Pioneer Venus Orbiter observations of a solar wind quasi-invariant

J. Fainberg
NASA/Goddard Space Flight Center, Greenbelt, MD

Vladimir A. Osherovich
NASA/Goddard Space Flight Center/Emergent, Greenbelt, MD

R.G. Stone
NASA/Goddard Space Flight Center, Greenbelt, MD

Abstract. The recently suggested solar wind quasi-invariant [QI ≡ (B^2/8π)/(ρv^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^* · QI_{Earth} where a^* = 1.134 ± 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 andDst), being aimed at studying the geoeffectiveness of variations of solar activity, measure the response of the Earth’s magnetosphere or ionosphere to interplanetary disturbances [Oliver 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 ≈ 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

\[ QI \equiv \frac{(B^2/8\pi)}{\rho v^2/2} = M_A^{-2} \]  

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 Alfvén speed, namely M_A = v/v_A. The linear relation found between the yearly median QI and SSN is the following: QI = a + b · SSN, where a = 7.6 · 10^{-3} ± 0.15 · 10^{-3} and b = 7.8 · 10^{-5} ± 0.3 · 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.
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 (~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 (~0.72 AU). 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, \( N_{\text{Venus}}/N_{\text{Earth}} \approx 2.3 \), \( B_{\text{Venus}}/B_{\text{Earth}} \approx 1.6 \), and \( v_{\text{Venus}}/v_{\text{Earth}} \approx 1 \). 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, 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

\[
QI_{\text{Venus}} = a + b \cdot \text{SSN}
\]

where \( a = 0.011(\pm 0.001) \) and \( b = 0.000152(\pm 0.000001) \) 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 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 1, 1904 as year 1904.0 exactly and have defined following years 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.](image1)

![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.](image2)
at 1 AU. The 13.4 percent difference is attributed to the 2.6
highly correlates with
sunspot numbers is 0.94, which is significantly higher than
close to unity with
scaling factor between the two
definition. The scatter plot of
where
a
13.4 percent higher than
than at 0.72 AU.
by the difference in kinetic energy of the flow which at 1 AU

is 2.3 times lower than at 0.72 AU.

The resulting scaling factor is 1


Summary and discussion

The following two results summarize our findings: 1) $QI_{Venus}$ is a quasi-invariant according to our defini-
tion. The scatter plot of $QI_{Venus}$ versus $QI_{Earth}$ is shown in Figure 3b.

\[ QI_{Venus} = a^* \cdot QI_{Earth} \] (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 ~
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 $QI$s 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 $1.134 \pm 0.001$. 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 so-
lar 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 so-
lar wind model which attempts to reproduce the solar cycle
variation of the solar wind.

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J. Fainberg, NASA/GSFC Code 692 Greenbelt, MD 20771.
(e-mail: joseph.fainberg@gsc.nasa.gov)

V.A. Osherovich, NASA/GSFC/Emergent Code 690.2, Green-
belt, MD 20771. (e-mail: vladimir@urap.gsfc.nasa.gov)

R.G. Stone, NASA/GSFC Code 690 Greenbelt, MD 20771.
(e-mail: stone@urap.gsfc.nasa.gov)

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