Is the correlation between flux tube expansion factor and solar wind speed near the Earth causal?

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Abstract

The solar wind speed near the Earth has been predicted using an empirical relation between the flux tube expansion factor (FTE) and the solar wind speed observed near the Earth. However, the computation of FTE is based on potential field source surface (PFSS) model of the corona which has arbitrary dependence on parameters such as the number of spherical harmonics and the inverse mapping technique which do not include the effect of stream–stream interaction taking place between the source surface and 1 AU (Poduval and Zhao, 2004). Also, the source surface magnetic field obtained using the PFSS model varies from one point to the other contrary to the Ulysses observation of the heliospheric magnetic field, which is latitude independent. Therefore, the correlation between FTE and solar wind speed observed near the Earth, is likely to be coincidental rather than causal. If at all there exists a relation between FTE and solar wind, it must be the wind near the Sun rather than near the Earth. The Horizontal Current Current–Sheet Source Surface (HCCSSS) model developed by Zhao and Hoeksema (1995) yields a uniform magnetic field and has been shown to reproduce the radial variation of non–radial mid–latitude helmet streamers between 2.5 and 30 $R_\odot$. We present the results of an investigation of the validity of the inverse correlation between the solar wind speed and FTE using our HCCSSS model.

Introduction

The solar wind speed predicted at 1 AU using the inverse correlation between the solar wind speed (SWS) observed at 1 AU and the flux expansion factor very close to the Sun ($r < R_{ss} = 2.5R_\odot$) does not always agree with the observed speed near the Earth. The discrepancies are very significant as pointed out by several authors (Bala, 2000, for instance). Poduval and Zhao (2004) speculated that if there exists a relation between FTE and SWS, it must be with the wind near the Sun rather than near the Earth because the interaction between fast and slow solar wind streams during their propagation from the corona to 1 AU and beyond alters the solar wind profile. The observations by Helios spacecraft presented a solar wind profile near the Sun that has two distinct components, the high speed separated sharply by a low speed (Schwenn 1990). The intermediate speed detected at 1 AU must be due to the interaction between fast and slow winds. Figure 1 depicts the solar wind profile at Helios I (top panel) and at 1 AU (bottom panel) during Carrington rotation CR 1660 (in 1977). It must be noted that the two profiles are completely different from each other.

In the present work, we made an attempt to see the correlation beteween FTE and SWS within a distance of 0.4 AU observed by HELIOS I and II. For a comparison, the near–Earth solar wind data observed during the same period have been made use of. We used both PFSS model as well as the Horizontal Current Current Sheet Source Surface (HCCSSS or CSSS) model of the corona to compute FTE.

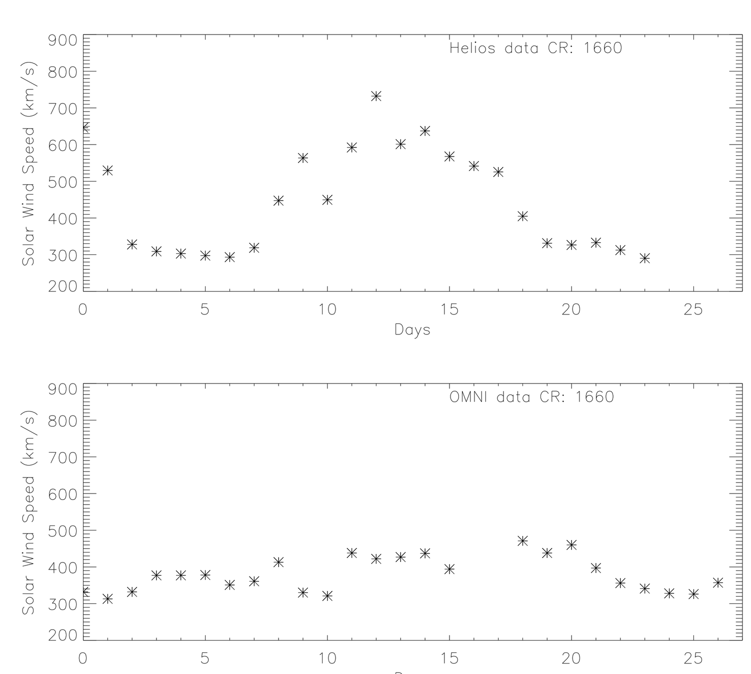

Figure 1. The solar wind profiles at Helios I (top panel) and near the Earth (bottom panel) for CR 1660.

Potential Field Source Surface (SS) Model

The coronal magnetic field, between the photosphere and the source surface, can be computed from the observed photospheric magnetic field by solving the LaPlace's equation, based on the following assumptions:

- Coronal field is a potential field since the currents carried by plasma are negligible
- Field at source surface, at 2.5 $R_\odot$, is purely radial

A coronal model of this kind is called Potential Field Source Surface (PFSS or SS) model and has been useful in predicting the observed structures, though discrepancies do exist. The SS model was first put forth by Schatten et al., (1969) and independently, by Altschuler and Newkirk (1969). The model has a few free parameters:

- Height of source surface: 2.5 or 2.35 $R_\odot$
- The radius of the inner surface: 1.0 $R_\odot$ or slightly different
- The number of multipole components included in the spherical harmonic expansion of fields, represented by N_{max}.

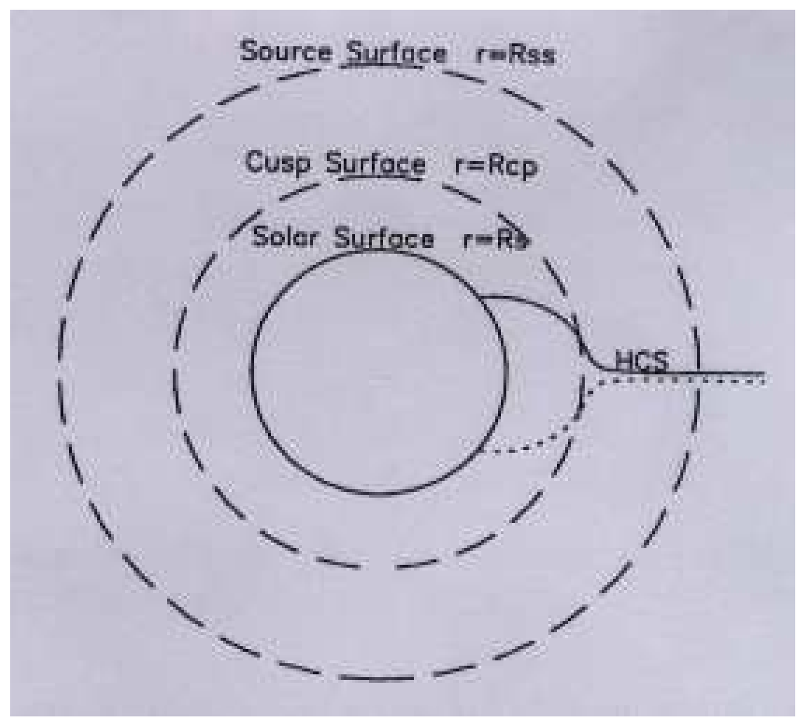

Figure 2. Geometry of the Current Sheet Source Surface Model.

Current Sheet–Source Surface (CSSS) Model

The SS model takes the effect of volume currents flowing beyond the source surface into account but neglects currents:

(a) between closed and open magnetic fields

(b) in the heliospheric current sheet (HCS)

which causes the discrepancy. Taking these currents into account Zhao and Hoeksema (1995) developed a coronal model known as Horizontal Current Current Sheet–Source Surface (CSSS) Model, which has the following features:

- Source surface is placed near the Alfvén critical point where all the magnetic fields are radial
- Introduced a cusp surface, where field lines are open but not necessarily radial, to include effects of streamer current sheets
- Used the source surface technique to include the effects of volume currents beyond the source surface

As in the SS model, there are several free parameters:

- a = 0.2 ; the height distribution of the horizontal current
- $R_{cp} = 2.0$; heliocentric distance of the cusp surface
- $R_{ss} = 15.0$; heliocentric distance of the source surface

Data and Procedure

Photospheric magnetic field data: Daily updated Wilcox Solar Observatory synoptic data.

Solar wind data: Data within 0.4 AU observed by HELIOS I and II, as well as near Earth (OMNI) data during 1976–1980.

Flux tube expansion factor FTE can be defined as:

$$FTE = \left(\frac{R_\odot}{R_{ss}}\right)^2 \frac{B_r(\theta_\odot, \phi_\odot)}{B_r(\theta_{ss}, \phi_{ss})} \quad (1)$$

where,

$B_r(\theta_{ss}, \phi_{ss})$: magnetic field strength at location (θ_{ss}, ϕ_{ss}) on the source surface

$B_r(\theta_\odot, \phi_\odot)$: field strength at the photospheric footpoint of the flux tube traversing (θ_{ss}, ϕ_{ss})

$R_\odot$ and R_{ss}: photospheric and source surface radii, respectively.

In order to correlate with FTE, solar wind observed in the heliosphere is traced back to the source surface using the following set of equations. (The separation between Helios and Earth is also taken into account.)

$$\theta_{ss} = \theta_E$$
$$\phi_{ss} = \phi_E + \frac{\omega R_E}{V} \quad (2)$$

where,

θ_{ss}, ϕ_{ss}: heliographic latitude and Carrington longitudes of the source of solar wind at the source surface

θ_E, ϕ_E: heliographic latitude and Carrington longitudes at distance R_E from Sun

ω: angular speed of solar rotation

V: solar wind speed

Constant speed approximation: Usually, an approximate value of 4, 4.5 or 5 days, the average transit time of solar wind from the Sun to Earth, will be used for V. The influence of *constant speed approximation* on the determination of the coronal sources of solar wind and there by on the computed FTE has been discussed in detail by Poduval and Zhao (2004), where we concluded that it is reasonable to use the observed values of solar wind in Eq. 2.

Scatter plots between FTE and SWS

FTE has been calculated using Eq. 1 and SS and CSSS models, for each point on the source surface corresponding to the solar wind mapped back from HELIOS I and II during 1976-1980. For a comparison, FTE is calculated corresponding to near Earth solar wind data for the same period. We used $N_{max} = 22$.

Justification:

(a) Poduval and Zhao (2004) have shown that $N_{max} = 22$ gives the highest correlation between observed and reproduced (using SS model) photospheric field.

(b) variation of the photospheric footpoint location with N_{max} was found to be negligible ablove 22 (Poduval and Zhao, 2004).

Table 1 summarises the correlation coefficient between FTE and SWS for both SS and CSSS models and the solar wind detected by Helios I and II and near the Earth.

Table 1. Correlation coefficient between LOG10(FTE) (computed using SS and CSSS models) and SWS (Helios and near Earth data).

Period of	Helios I and II Data		OMNI Data
Study	CSSS Model	SS Model	SS Model
1976	-0.31	-0.07	-0.39
1977	0.06	-0.27	-0.28
1978	-0.31	-0.18	-0.43
1979	0.15	-0.37	-0.35
1980	-0.11	-0.02	-0.25
1976-77	-0.07	-0.20	-0.32
1978-80	-0.19	-0.23	-0.35
1976-80	0.003	-0.21	-0.34

Figures 3–5 depict scatter plots of LOG10(FTE) *vs* SWS obtained for different phases of solar cycle.

Left hand panels: 1976, 1978 1980 and 1978-1990

Right hand panels: 1977, 1979, 1976-1977, and 1976-1980

Figure 3: CSSS Model and Helios I and II data

Figure 4: SS Model and Helios I and II data

Figure 5: SS Model and OMNI data

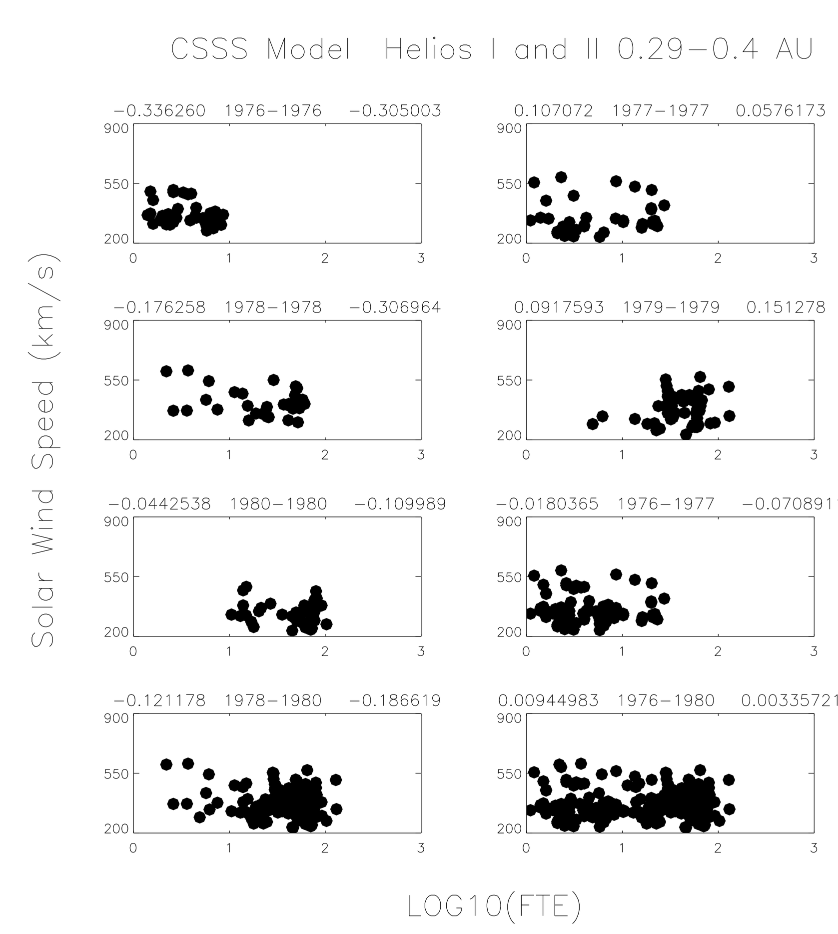

Figure 3. Scatter plot between LOG10(FTE) and SWS obtained for different phases of solar cycle. FTE is computed using CSSS model and the solar wind data is from HELIOS I and II observations.

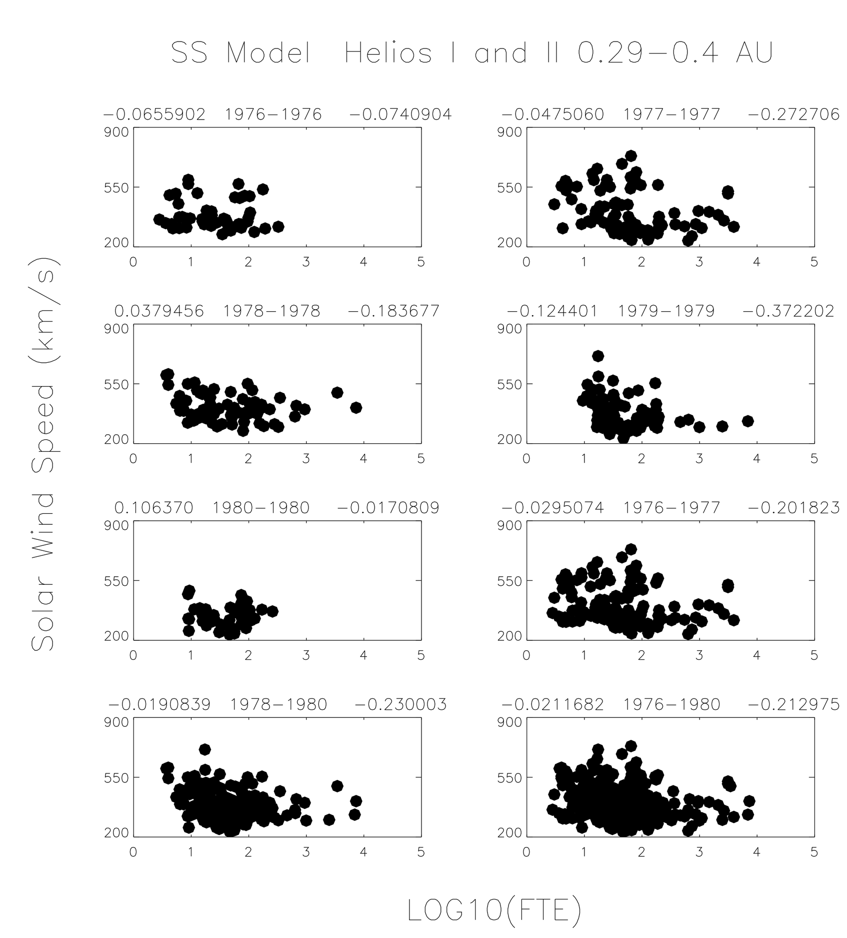

Figure 4. Same as Figure 3 but for SS model.

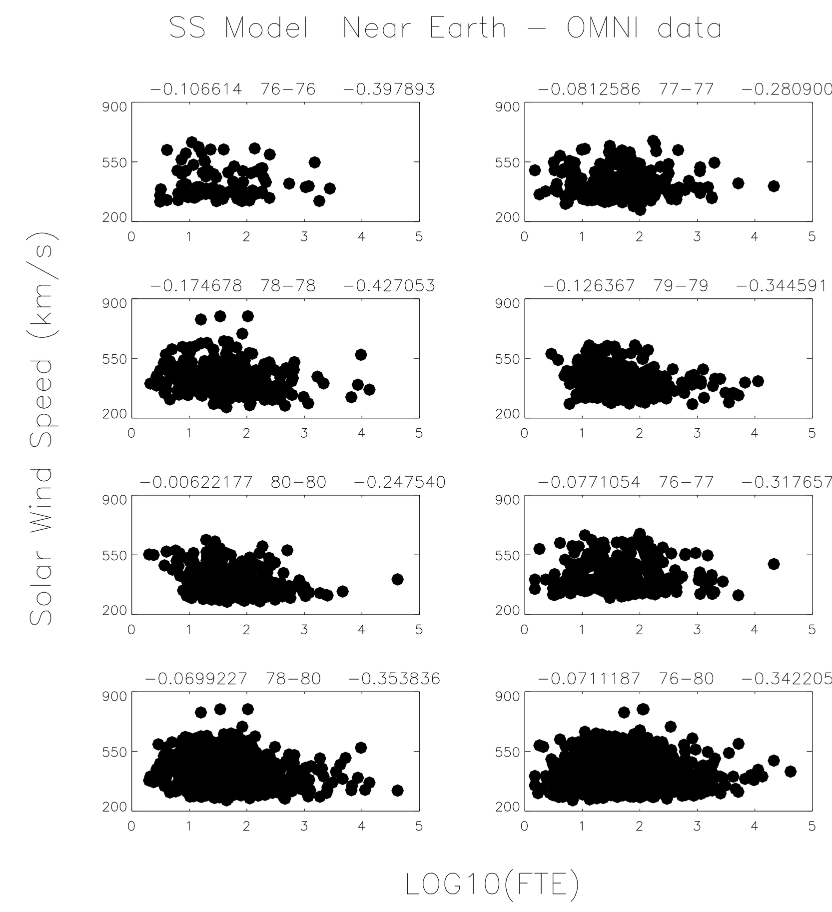

Figure 5. Scatter plot between LOG10(FTE) and SWS for different phases of solar cycle. FTE is computed using SS model. SWS is from the solar wind data near the Earth (OMNI data).

Discussion and Conclusion

The inverse relation between SWS and FTE computed at 2.5 $R_\odot$ using SS model, established by Wang and Sheeley (1990) has been made use of in the prediction of solar wind at 1 AU (Arge and Pizzo, 2000). The predicted solar wind speed does not always agree with the observed one and the discrepancies are significant. Poduval and Zhao (2004) have found that the correlation between SWS and FTE is not very significant nor is consistent always. The coronal magnetic field computed using SS model is highly structured and exhibits a profile similar to that of SWS at 1 AU, contrary to the Ulysses observation of a rather uniform heliospheric magnetic field. This similarity appears to be coincidental rather than causal since the solar wind profile at 1 AU results from the interaction between fast and slow winds during their outward propagation from the corona and is different from the profile near the Sun where the interaction is negligible (See Figure 1 and Schwenn, 1990). Based on the two types of stream–stream interaction, we speculated that the apparent correlation between SWS and FTE could be coincidental rather than causal (Poduval and Zhao, 2004). This speculation is partially supported by the fact that the coronal magnetic field computed using CSSS model is rather uniform (Zhao et al., 2001), consistent with Ulysses observation. We hypothesised that if there exists a physical relationship between FTE and SWS, then FTE must correlate with the SWS near the Sun, where the stream–stream interaction is negligible (Poduval and Zhao, 2004). To check this hypothesis, we used the Helios I and II data within 0.4 AU to obtain the correlation between FTE and SWS.

From the present analysis, we find that the correlation between FTE and the near–Sun SWS is also week and insignificant. Neither SS nor CSSS model yielded a significant correlation during the period of study. This fact strongly suggests that the correlation between FTE and SWS near the Sun is not causal. Moreover, it is to be noted that the correlation between SWS near the Earth and FTE using SS model is higher than the correlation between SWS near the Sun and FTE. This further supports our speculation that the greater correlation of FTE with near–Earth solar wind is due to the fact that solar wind profile at 1 AU is modified by Type I stream–stream interaction, which coincidentally matches with the coronal magnetic field profile.

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