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THE ROLE OF PICKUP IONS ON THE STRUCTURE OF THE VENUSIAN BOW SHOCK AND ITS IMPLICATIONS FOR THE TERMINATION SHOCK

Quanming Lu[1], Lican Shan[1], Tielong Zhang[1,2], Gary P. Zank[3], Zhongwei Yang[4], Mingyu Wu[1], Aimin Du[5], and Shui Wang[1]
[1] CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Science, University of Science and Technology of China, Hefei 230026, China; qmlu@ustc.edu.cn
[2] Space Research Institute, Austrian Academy of Sciences, Graz, Austria
[3] Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama in Huntsville, Huntsville, AL 35899, USA
[4] SOA Key Laboratory for Polar Science, Polar Research Institute of China, Shanghai, China
[5] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
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ABSTRACT

The recent crossing of the termination shock by *Voyager 2* has demonstrated the important role of pickup ions (PUIs) in the physics of collisionless shocks. The *Venus Express* (*VEX*) spacecraft orbits Venus in a 24 hr elliptical orbit that crosses the bow shock twice a day. *VEX* provides a unique opportunity to investigate the role of PUIs on the structure of collisionless shocks more generally. Using *VEX* observations, we find that the strength of the Venusian bow shock is weaker when solar activity is strong. We demonstrate that this surprising anti-correlation is due to PUIs mediating the Venusian bow shock.

Key words: shock waves – Sun: activity

1. INTRODUCTION

Solar wind, which is continuously emitted from the Sun, flows supersonically outward at a speed of $\sim$300 km s^{-1} to 800 km s^{-1} until it reaches the heliospheric termination shock, at which it is decelerated and heated (see the review by Zank 1999). The heliospheric bubble is bounded by the heliopause, which separates the solar wind from the partially ionized local interstellar medium (LISM). The partially ionized LISM comprises an equilibrated admixture of neutral hydrogen (H; and other neutral gases) and plasma at a temperature of $\sim$6200 K. The cold interstellar neutral H gas drifts into the heliosphere, where it is ionized and becomes a suprathermal pickup ion (PUI) population (e.g., Fahr et al. 2007; Zank et al. 2009; McComas et al. 2009). The PUI-contaminated solar wind modifies the properties of the heliospheric termination shock, as predicted by Zank et al. (1996a) and subsequently confirmed by *Voyager 2* observations of the termination shock (Richardson et al. 2008; Richardson 2008).

With the *Voyager 1* (*V1*) and *Voyager 2* (*V2*) crossings of the termination shock in 2004 and 2007, respectively, the role that PUIs play in determining the structure and dissipation mechanism of the termination shock (Zank et al. 1996a; Richardson et al. 2008; Richardson 2008; Burlaga et al. 2005, 2008) has attracted considerable attention. The termination shock is weaker than corresponding shocks under apparently similar conditions (Richardson et al. 2008; Burlaga et al. 2005), in part due to the deceleration of the bulk solar wind by PUI deceleration (Pauls et al. 1995; Zank et al. 1996b; Fahr & Rucinski 1999), and due to the mediation of the shock by anomalous cosmic rays (Chalov & Fahr 1996, 1997; Le Roux & Fichtner 1997; Florinski et al. 2009). Both theory (Zank et al. 1996a, 2010) and simulations (Liewer et al. 1993; Lipatov & Zank 1999) have predicted that the presence of PUIs will decrease the strength of a collisionless shock. However, due to relatively few crossings of the heliospheric termination shock by *V2*, it is difficult to develop more general conclusions and a deeper understanding of the role of PUIs in collisionless shocks.

Fortunately, the *Venus Express* (*VEX*) spacecraft, which was launched on 2005 November 9 and reached Venus on 2006 April 11, provides a novel opportunity to investigate the influence of PUIs on the physics of the Venusian bow shock. PUIs on Venus are created by charge exchange or photoionization from cold neutral ionospheric atoms (Luhmann 1986) that have been observed in the near-planet magnetosheath by the Pioneer Venus Orbiter (PVO); the most abundant particles are oxygen (Mihalov & Barnes 1981). Rather remarkably, solar cycle variation has a profound influence on the density of neutral particles in the Venusian ionosphere and their escape from Venus. It is found that almost all of the hydrogen that escapes from Venus does so during periods of solar maximum (Donahue & Hartle 1992), and the density of neutral particles in the Venusian ionosphere is larger when solar activity is stronger (Groller et al. 2010). Another source of PUIs near the Venusian bow shock is the interplanetary helium, whose density also becomes larger when solar activity is stronger (Rucinski et al. 2003). This suggests that during periods of increased solar activity, more PUIs will be present in the vicinity of the Venusian bow shock. Repeated measurements of the bow shock strength during different phases of solar activity should therefore reveal whether a correlation exists between shock strength and solar activity, which would suggest that the PUIs possibly play a role in modifying the characteristics of the shock.

2. *VEX* OBSERVATIONS

The orbit of *VEX* is an ellipse with the periapsis at about 300 km, and a period of about 24 hr, which crosses the bow shock twice a day (Barabash et al. 2007). The *VEX* spacecraft has crossed the Venusian bow shock thousands of times, and it provides excellent statistics for detailed studies of the role that Venusian PUIs play in determining the properties of the bow shock. The magnetic field structure of the collisionless Venusian bow shock can be investigated using the fluxgate magnetometer in *VEX*. The magnetic field data have a sampling rate of 1 Hz,

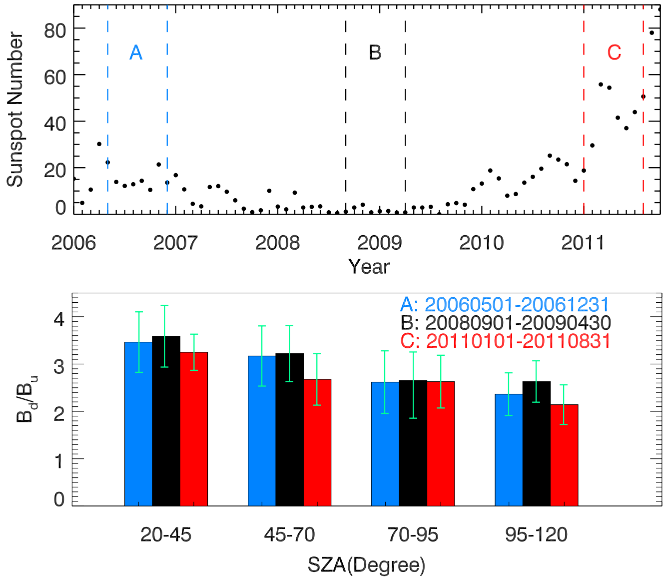

Figure 1. The top panel shows the monthly sunspot number from 200601 to 201112. The bottom panel shows the average ratio of the downstream total field strength to the upstream field strength B_d/B_u at different solar zenith angles (SZA) during three selected periods. (A) 20060501–20061231, (B) 20080901–20090430, and (C) 20110101–20110831. B_u and B_d are the two minute average of the total magnetic field in the upstream and downstream. Here, only shocks with a shock angle $\theta_{\rm Bn}$ larger than 50° (where $\theta_{\rm Bn}$ is the angle between the upstream magnetic field and the shock normal, and the shock normal is determined by the minimum variance analysis (MVA) method) are selected. The total number of selected cases during periods A, B, and C is 79, 85, and 64, respectively. The error bars show the standard deviation in the measurements.

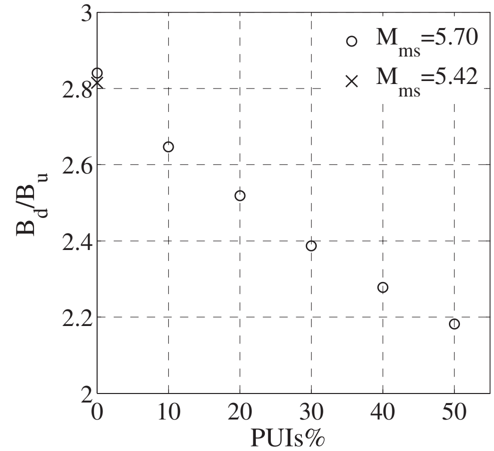

Figure 2. The field jump B_d/B_u at a perpendicular shock for different percentages of PUIs. The results were obtained using 1D PIC simulations, and the field jump is calculated when the shock reaches an almost stationary state. In the simulations, the mass ratio of the ion to the electron is $m_i/m_e = 100$, $\beta_i = \beta_e = 0.5$, and $c/v_A = 20$ (where c is the light speed, and v_A is the Alfvén speed based on the magnetic field upstream and the density of the solar wind). The grid size $\Delta x = 0.005c/\omega_{\rm pi}$ ($c/\omega_{\rm pi}$ is the ion inertial length in the solar wind), and the time step $\Omega_i \Delta t = 0.0002$ (Ω_i is the ion gyrofrequency based on the magnetic field in the upstream region).

and the accuracy of the absolute field is ~1 nT (Zhang et al. 2006).

Figure 1 shows the average magnetic field jump of the Venusian bow shock B_d/B_u at different solar zenith angles (SZAs) during three selected periods: 20060501–20061231, 20080901–20090430, and 20110101–20110831. B_u and B_d are the two minute average of the total magnetic field in the upstream and downstream, respectively. Large amplitude low-frequency waves are present in both the upstream and downstream of a quasi-parallel shock, so we select only those cases with a shock angle $\theta_{\rm Bn}$ larger than 50° (where $\theta_{\rm Bn}$ is the angle between the upstream magnetic field and the shock normal, and the shock normal is determined by the minimum variance analysis (MVA) method; Sonnerup & Cahill 1967). The average sunspot numbers during the three selected periods are 15.2, 1.6, and 41.5, respectively. Evidently B_d/B_u is smaller for all SZA ranges considered here when solar activity is strong.

There are three factors that may lead to the variability of B_d/B_u with different periods of solar activity: the shock geometry, the upstream Mach number, and PUIs. As demonstrated by Zhang et al. (1990), the difference in shock geometry is negligible during different periods of solar activity. Although we do not know the average upstream magnetosonic Mach number at Venus from satellite observations, we can calculate the average magnetosonic Mach number of the solar wind at 1 AU using Advanced Composition Explorer observations (from the Web site http://cdaweb.gsfc.nasa.gov/sp_phys/). We find values of about 6.13, 6.07 and 5.83 during the periods 20060501–20061231, 20080901–20090430, and 20110101–20110831, respectively. The average upstream magnetosonic Mach number at the Venusian bow shock is about 93% of that at 1 AU (Kivelson & Russell 1995). This yields average magnetosonic Mach numbers upstream of the Venusian bow shock during the three selected periods of about 5.70, 5.66, and 5.42, respectively. Note that this neglects the possible contribution of PUIs to the upstream thermal pressure, which would further reduce the magnetosonic Mach number. Nonetheless, we do not anticipate a significant change in Mach number, and, with these values, the modification of the value of the compression ratio B_d/B_u is negligible (Tatrallyay et al. 1984). For example, at a perpendicular shock, the predicted B_d/B_u is about 3.62 and 3.58 when the upstream magnetosonic Mach numbers are 5.70 and 5.42. Therefore, we conclude that PUIs at the Venusian bow shock lead to the different B_d/B_u values during different periods of solar activity. Further evidence that supports this conclusion is that during the SZA range from 55° to 80°, the observed jump at the terrestrial bow shock (we also choose cases with $\theta_{\rm Bn} > 50°$ using magnetic field measurements (Balogh et al. 2001) from the Cluster spacecraft during the two selected periods, 20081212–20090329 and 20110101–20110410) are about 3.21 and 3.20. In this SZA range the shock shape is almost the same for the two planets (Slavin et al. 1979). The observed field jump at the terrestrial bow shock is larger than that at the Venusian bow shock, as reported previously with the ISEE and Pioneer Venus (PVO) spacecraft (Russell et al. 1979). At the same time, the difference between the observed jump at the terrestrial bow shock is negligible during different periods of solar activity. Accordingly, we conclude that Venusian bow shock strength responds in a manner that is anti-correlated with strong solar activity, and that this is due to PUIs modifying the shock compression ratio.

The influence of PUIs on the compression ratio of a collisionless shock can be investigated by one-dimensional (1D) particle-in-cell (PIC) simulations. In the simulations, the particles are injected from the left boundary, and the shock is launched by reflecting the plasma at a rigid right boundary wall. The plasma consists of three components: the electrons, the background solar wind protons with a Maxwellian distribution, and pickup protons which have a shell distribution with a radius equal to the solar wind speed. Figure 2 shows the field jump B_d/B_u at a perpendicular shock with varying percentages of PUIs. As the percentage of PUIs increases, the field jump B_d/B_u decreases. For a magnetosonic Mach number $M_{ms} = 5.70$, the field jump B_d/B_u decreases from about 2.82 to 2.19 as the PUI percentage increases from 0 to 40%. If the density of neutral particles on Venus is considered to fall off with an exponential form, according to the density at an altitude of 1000 km (Groller et al. 2010), we can estimate that the density of oxygen near the Venusian bow shock is about 1 cm^{-3}. The density of the solar wind at Venus is about 14 cm^{-3}, therefore, the PUIs may reduce the field jump B_d/B_u of the Venusian shock significantly. For reference, we also plot the value of $B_d/B_u(=2.81)$ for $M_{\mathrm{ms}} = 5.42$ in the absence of PUIs, illustrating that the variability of the upstream magnetosonic Mach number as observed by *VEX* during different periods of solar activity on B_d/B_u is almost negligible. We conclude that the observed differences in the field jump B_d/B_u during different periods of solar activity are due to the presence of PUIs at the Venusian bow shock. In the simulations, we simply consider that the PUIs have a shell distribution, and in reality the PUIs may have a complicated distribution. At the same time, with the similar upstream conditions, the field jump of the shock in the simulations is smaller than that in the observations, and this may be due to the omission of several heating process in the simulations. However, these will not change our conclusion: the existence of PUIs will reduce the field jump of a shock.

3. CONCLUSIONS AND DISCUSSION

Our important conclusions are that *VEX* observations of the Venusian bow shock show that the magnetic field jump is smaller when solar activity is strong, and that the anti-correlation can be attributed to the presence of more PUIs at the Venusian bow shock when solar activity is strong. Our conclusions are supported by 1D PIC simulations which show that the magnetic field compression ratio decreases as the percentage of PUIs present in the background plasma increases. This is an important universal result. At the heliospheric termination shock, V2 has found evidence supporting the notion that PUIs can weaken the heliospheric termination shock. More recent observations made by the *IBEX* spacecraft (McComas et al. 2012) and supporting modeling (Zank et al. 2013) suggest that the heliospheric bow shock may be mediated by interstellar neutral hydrogen. Therefore, we believe that the Venusian bow shock provides an excellent opportunity to study the interaction between PUIs and collisionless shocks in general.

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REFERENCES

Balogh, A., Carr, C. M., Acuna, M. H., et al. 2001, AnGp, 19, 1207
Barabash, S., Sauvaud, J. A., Gunell, H., et al. 2007, P&SS, 55, 1805
Burlaga, L. F., Ness, N. F., Acuna, M. H., et al. 2005, Sci, 309, 2027
Burlaga, L. F., Ness, N. F., Acuna, M. H., et al. 2008, Natur, 454, 75
Chalov, S. V., & Fahr, H. J. 1996, A&A, 311, 317
Chalov, S. V., & Fahr, H. J. 1997, A&A, 326, 860
Donahue, T. M., & Hartle, R. E. 1992, GeoRL, 19, 2449
Fahr, H., Fichtner, H., & Scherer, K. 2007, RvGeo, 45, RG4003
Fahr, H. J., & Rucinski, D. 1999, A&A, 350, 1071
Florinski, V., Decker, R. B., le Roux, J. A., & Zank, G. P. 2009, GeoRL, 36, L12101
Groller, H., Shematovich, V. I., Lichtenegger, H. I. M., et al. 2010, JGR, 115, E12017
Kivelson, M. G., & Russell, C. T. 1995, Introduction to Space Physics (New York: Cambridge Univ. Press), 505
Le Roux, J. A., & Fichtner, H. 1997, JGR, 102, 17365
Liewer, P. C., Goldstein, B. E., & Omidi, N. 1993, JGR, 98, 15211
Lipatov, A. S., & Zank, G. P. 1999, PhRvL, 82, 3609
Luhmann, J. G. 1986, SSRv, 44, 241
McComas, D. J., Allegrini, F., Bochsler, P., et al. 2009, Sci, 326, 959
McComas, D. J., Alexashov, D., Bzowski, M., et al. 2012, Sci, 336, 1291
Milhalov, J. D., & Barnes, A. 1981, GeoRL, 8, 1277
Pauls, H. L., Zank, G. P., & Williams, L. L. 1995, JGR, 100, 21595
Richardson, J. D. 2008, GeoRL, 35, L23104
Richardson, J. D., Kasper, J. C., Wang, C., Belcher, J. W., & Lazarus, A. J. 2008, Natur, 454, 63
Rucinski, D., Bzowski, M., & Fahr, H. J. 2003, AnGp, 21, 1315
Russell, C. T., Elphic, R. C., & Slavin, J. A. 1979, Natur, 282, 815
Slavin, J. A., Elphic, R. C., & Russell, C. T. 1979, GeoRL, 6, 901
Sonnerup, B. U. O., & Cahill, L. J. 1967, JGR, 72, 171
Tatrallyay, M., Russell, C. T., & Luhmann, J. 1984, JGR, 89, 7381
Zank, G. P. 1999, SSRv, 89, 413
Zank, G. P., Heerikhuisen, J., Wood, B. E., et al. 2013, ApJ, 763, 20
Zank, G. P., Pauls, H. L., Cairns, I. H., & Webb, G. M. 1996a, JGR, 101, 457
Zank, G. P., Pauls, H. L., Hall, D., & Williams, L. L. 1996b, JGR, 101, 21639
Zank, G. P., Pogorelov, N. V., Heerikhuisen, J., et al. 2009, SSRv, 146, 295
Zank, G.P., Heerikhuisen, J., Burrows, R., Pogorelov, N. V., & McComas, D. 2010, ApJ, 708, 1092
Zhang, T. L., Baumjohann, W., Delva, M., et al. 2006, P&SS, 54, 1336
Zhang, T. L., Luhmann, J. G., & Russell, C. T. 1990, JGR, 95, 14961