

Fig. 1. Bow shocks of the terrestrial planets, from Slavin and Holzer (1991). The left-hand figure shows the shocks relative to the size of the planet. The right-hand figure shows the shocks normalized to the subsolar distance from the center of the planet.

than the Venus shock relative to the size of the planet; this may be a result of mass loading of the solar wind flow at Mars by its extended exosphere (Russell et al., 1992a). The Martian shock is however physically smaller than the shock at Venus. The flowing solar wind must be decelerated and heated in a much shorter distance downstream from the Martian shock, which has possible implications for the thermalization of protons in the Martian sheath (Dubinin et al., 1995).

Overall, the Martian shock is more turbulent and its location is twice as variable as the shock at Venus (Schwingenschuh et al., 1990; Slavin et al., 1991). The location of the shock at Venus varies with the solar cycle (Russell et al., 1990b); this variation is believed to result from variations in the amount of mass-loading from solar EUV at Venus, though models have difficulty reproducing this effect (Spreiter and Stahara, 1995). Suprisingly, the shock at Mars (where mass loading is believed to play a more important role than at Venus due to the extent of the Martian exosphere) is less sensitive to solar EUV and exhibits at most a small variation in size over the solar cycle (Russell et al., 1992a; Slavin et al., 1991; Vignes et al., 2000).

Not shown in Fig. 1 is the observation that both bow shocks are more distant in the hemisphere of the planet in which the solar wind electric field is “up” (away from the planet) (Russell et al., 1992a; Vignes et al., 2002). This asymmetry has been reproduced in kinetic simulations of the Martian magnetic environment (Brecht, 1997), and indicates that mass-loading of the plasma flow downstream from the shock may play a role in making the shock larger in the hemisphere in which newly created charged particles are carried away from the planet by the solar wind electric field. These observational results provide critical evidence that kinetic effects may be important in the Martian solar wind interaction.

Shock crossings at Venus, Mars, and Earth have similar magnetic field morphologies despite the enormously different scale-sizes at each planet. Quasi-perpendicular shock crossings (where the upstream field is roughly perpendicular to the shock normal vector) at these planets have foot, ramp, and overshoot regions. The thickness of the overshoot regions scale with the proton gyroradius (which is quite different relative to the size of the sheath at each planet), and corresponds to a thickness of 4–8 times the ion inertial length (Tatrallyay et al., 1997). Further, the magnitude of the overshoot is correlated with the fast Mach number (Tatrallyay et al., 1997). These results suggest that reflection of ions (first suggested in Russell et al. (1982)) plays an important role in the structure of perpendicular shocks.

Another way in which the terrestrial shock is similar to that at an unmagnetized planet was recently noted by Øieroset et al. (2001). who identified hot flow anomalies (HFAs) upstream from the Martian shock using MGS electron and magnetic field data. HFAs are regions of hot plasma and turbulent magnetic field surrounded by high electron density and strong magnetic field. They are observed in Earth’s foreshock only rarely (Thomsen et al., 1988), and are thought to result from the interaction of an interplanetary current sheet with ions reflected from the bow shock. It was suggested that HFAs should be commonplace at Mars due to the “overreflection” of protons from the Martian shock (Dubinin et al., 1995). However, HFAs occur only rarely in MGS observations, similar to Earth. The fact that HFAs are not common in observations at these two planets means either: HFAs are not common; or observation of HFAs requires that a spacecraft be located close to the intersection of an interplanetary current sheet with the bow shock at the time of its arrival (Sibeck et al., 1999). These observations teach us that the physics responsible for HFAs at Mars and Earth are similar. Further, the Martian observations contradict early ideas (e.g., Thomsen et al., 1986; Paschmann et al., 1988) that HFAs originate at Earth’s magnetopause (since Mars’ lack of a global magnetic field implies that it does not have a magnetopause) (Øieroset et al., 2001).

One unique aspect of the Martian shock is the observed deceleration of the solar wind upstream from the shock (Verigin et al., 1992). Deceleration of the upstream solar wind near the shock is observed at Earth, and is attributed to interaction of the solar wind with charged particles reflected from the shock (c.f. Kotova et al. (1997) and references therein). The observed deceleration at Earth, however, is quite small (7–10 km/s – see Bame et al. (1980)) compared to decelerations as high as 100 km/s observed by the ion mass spectrometer on Phobos 2. Two mechanisms were proposed for this observation at Mars: mass-loading by heavy planetary ions from the Martian exosphere (Verigin et al., 1992) and interaction with reflected protons (solar wind and/or exospheric) from the shock (Ip, 1992). Analyses of Phobos 2 data show a correlation between the magnitude of the solar wind deceleration and the upstream solar wind density, consistent with the mass-loading explanation (Kotova et al., 1997). However, the neutral oxygen number density required for this process is 3–10 times greater than the observed number density, and Mars’ small size may not provide enough room for mass loading upstream from the shock. Recently Dubinin et al. (2000a,b) have shown that the deceleration is observed mainly in the Martian foreshock, and that flow and field perturbations are correlated. They propose that the solar wind deceleration is caused not by mass loading, but by Alfven waves propagating in the solar wind. They also show that mass-loading is an important process at lower altitudes.

3. Upstream plasma waves

Though the bow shock is commonly considered the most sunward indication of the solar wind interaction with a planet, plasma waves are often observed upstream from planetary bow shocks. Most of these waves are observed in a region called the foreshock, where interplanetary magnetic field lines intersect the bow shock. Charged particles in the foreshock are able to propagate upstream from the bow shock in the solar wind, which flows toward the planet at speeds of roughly 400 km/s. Electrons propagate faster than ions, and can be found further upstream (in the electron foreshock) than ions (located in the ion foreshock). Charged particles propagating upstream may have been reflected from the shock, may have leaked through the shock from the magnetosheath, and may even have originated at the shock (there is some evidence that the Martian shock is a source of cold ions). Plasma waves have been observed in the foreshocks of every planet visited by spacecraft. In addition to shock-related plasma waves or waves associated with back-streaming particles, it is also possible that ionization of the extended neutral Martian exosphere upstream from the shock can result in plasma waves. The goal of plasma wave studies at any planet are to take the observed characteristics of the plasma waves (e.g., location, frequency range, electrostatic vs. electromagnetic, polarization, amplitude) determined using the available instrumentation and use them to identify as much as possible about the wave (e.g., wave mode, generation mechanism, spatial origin).

A large number of upstream waves have been reported at Venus and at Mars; many of these waves have been observed at Earth as well. Work on upstream waves at Mars in the past five years has yielded a number of new wave observations, as well as updates to observations made by previous spacecraft. Several examples are discussed below.

Delva and Dubinin (1998) performed a statistical analysis of ULF waves upstream from Mars, finding that the distribution of ULF waves in the Martian ion foreshock is similar to the distribution at Venus and Earth. They also found ULF waves upstream from the foreshock boundary (similar waves are not reported for Venus or Earth), which may be attributable to pickup of planetary ions upstream from the shock or to effects in the solar wind.

Whistler waves have recently been reported upstream from the Martian shock (Brain et al., 2002). Similar waves have been observed at Mercury, Venus, Earth, and Saturn (Orlowski and Russell, 1995). Upstream whistlers (or 1 Hz waves) were first reported at Earth by Russell et al. (1971), and were subsequently identified by Fairfield (1974). The observed wave signatures are caused by right-hand polarized waves (electron generated) propagating upstream from the shock with group velocity greater than the solar windflow velocity and phase velocity smaller than the solar wind velocity. The waves are doppler-shifted in the spacecraft frame, and their observed polarization depends upon the angle between the wave propagation vector and the solar wind velocity vector. When the two vectors are roughly parallel the wave is observed as left-hand polarized. Fig. 2 shows a power spectrum and hodogram for upstream whistlers at Venus. Fig. 3 shows the frequency and polarization of whistler waves at Mars.

Table 1 summarizes the characteristics of upstream whistlers at the different planets at which they have been observed. The fact that these waves have been observed at all of these planets indicates that the physics responsible for these waves operates at all solar system shocks. The trends in the waves with increasing heliocentric distance (frequency and amplitude decrease, propagation angles with respect to the solar wind flow and background magnetic field increase) indicate that solar wind parameters such as the spiral angle of the

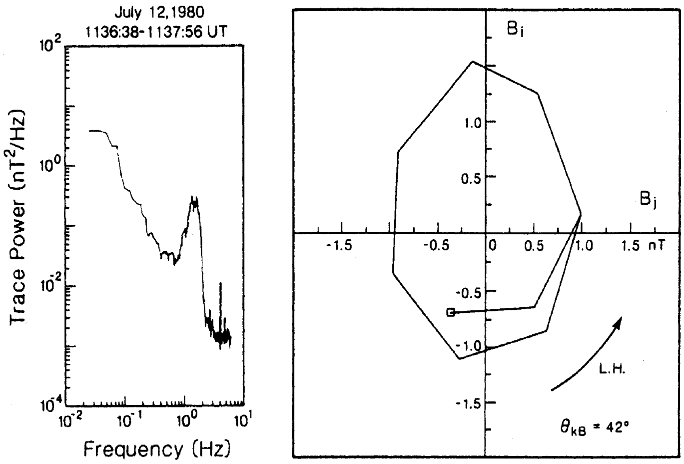

Fig. 2. Upstream whistler waves at Venus, from Orlowski and Russell (1991). At left is a power spectrum of left-hand polarized whistlers. At right is a hodogram of the wave polarization.

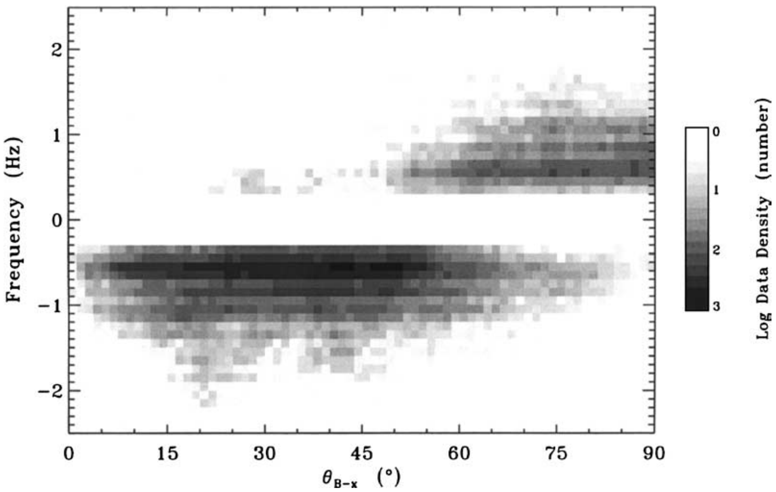

Fig. 3. Polarization of upstream whistler waves at Mars as a function of the angle between the background magnetic field vector and the solar wind flow (assumed to be flowing radially away from the Sun). Negative frequencies are left-hand polarized waves. The figure is from Brain et al. (2002).

Table 1
Properties of upstream whistler waves in the solar system, from Brain et al. (2002)

	Mercury	Venus	Earth	Mars	Saturn
Frequency (Hz)	2.5–3.0	1.0–1.8	0.8–1.5	0.5–0.8	0.1–0.2
Amplitude (nT)	0.2–3.2	0.3–1.9	0.1–0.6	0.2–0.5	0.01–0.04
Eccentricity	0.2–0.65	0.75–0.99	0.71–0.9	0.73–0.89	0.6
θ_{kB} (°)	7–53	5–51	5–57	19–40	40–60
θ_{kx} (°)	0–37	8–30	9–36	21–38	60–70

magnetic field play a role in the formation of the waves. Several outstanding questions remain about upstream whistlers: the generation mechanism for the waves is debated and it is not known whether temperature anisotropies play a role in the formation or damping of the waves.

Waves at the local proton gyrofrequency (in the rest frame of the spacecraft) were first observed at Mars by Russell et al. (1990a) using Phobos 2 magnetometer data (Fig. 4). The orbit geometry of the MGS spacecraft at Mars enabled identification of a large number of waves at the local gyrofrequency – both upstream and downstream of the Martian shock (Brain et al., 2002). The spatial distribution of those waves observed upstream from the shock is shown in Fig. 5. This distribution likely includes more than one type of plasma wave; however a significant fraction of the waves identified in MGS data have characteristics similar to the waves identified in Phobos data. There is still some question as to the generation mechanism for waves near the local gyrofrequency. A fairly straightforward explanation is that these waves result from pickup of the Mars' extended hydrogen exosphere (Russell et al., 1990a). A second explanation is that these waves result from the fact that recently ionized exospheric particles act as a beam in the solar wind (Sauer et al., 2001). The resulting beam instability generates waves which are observed at the local gyrofrequency in the planetary rest frame (which is nearly identical to the spacecraft rest frame) (Mazelle et al., 2001). In either case, upstream waves near the local gyrofrequency indicate an interaction between the Martian exosphere and the solar wind and have little to do with the Martian shock. Russell et al. (1992b) noted that similar waves are not observed upstream from Venus, where the exosphere is less extended than at Mars.

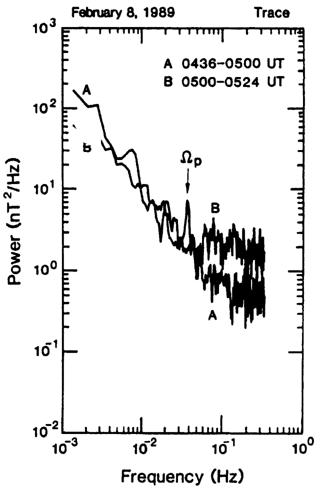

Fig. 4. Power spectrum of upstream waves at the local proton gyrofrequency at Mars from Phobos data. The figure is from Russell et al. (1990a).

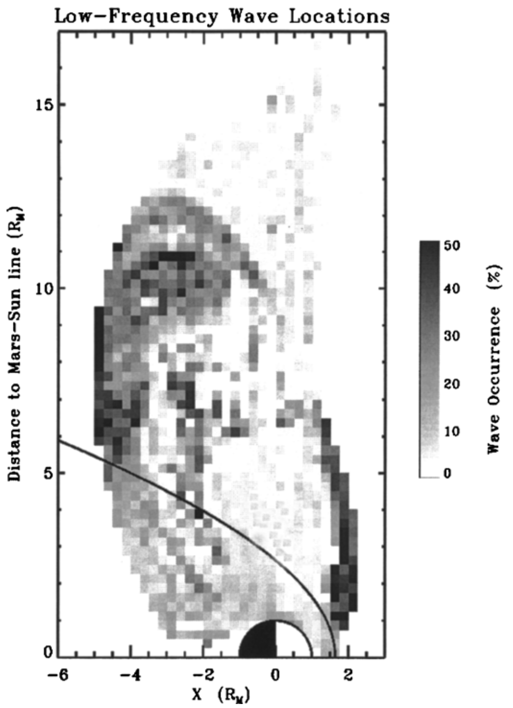

Fig. 5. Spatial distribution of waves at the local proton gyrofrequency at Mars from MGS observations. The figure is from Brain et al. (2002).

The recent work summarized above is by no means a complete accounting of the active research on upstream waves at Mars and Venus. The addition of MGS magnetic field and electron data to the available observations has enabled several new and more detailed studies of low frequency electromagnetic waves throughout the Martian system (e.g., Bertucci et al., 2004). Older data sets, however, continue to offer information about higher frequency waves in the foreshock regions of both Mars and Venus. Of particular interest is the relationship between the size and curvature of the shock and waves observed in the foreshock region. VLF waves at Venus have been identified as Langmuir waves in the electron foreshock and ion acoustic waves in the ion foreshock (see Crawford et al. (1998) and Strangeway (2004) for more detailed discussion of the Langmuir waves). Statistical analyses of the observed locations and wave characteristics at Venus provide insight into the source of charged particles generating the Langmuir waves (reflected solar wind electrons) and the nature of the ion distributions causing the ion acoustic waves (diffuse). Trotignon et al. (2000) "imaged" the electron foreshock at Mars using electron plasma waves in the frequency range 6–130 kHz measured by the PWS instrument on the Phobos spacecraft. Their results are consistent with the idea of Strangeway and Crawford (1995) that the energization of electrons is limited by the small size of the Martian shock. Skalsky et al. (1998) presented additional results from the same instrument on Phobos 2, showing that waves in the frequency range 50–200 Hz are evident upstream of the electron foreshock approximately 30% of the time. The origin of these waves (in the foreshock or in the solar wind) is unclear, but may be related to the mechanism proposed by Dubinin et al. (2000a,b).

4. Discussion

A few main points should be emphasized from the preceding sections. First, the bow shocks at Venus and Mars are smaller than at other planets, relative to the size of the planet. The Martian shock is physically smaller than the shock at Venus, which has implications for the plasma processes active at the shock and the amount of space available for the deceleration of the solar wind downstream from the Martian shock. The Martian shock is more variable than the shock at Venus. A great variety of upstream waves have been detected at both Venus and Mars (see the review by Strangeway (2004) for more information about waves at Venus), providing valuable clues about the physics of the shock and foreshock regions at these planets. Mars differs from Earth and from Venus in that upstream waves are caused not only by particles reflected or leaked upstream through the bow shock, but waves are also caused by interactions between the solar wind and the exosphere.

Several outstanding questions should be addressed in future analyses and observations. What processes account for the differences between the shocks at Venus and Mars? How important are kinetic effects at these planets? If mass-loading makes the Martian shock slightly larger than the shock at Venus, why is there not a significant variation in the size of the Martian shock with the solar cycle as there is at Venus? Which fundamental properties of a shock and the solar wind affect upstream waves at Venus, Earth, and Mars? What more can we learn about the different particle populations (incident solar wind, reflected particles, shocked solar wind, and exosphere) from upstream waves? Answers to these questions may come from continued analysis of existing data sets and from comparisons of data sets from different spacecraft missions at different planets. Answers may also come from future observations made at these planets, such as those that will be made by NOZOMI when it arrives at Mars in 2003.

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