GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 8, PAGES 1447-1449, APRIL 15 , 2001

Pioneer Venus Orbiter observations of a solar wind quasi-invariant

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Abstract. The recently suggested solar wind quasi-invariant [$QI \equiv (B^2/8\pi)/(\rho v^2/2)$] is a combination of magnetic field strength B, plasma density ρ and solar wind speed v. Measured in the solar wind near the Earth, the median value of QI was shown to be a reliable index of solar activity for the 28 year period holding a linear relation with sunspot numbers (SSN) with a high correlation coefficient (cc) of 0.98 [*Osherovich, Fainberg and Stone*, 1999]. Here,using hourly data from the Pioneer Venus Orbiter for the period from 1978-1988, we demonstrate that QI near Venus also closely follow SSN with a correlation coefficient of 0.94 for the yearly mean values. We found that the calibration coefficient between QI_{Venus} and QI_{Earth} is slightly larger than unity, namely, $QI_{Venus} = a^* \cdot QI_{Earth}$ where $a^* = 1.134 \pm 0.001$. We suggest that, for any point in the heliosphere, QI can be viewed as a useful measure of solar activity.

1. Introduction

In attempts to gauge solar activity, a number of indices have been developed. Some solar parameters like sunspot numbers (SSN) or 10.7 cm flux, reflecting the state of the sun, are based on remote observations of the solar disk [*Hathaway*, 1998 and references therein]. Other indices (namely AA, Kp and Dst), being aimed at studying the geoeffectiveness of variations of solar activity, measure the response of the Earth's magnetosphere or ionosphere to interplanetary disturbances [*Cliver et al.*, 1999 and references therein]. Parameters measured by satellites outside the Earth's magnetosphere in the solar wind form their own class, which characterize the state of the magnetized plasma in the solar heliosphere in general or in the part of the heliosphere immediately surrounding the Earth. From the beginning of the space age, work has been done to relate interplanetary field strength B with SSN and other solar indices [*King*, 1979; *Slavin, Jungman and Smith*, 1986]. These yearly studies established the relation between B and SSN with $cc \approx 0.6 - 0.7$. Recently, an idea of a solar wind quasi-invariant (QI) has been put forward by *Osherovich, Fainberg and Stone* [1999]. This QI is defined by the authors as a combination of physical parameters (components) which all depend on the same process. A chosen combination of components, according to the definition, is a QI if the cc of the combination is appreciably higher than for each component separately. In the above mentioned paper [*Osherovich, Fainberg and Stone*, 1999], it has been shown that the energy ratio

$$QI \equiv (B^2/8\pi)/(\rho v^2/2) = M_A^{-2} \tag{1}$$

is a true quasi-invariant with $cc = 0.98$ for the median value relative to the SSN for the period 1971-1998. The value M_A is the magnetic Mach number which is related to the Alfven speed, namely $M_A = v/v_A$. The linear relation found between the yearly median QI and SSN is the following: $QI = a + b \cdot SSN$, where $a = 7.6 \cdot 10^{-3} \pm 0.15 \cdot 10^{-3}$ and $b = 7.8 \cdot 10^{-5} \pm 0.3 \cdot 10^{-5}$. Using the longest and most complete data set collected near the Earth and assembled at NSSDC at NASA/GSFC by J. King and coworkers, we showed that QI defined by formula (1) is indeed a reliable index of solar activity. This new index (expressed in terms of the physical parameters B, ρ and v) is directly measured in situ in solar plasma near the Earth. Relating the new index with the traditional index of SSN, in principle, allows one to reconstruct conditions in the solar wind surrounding the Earth in terms of QI or M_A for the past (even before the space age). The QI can be used as an input in the development of a solar wind model, adjusted for the level of solar activity; the corresponding work is in progress. All the above and other reasons discussed below provide a strong motivation for further research on QI. The present paper addresses three questions: 1) Does the QI also correlate with SSN at different distances from the sun in the heliosphere if measurements are done at small heliospheric latitudes (close to the solar equatorial plane)? 2) Is the value of QI different at different distances? 3) How is the value of QI at one distance related to the value at a different distance? Specifically, in this paper we check the concept of QI with the data set collected by the Pioneer Venus Orbiter for the period 1978-1989. This period is sufficient to confirm the concept and to calibrate QI_{Venus} versus QI_{Earth} for the same time period, where, in each case, yearly mean values of the solar wind near the planet are used.

Paper number 2000GL012160.
0094-8276/01/2000GL012160$05.00

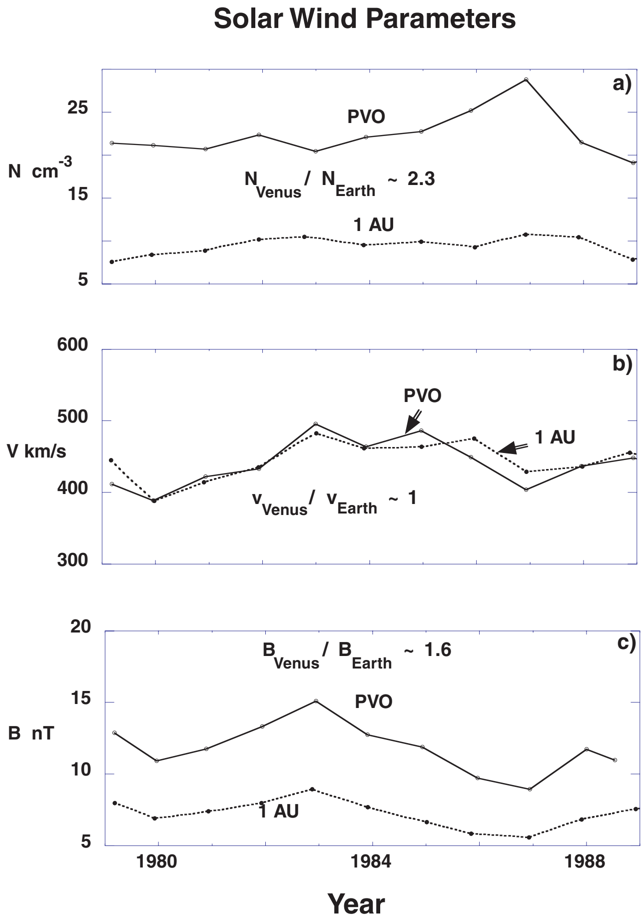

Figure 1. Yearly values of proton number densities N, bulk solar wind speed v and total magnetic field strength B measured by Pioneer-Venus Orbiter. For this figure, as well as the following figures, we have not used calendar years. We have taken January 1, 1904 as year 1904.0 exactly and have defined following years to be exactly 365.25 days in length. We have taken such years to start at 0.431 into the year and, for purposes of computing errors, have taken mean hourly values of the IP parameters and SSN for 1/12 of a year and then averaged over those values to form a yearly mean. The times of the yearly means were taken as the averages of the times of the corresponding values. The standard error of the yearly means is computed from the 12 (or less because of data coverage) values used to form them. We believe that this approach yields a somewhat over-estimate of the errors but, nevertheless, all quantities were treated in a similar manner. The fits shown were obtained by using the errors in both coordinates.

2. Components of QI, observed by PVO and their relation to SSN

Due to the weak magnetic field of Venus and the highly elliptical orbit of PVO ($\sim 66,000x200$ km), most of the time the spacecraft was in the solar wind near Venus. Therefore, in the averages below, we take the mean parameters of the solar wind at the orbit of Venus ($\sim 0.72AU$). The yearly values of N, v and B are presented for the period of PVO observations in Figure 1 (solid lines). The corresponding values at 1 AU are shown by the dashed lines. On average, $N_{Venus}/N_{Earth} \approx 2.3$, $B_{Venus}/B_{Earth} \approx 1.6$, and $v_{Venus}/v_{Earth} \approx 1$. None of the 3 values N, v and B observed at 0.72 AU by PVO shows a particularly strong dependence on the solar cycle. For both positions, at 1 AU and at 0.72 AU, the magnetic field strength reaches a maximum near year 1983 (Figure 1c), which is a couple of years later than the time of solar maximum (dotted line in Figure 3a). Indeed, the correlation coefficient between B and SSN is only 0.63 as shown in Figure 2a. For v and SSN, $cc = -0.07$ (see Figure 2b) and N also anticorrelates with SSN with $cc = -0.67$. These relations of N, v and B found at 0.72 AU are qualitatively similar to those found at 1 AU. However, out of the three components, N has the strongest relation (anti correlation) with SSN in the solar wind surrounding Venus and, in this sense, is a leading component of the QI defined by formula (1). Notice that at 1 AU the leading component is B [*Osherovich, Fainberg and Stone*, 1999].

3. QI at 0.72 AU versus QI at 1 AU

In contrast to N, v and B individually, the combination defined by formula (1) follows SSN closely, as shown in Figure 3a (solid line). The dotted line in this figure represents SSN and the dashed line QI at 1 AU. For the mean values

$$QI_{Venus} = a + b \cdot SSN \tag{2}$$

where $a = 0.011(\pm 0.001)$ and $b = 0.000152(\pm 0.00001)$ with $cc = 0.94$ (see Figure 3a). Comparing this high value of cc with the corresponding values for N, v and B one can

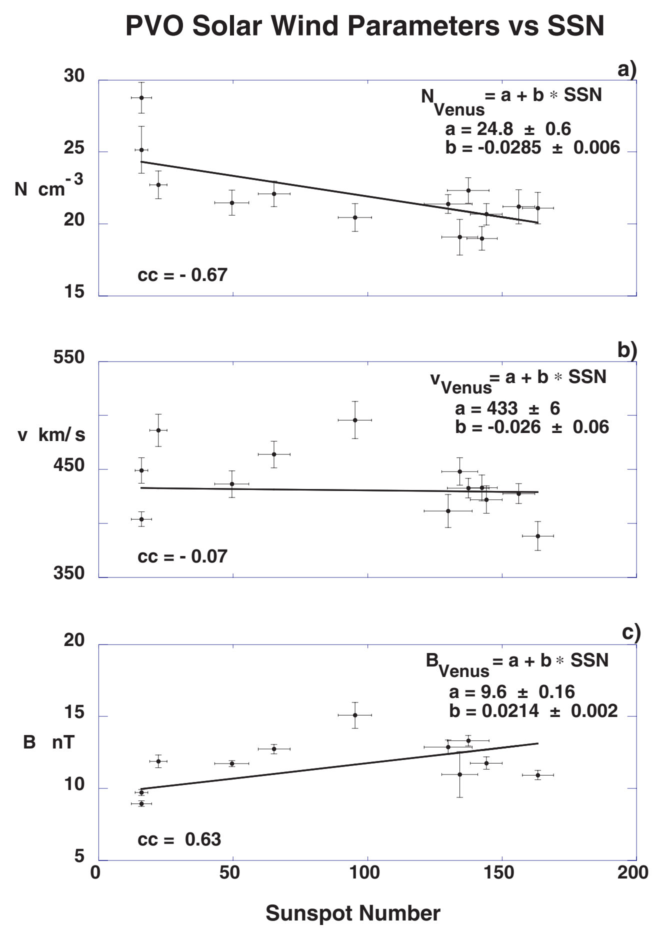

Figure 2. Components of QI measured by Pioneer-Venus Orbiter during the period 1979-1989 versus sunspot numbers. Time, errors and fits as in Figure 1 caption.

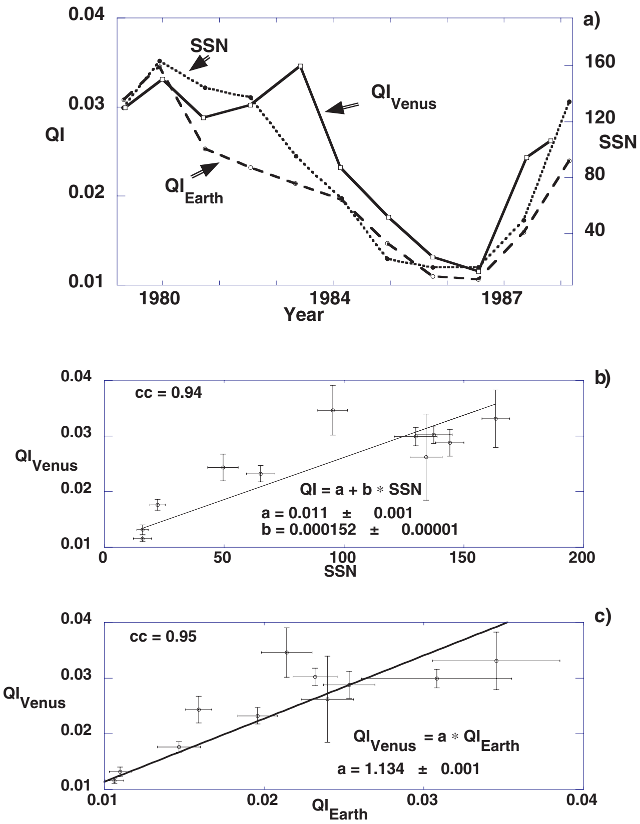

Figure 3. a) Comparison between QI_{Venus} (solid line) with SSN (dotted line) and QI_{Earth} (dashed line), b) Yearly values of QI_{Venus} versus SSN and c) QI_{Venus} versus QI_{Earth}. Time, errors and fits as in Figure 1 caption.

conclude QI_{Venus} is a quasi-invariant according to our definition. The scatter plot of QI_{Venus} versus QI_{Earth} is shown in Figure 3b.

$$QI_{Venus} = a^* \cdot QI_{Earth} \tag{3}$$

where $a^* = 1.134(\pm 0.001)$. Thus, on average, QI_{Venus} is 13.4 percent higher than QI_{Earth} as a result of the difference in $B^2/8\pi$ by a factor of 2.6 which is only partly compensated by the difference in kinetic energy of the flow which at 1 AU is 2.3 times lower than at 0.72 AU.

4. Summary and discussion

The following two results summarize our findings: 1) QI measured by the Pioneer Venus Orbiter at 0.72 AU for a $\sim$ ten year period is found to be a good index of solar activity. The correlation of the yearly mean QI_{Venus} with yearly sunspot numbers is 0.94, which is significantly higher than for N, v and B taken separately. 2) QI_{Venus} (at 0.72 AU) highly correlates with QI_{Earth} (at 1 AU) with $cc = 0.95$. The scaling factor between the two QIs for the two locations is close to unity with QI at 0.72 AU slightly higher than QI at 1 AU. The 13.4 percent difference is attributed to the 2.6 times decrease in $B^2/8\pi$ while the decrease in kinetic energy $\rho v^2/2$ is only 2.3 times and is mainly due to the decrease in density. The resulting scaling factor is 1.134 ± 0.001. We suggest that QI at any point in the heliosphere can serve as a reliable index of solar activity. Further research is required to calibrate QI measured by different spacecraft, especially studies of the radial and latitudinal dependence of QI in the heliosphere. Our preliminary results indicate that the QI concept may lead to a unification of data sets collected in the solar wind in order to establish one global parameter which characterizes the state of the solar heliosphere. The QI is expressed in terms of parameters which are already in fundamental physical equations. The mean and median values of QI are only two of the different moments of the QI distribution. These two moments, as we have shown, highly correlate with SSN in a way that gives a clear new physical sense to SSN as a traditional index of solar activity. There is much more information about the solar cycle in the full QI distribution which can be presented in the form of higher moments and partitions of the total QI distribution. Such information is of potential use to researchers developing solar wind models. It is reasonable to ask the question: can such models reproduce this relation of QI to solar activity. We believe our results provide an additional test for any solar wind model which attempts to reproduce the solar cycle variation of the solar wind.

Acknowledgments. The authors thank J. Slavin and M. Acuna for discussions and suggestions. Without the work done by J. King and coworkers, who assembled the data sets for COHO-WEB at NSSDC, this research could not have been done. The efforts of the principal investigators of the corresponding many missions including PVO are also greatly appreciated. The referees' comments, certainly, have allowed us to improve the paper.

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(Received August 2, 2000; revised December 13, 2000; accepted January 13, 2001.)