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Do Inner Planets Modulate the Solar Wind Velocity at 1 AU from the Sun?

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Quite recently, it has been suggested that the interaction of the solar wind with Mercury results in the variation in the solar wind velocity in the Earth's neighborhood during inferior conjunctions with Mercury. This suggestion has important implications both on the plasma physics of the interplanetary space and on the space weather forecast. In this study we have attempted to answer a question of whether the claim is properly tested. We confirm that there are indeed ups and downs in the profile of the solar wind velocity measured at the distance of 1 AU from the Sun. However, the characteristic attribute of the variation in the solar wind velocity during the inferior conjunctions with Mercury is found to be insensitive to the phase of the solar cycles, contrary to an earlier suggestion. We have found that the cases of the superior conjunctions with Mercury and of even randomly chosen data sets rather result in similar features. Cases of Venus are also examined, where it is found that the ups and downs with a period of ~ 10 to 15 days can be also seen. We conclude, therefore, that those variations in the solar wind velocity turn out to be a part of random fluctuations and have nothing to do with the relative position of inner planets. At least, one should conclude that the solar wind velocity is not a proper observable modulated by inner planets at the distance of 1 AU from the Sun in the Earth's neighborhood during inferior conjunctions.

Keywords: solar wind, Mercury, magnetospheres

1. INTRODUCTION

Solar system bodies that lack a significant atmosphere and magnetic fields, such as the Moon and Mercury, have been considered as passive absorbers of the solar wind. However, as ion observations near the Moon by the Selenological and Engineering Explorer (SELENE, or Kaguya) spacecraft show, a fraction of the impacting solar wind protons are reflected by the surface of the Moon (Saito et al. 2008) and the reflection of solar wind protons subsequently affects the global plasma environment (Halekas et al. 2011). Interactions of the solar wind and the Moon generate a number of interesting plasma effects. These include electrostatic charging of the surface, magnetic mirroring, and the coupling between various parts of the plasma environment and electrostatic forces (Helekas et al. 2011). Most of all the interesting phenomena, the near-Moon space environment is characterized by formation of a plasma cavity region on the night side along the solar wind flow, which is called the lunar wake. In the wake, the flow can be sub-Alfvénic (and thus sub-sonic) because of its low-density and gradually filled by solar wind plasma downstream of the body through thermal expansion, resulting in ambipolar electric field along the magnetic field lines (Farrell et al. 1998, Birch & Chapman 2001, Nishino et al. 2010, 2011, 2013, Harnett & Winglee 2013).

As for Mercury, under typical conditions of interplanetary space, it possesses a very small magnetosphere with a distinct magnetopause. It is only 0.1% the size of the largest magnetosphere in the solar system, the Jovian magnetosphere. The small intrinsic magnetic field of Mercury together with its proximity to the Sun makes the hermean magnetosphere unique and specially interesting in the context of comparative magnetosphere study (Kabin et al. 2000, Fujimoto et al. 2007). For instance, open field lines cover more than 50% of the surface of the planet, so the

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hermean magnetosphere is very open. Moreover, the thin atmosphere of Mercury cannot produce a highly conducting ionosphere. Prior to the Mariner 10 encounters, it was thought that Mercury had no active dynamo. If the planet ever had a dynamo it would have ceased to work when the rapid cooling of the comparatively small planet led to a completely frozen core. During the flyby of the Mariner 10 the magnetic field peaked at about 400 nT and it clearly displayed its intrinsic character (Ness et al. 1975). Although the magnetosphere of Mercury is qualitatively similar to the Earth's magnetosphere, its much smaller size obviously results in many quantitative differences. Observations by the MESSENGER spacecraft during the three flybys of Mercury brought additional information and set on the front page the investigation of the structure and the origin of Mercury's magnetic field (Anderson et al. 2008, Raines et al. 2011). The interaction of the solar wind with the magnetic field of Mercury is currently being investigated (Anderson et al. 2011, Richer et al. 2012).

Quite recently, Nikulin (2013) has studied the interaction of the solar wind with Mercury in terms of the variation in the solar wind velocity in the Earth's neighborhood during inferior conjunctions with Mercury. He has analyzed the mean daily velocity of the solar wind of 54 cases in the period from 1995 to 2012 using Advanced Composition Explorer (ACE) data by the superimposed epoch method. As a result, he has drawn his attention to a noticeable increase in the velocity both before and after the inferior conjunctions as well as decrease in the velocity within 3-4 days after them. He has consequently associated his finding with Mercury's wake, or what he called a shadow. If this is the case, it has crucial implications. First, it may demonstrate a possibility of survival of the hermean trace to a far extent in the interplanetary medium in the course of propagation of the solar wind. That is, if his suggestion is valid it turns out that the trace of Mercury in the solar wind survives in the interplanetary space up to the distances of, at least, 0.6 AU, and thus requires further investigations. As far as we understand this is very difficult to take place since there must be instabilities on the boundary of the wake causing smoothing-out long before such a great distance. Second, it may also suggest that one should take into account a phase of inner planets when the space weather prediction is attempted (Chang 2013). It is because a forecast of the solar wind velocity is a crucial factor in the space weather prediction and the solar wind velocity concerns not only the solar activity but also a relative position of inner planets with respect to the Earth.

The present study aims to verify/disprove his suggestion that the solar wind interacts with Mercury so that the solar wind velocity at the distance of 1 AU from the Sun varies in the Earth's neighborhood during inferior conjunctions. We are dealing with a question of whether the effect he has found is statistically properly tested. This paper is organized as follows. We begin with brief descriptions of data in Section 2. We present and discuss results based on the test in various occasions including the superior conjunction with Mercury and similar cases with Venus in Section 3. Finally, we summarize and conclude in Section 4.

2. DATA

For the present analysis we have used the mean daily velocity of the solar wind during the period from February in 1998 to September in 2013. The mean daily velocity is derived from the mean hourly ones obtained by the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) on the ACE spacecraft. The ACE spacecraft accommodates a total of ten instruments; nine scientific instruments for the primary mission and one engineering instrument for a secondary mission. The SWEPAM on ACE, which is one of nine science instruments, measures electron and ion fluxes of the solar wind plasma as functions of direction and energy. These data provide detailed knowledge of the solar wind conditions and internal state every minute. The SWEPAM provides real-time solar wind observations which are continuously telemetered to the ground for space weather purposes. We have taken data from the ACE Science Center website[1] . The entire data set is available as ASCII text files, which may be downloaded for time-spans that cross yearly, monthly, Bartels-rotation boundaries, and so on, too. Autoplot can also be used to create online plots. The ACE spacecraft has measured them in L1 Lagrangian point in the vicinity of the Earth (approximately 1/100 of the distance from the Earth to the Sun). Such a location of ACE enables us to perform a continuous measurement of the solar wind parameters and to give approximately a one-hour-advance warning of encroaching geomagnetic storms that disrupt communications and that are hazardous to astronauts.

3. MODULATION OF SOLAR WIND IN THE EARTH'S NEIGHBORHOOD

To reveal the effect suggested by Nikulin (2013), we extract strings of data from the daily velocity of the solar wind for periods of inferior conjunctions with Mercury

[1]http://www.srl.caltech.edu/ACE/ASC/level2/new/intro.html

from 1998 to 2013. We have marked the epoch of the inferior conjunction with the Mercury from the website of Korea Astronomy and Space Science Institute[2] . By doing so, we end up with 49 data strings whose length is 29 days. Each of the data string is centered (i.e., T = 0) at the day when Mercury locates at the inferior conjunction. We superimpose 49 data strings and then average them so that the variation of the mean velocity of the solar wind is obtained during the inferior conjunction with Mercury. This is what is called the superimposed epoch method. In Fig. 1, we show the variation of the mean velocity of the solar wind over 49 events of the inferior conjunction with Mercury. A typical size of error bars is about 20 km/s. As Nikulin claimed (2013), a noticeable increase in the solar wind velocity within ~ 4 days before the inferior conjunction and ~ 8 days after it along with a decrease in the velocity within ~ 3-4 days after the inferior conjunction can be seen. In his paper, he attempted to establish its possible dependence on the solar cycle phase as well. In his fig. 2, he separately showed results of the ascending phase of the solar cycle 23, the descending phase of the solar cycle 23, and the ascending phase of the solar cycle 24 without the scale of the axis for the solar wind velocity. Nikulin (2013) claimed that the general tendencies are less expressed at the stage of the ascending phase of the solar cycle 23 based on his fig. 2. Truly, the variation in the solar wind velocity during the inferior conjunctions with Mercury from 1995 to 2001 seemed less clear in his fig. 2 which does not have the vertical scale. We too perform the same analysis for two subsets of data, that is, one for the ascending phase and the other for the descending phase of the solar cycles 23 and 24. In Fig. 2, we show the variation of the mean velocity of the solar wind during the inferior conjunctions with Mercury in different phases of the solar cycle. The upper and lower panels result from the ascending phase of the solar cycles 23 and 24 and the descending phase of the solar cycle 23, respectively. It seems that a general feature that can be found in Fig. 1 can be also seen in both panels, though the details, such as, the leading/lag times and the contrast of max/min velocity of the solar wind, do not exactly conform with Fig. 1. The characteristic attribute of variations in the solar wind velocity during the inferior conjunctions with Mercury is apparently insensitive to the phase of the solar cycles. What we have found in our analysis is in fact that the absolute scale in variations of the period from 1995 to 2001 is large, which is contrary to what he showed in his work (Nikulin 2013). This optical illusion has arisen simply because he missed the vertical scale in his paper (Nikulin 2013). It should be pointed out that, therefore, his claim of the dependence on the phase seems somewhat premature.

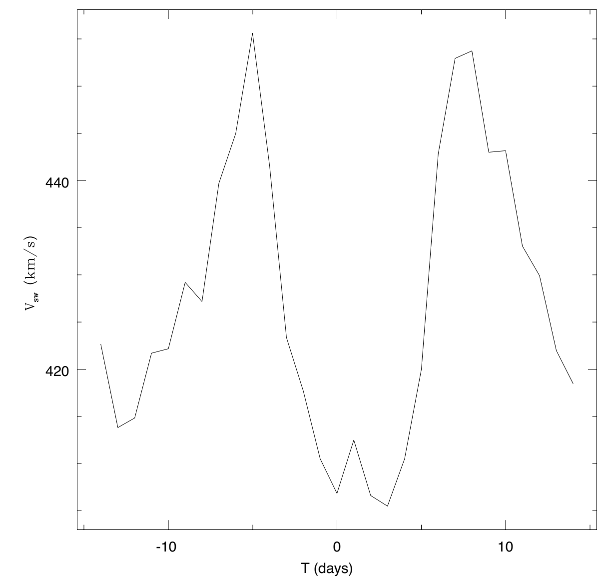

Fig. 1. Variation of the mean velocity of the solar wind over 49 events of the inferior conjunction with Mercury. Each of the data string is centered (i.e., T = 0) at the day when Mercury locates at the inferior conjunction. The mean daily velocity is derived from the period from February in 1998 to September in 2013. A typical size of error bars is about 20 km/s.

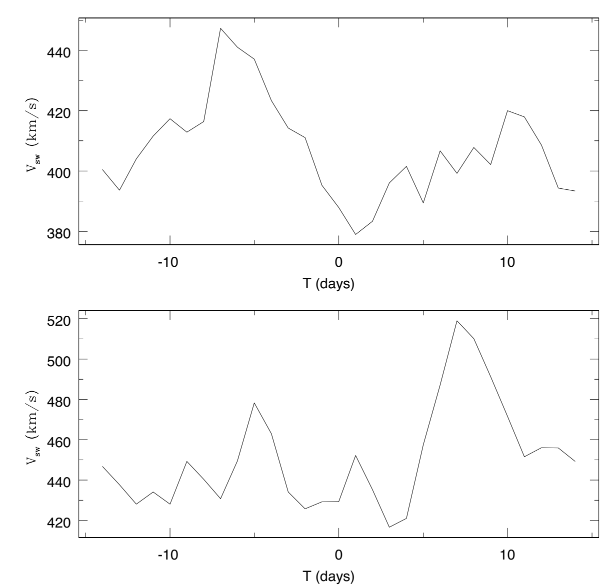

Fig. 2. Mean variation of the velocity of the solar wind depending on the phase of the solar cycle. The upper panel and the lower panel result from the ascending phase of the solar cycles 23 and 24 and the descending phase of the solar cycle 23, respectively. A typical size of error bars is about 20 km/s.

In Fig. 3, we show results from data strings of the daily velocity of the solar wind for the periods of the superior conjunctions with Mercury. The purpose of this analysis is to see if the results from data for the inferior conjunctions

[2]http://www.kasi.re.kr

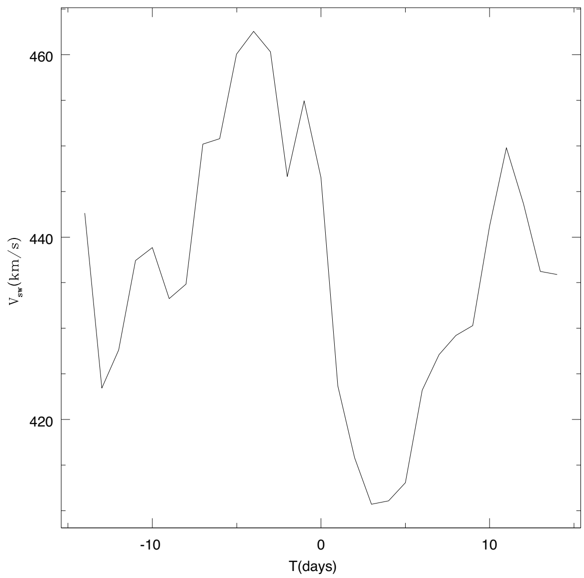

Fig. 3. Similar to Fig. 1, except resulting from data strings of the daily velocity of the solar wind for the periods of the superior conjunctions with Mercury. We have 50 cases of the superior conjunctions with Mercury. A typical size of error bars is about 20 km/s.

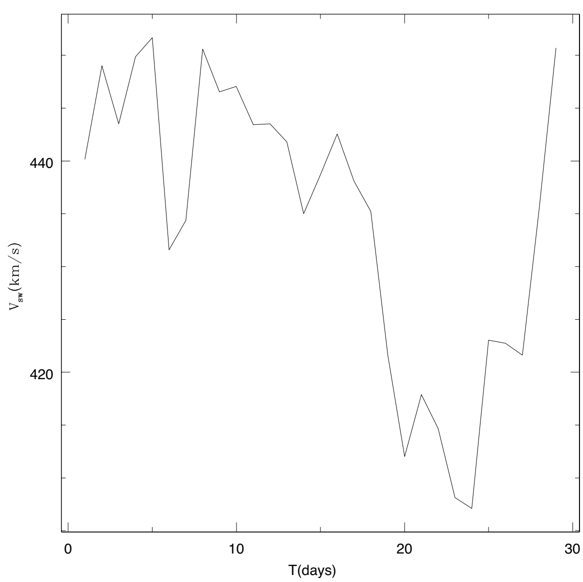

Fig. 4. Similar to Fig.1, except resulting from the velocity of the solar wind over 49 randomly chosen data strings regardless of Mercury's relative position with respect to the Earth. A typical size of error bars is about 20 km/s.

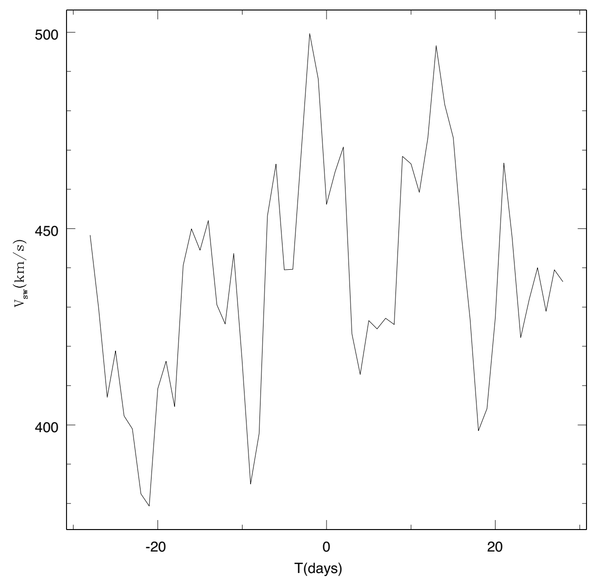

Fig. 5. Similar to Fig. 1, except resulting from Venus. The data strings are with a length of 57 days. We have 9 cases of the inferior conjunctions with Venus. A typical size of error bars is about 50 km/s, due to a smaller number of events.

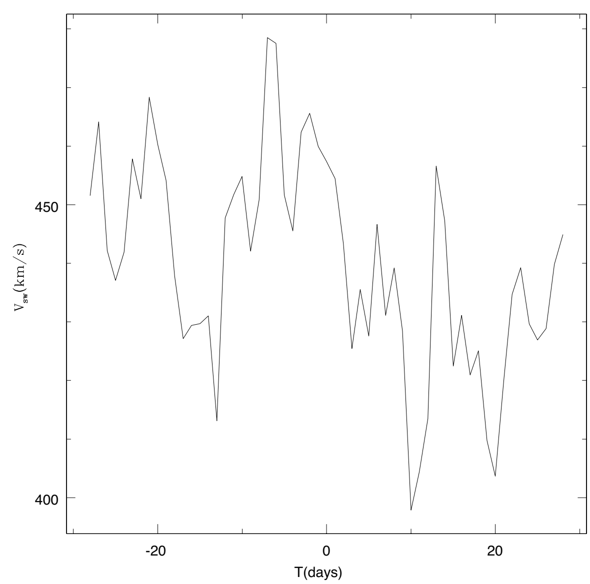

Fig. 6. Similar to Fig. 3, except resulting from Venus. We have 10 cases of the superior conjunctions with Venus. A typical size of error bars is about 50 km/s.

are indeed special. We have 50 cases of the superior conjunctions with Mercury. Basically, same main features can be seen in Fig. 3 as shown in Fig. 1. If the result presented in Fig. 1 demonstrates that the trace of Mercury in the solar wind survives in the interplanetary space up to the distances of, at least, 0.6 AU, that in Fig. 3 demonstrates in fact that the trace of Mercury in the planetary space survives up to the distances of, at least, 1.4 AU, over the Sun itself, which is extremely hard to occur in the interplanetary space with the swirling solar magnetic field lines. We doubt that the variation in the solar wind velocity with the period of ~10 to 15 days, which is commonly seen in Figs. 1-3, is essentially a random fluctuation so that what we have seen in Figs. 1-3 have nothing to do with the conjunctions with Mercury. To see whether the effect Nikulin suggested (2013) could ever happens, in addition, we randomly chop whole

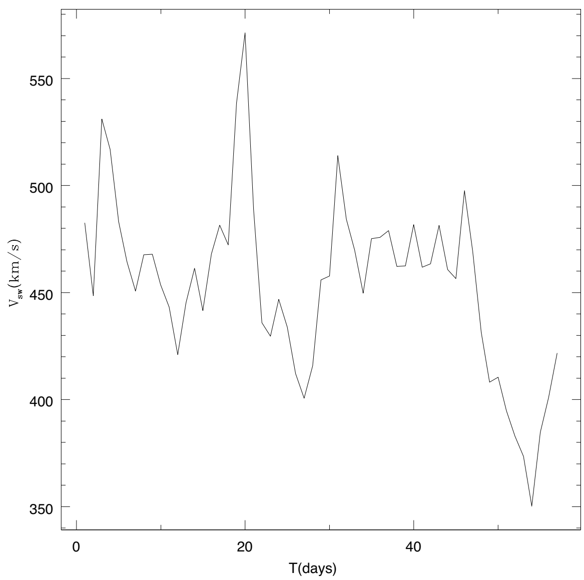

Fig. 7. Similar to Fig. 4, except resulting from Venus over 9 randomly chosen data strings. A typical size of error bars is about 50 km/s.

data sets into a string with a length of 29 days and select 49 data strings. We repeat the same procedure in averaging data strings, which have nothing to do with positions of Mercury with respect to us. Now, in Fig. 4, we show the mean variation of the velocity of the solar wind over 49 randomly chosen data strings regardless of Mercury's relative position with respect to the Earth. Again, a typical size of error bars is about 20 km/s. Apparently, variations are moderately significant in a statistical sense, though the epochs that maxima and minima occur are slightly different. On the basis of what we observe in Figs. 3 and 4, we come to conclusions that the effect suggested by Nikulin (2013) is inconclusive.

It would be very interesting to compare the features for Mercury with the flow of the solar wind around Venus, which possesses the ionosphere but does not have a global magnetic field. In Figs. 5-7, we show results of cases where Venus is at the 9 inferior conjunctions, at the 10 superior conjunctions, and at 9 random position with respect to the Earth during the period from 1998 to 2013, respectively. The data strings are with a length of 57 days. A typical size of error bars is about 50 km/s, due to a smaller number of events. The ups and downs with a period of ~ 10 to 15 days can be seen so that one should consider these characteristic feature is a part of random fluctuations of solar wind velocity in the course of its propagation in the interplanetary space rather than one that is associated with the interaction with the flow of the solar wind with inner planets. The fact that the periodicity is insensitive to which inner planet blocks the solar wind is another supporting evidence of the stochastic behavior of the solar wind velocity in the Earth's neighborhood. For, supposed that the solid angles of the conical wake due to Mercury at the distance of ~ 0.4 AU from the Sun and due to Venus at ~ 0.7 AU are somewhat similar, the crossing time of the Earth at 1 AU over the perturbed regions of the flow of the solar wind should be quite different. In other words, according to a simple geometry, the crossing time of the Earth over the conical wake caused by Mercury located at the distance of ~ 0.6 AU from the Earth is roughly 1.4 times longer than that due to Venus at ~ 0.3 AU from the Earth, since the ratio of the sweeping distance of Venus to Mercury is ~ 0.5 and the ratio of the sweeping speed due to Venus to Mercury is ~ 0.35.

4. SUMMARY AND CONCLUSION

The solar wind is a quasi-steady radial supersonic outflow of the solar coronal plasma through the entire Solar system, whose velocity is a few hundreds km/s, and density is about a few particles in a cubic cm, interacting with the planetary magnetospheres. The velocity of the solar wind depends on many parameters, such as, a magnitude of the solar flare, direction of the outburst, magnetic field structure in the active region and interplanetary space. Quite recently, Nikulin (2013) has studied the interaction of the solar wind with Mercury in terms of the variation in the solar wind velocity in the Earth's neighborhood during inferior conjunctions with Mercury, using the mean daily velocity of the solar wind of 54 cases in the period from 1995 to 2012 using ACE data. As a result, he has found a noticeable increase in the velocity both before and after the inferior conjunctions as well as decrease in the velocity within a few days after them. He has consequently associated his finding with Mercury's wake.

In this study, we have attempted to verify/disprove his claim that the solar wind velocity at the distance of 1 AU from the Sun varies in the Earth's neighborhood during inferior conjunctions with Mercury. We confirm that there are indeed ups and downs in the solar wind profiles measured at the distance of 1 AU from the Sun. However, the characteristic attribute of variations in the solar wind velocity during the inferior conjunctions with Mercury is found to be insensitive to the phase of the solar cycles, contrary to what he claimed. We have also repeated the same analysis with the cases of the superior conjunctions with Mercury, in which same features can be seen. Even randomly chosen data sets are found to result in showing a similar behavior. Cases of Venus are also examined, where it is found that the ups and downs with a period of

~10 to 15 days can be seen, which cannot be explained by a simple geometrical account. We conclude, therefore, that those variations in the solar wind velocity turn out to be a part of random fluctuations and have nothing to do with the relative position of inner planets. At least, one should conclude that the solar wind velocity is not a proper observable modulated by inner planets at the distance of 1 AU from the Sun in the Earth's neighborhood during inferior conjunctions.

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