Comment on "The underlying magnetic field direction in Ulysses observations of the southern polar heliosphere" by Forsyth et al.

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A recent paper by *Forsyth et al.* [1995] reported an apparent overwinding of the interplanetary magnetic field (IMF) relative to the Parker prediction as observed by the Ulysses spacecraft at latitudes greater than 60°. Specifically, the overwinding begins at $\sim 50°$ south latitude during the first poleward pass of the spacecraft, maintains a value in excess of 24° at latitudes greater than $\sim 60°$ south latitude, and then abruptly returns to the value predicted by *Parker* [1958] before the spacecraft reaches 60° south latitude on its equatorward trajectory. All of this takes only ~ 7 months.

We take no fault with these reported observations; indeed, they constitute a remarkable and pioneering look at the high-latitude IMF. What we do fault is the inaccurate representation of our past efforts to understand the possibly related observations of long-term IMF overwinding near the ecliptic plane and the incorrect application of our analysis of those observations to these new results. Specifically, *Smith and Bieber* [1991] proposed that the long-term overwinding of the IMF which spans over 2 decades of observations may be the result of small azimuthal fields near the source surface of the solar wind. *Forsyth et al.* [1995] however reject this proposed mechanism with the following statement:

> "...They [Smith and Bieber] postulated the presence of a systematic azimuthal magnetic field component near the source surface, persisting out into the heliosphere, as a possible cause [of the near-ecliptic overwinding]. To avoid violating the frozen-in field condition a systematic azimuthal component of the solar wind velocity would be required to maintain this azimuthal field component. To produce overwinding of the extent that we observe would require this azimuthal velocity to be of the order 500 km/s compared to the 15–20 km/s observed by the plasma instrument. We thus have no evidence relating the large deviation of the most probable $\phi_B - \phi_P$ observed by Ulysses at the highest latitudes with the much smaller near ecliptic effect reported by *Smith and Bieber.*"

The variables ϕ_B and ϕ_P of Forsyth et al. are the most-probable winding angle of the observed distribution and the winding angle predicted by *Parker* [1958].

The purpose of this "Comment" is to show that relatively small ($\sim 5°$) azimuthal fields on the source surface can easily produce overwinding of the magnitude observed, and they can do so without producing absurdly large azimuthal flows or violating the frozen-in field condition.

We neglect the consideration included in *Smith and Bieber* [1991] wherein the source latitude may differ from the latitude of the observation point. We perform the calculation in heliocentric (R, T, N) coordinates.

Assuming azimuthal symmetry, magnetic flux conservation yields the following expression for the radial component of the field:

$$B_R(r) = B_R(b)\left(\frac{b}{r}\right)^2 \tag{1}$$

where b and r denote the source radius and observation radius respectively.

To obtain the azimuthal component of the IMF, we consider a closed loop path extending from b to r within a meridional plane. Under steady-state conditions and adopting the frozen-in field assumption, Faraday's law can be written as an integration about the closed path:

$$\oint_C \mathbf{V} \times \mathbf{B} \cdot \mathbf{dl} = 0 \tag{2}$$

where $\mathbf{V}$ is the wind velocity and $\mathbf{B}$ is the IMF.

Assuming $B_N = 0$ for the long-term field, and since $V_N = 0$ from our assumption that there is no latitudinal transport, the total path integral yields:

$$rV_R(r)B_T(r) = rV_T(r)B_R(r) + bV_R(b)B_T(b) - bV_T(b)B_R(b). \tag{3}$$

The *Parker* [1958, eq. (24)] assumption for $V_T(r)$ is

$$V_T(r) = V_T(b); \qquad r > b. \tag{4}$$

Smith and Bieber [1991] adhered to this same assumption. The azimuthal velocity at the source is given by corotation of the solar atmosphere:

$$V_T(b) = \frac{2\pi}{T_S} b \sin(\Theta) \tag{5}$$

where T_S is the rotation period of the sun at the source radius and Θ is the colatitude of the source point.

If an azimuthal component to the magnetic field exists at the source surface, then the general expression for the winding angle, $\Psi \equiv \tan^{-1}(-B_T/B_R)$, is:

$$\tan[\Psi] = \frac{2\pi r \sin(\Theta)}{T_S V_R(r)}\left[1 - \frac{b}{r}\right] - \frac{B_T(b)}{B_R(b)}\frac{V_R(b)}{V_R(r)}\left(\frac{r}{b}\right). \tag{6}$$

The first term on the right-hand side is $\tan(\Psi^{(P)})$ with $\Psi^{(P)}$ being the standard Parker angle. The second term represents the alteration to Ψ resulting from azimuthal fields on the source surface. Numerous potential sources exist to provide $B_T(b)$ and do undoubtedly act to seed the solar wind with azimuthal fields in a transient fashion [*Bieber and Rust* 1995; *Smith and Phillips* 1995].

The Ulysses observation [*Forsyth et al.*, 1995] lasts for 7 months while the spacecraft was above the sun's southern polar hole. *Forsyth et al.* [1995] state that the predicted winding angle reaches a minimum of $\Psi^{(P)} = 12^\circ$ at a latitude of 80° ($\Theta = 10^\circ$). The heliocentric distance is ~ 2 AU with an average wind speed of 800 km/s over the pole [*McComas et al.*, 1995]. The value of $B_T(b)$ required to accomplish the apparent overwinding of the IMF to $\Psi = 47^\circ$, [*Forsyth et al.*, 1995, Figure 3] is given by:

$$\tan[47^\circ] \;=\; \tan[12^\circ] - \frac{B_T(b)}{B_R(b)}\frac{V_R(b)}{V_R(r)}\left(\frac{r}{b}\right). \tag{7}$$

We are free to set the inner boundary at any distance where corotation of the solar atmosphere is still in effect. If we set this boundary to be the Alfvén radius at $b = 20\ \mathrm{R_S}$ with $V_R(b)/V_R(r) = 1/2$ [*Lotova et al.*, 1985], the required azimuthal component of the source field is:

$$-\frac{B_T(b)}{B_R(b)} = 0.08. \tag{8}$$

This corresponds to a 5° angle between the radial direction and the IMF at the inner boundary.

We can estimate the magnitude of the azimuthal flow implicit in the model. Using the constant azimuthal flow speed assumption of equation (4) we obtain a predicted azimuthal flow speed at the spacecraft of 7 km/s.

We can refine the calculation of *Smith and Bieber* [1991] by considering that the wind does not maintain a constant azimuthal speed. Conservation of angular momentum [*Weber and Davis*, 1967] requires that:

$$V_T(r) = V_T(b)\left(\frac{b}{r}\right); \qquad r > b. \tag{9}$$

Under this assumption the predicted form for $B_T(r)$ is modified slightly and the winding angle becomes:

$$\tan[\Psi] = \frac{2\pi r \sin(\Theta)}{T_S V_R(r)}\left[1 - \left(\frac{b}{r}\right)^2\right] - \frac{B_T(b)}{B_R(b)}\frac{V_R(b)}{V_R(r)}\left(\frac{r}{b}\right). \tag{10}$$

The expression for the overwinding resulting from $B_T(b)$ is unchanged. The magnitude of the azimuthal flow implicit in this model is < 1 km/s at 2 AU.

Variation of b to $\sim 2\ \mathrm{R_S}$ in either of these models implies a corresponding reduction in $V_R(b)$ and still leads to values of the azimuthal source field that are a few percent of the radial component. The implied azimuthal wind speed at 2 AU is even smaller when $b \sim 2\ \mathrm{R_S}$ and is far below the value claimed by *Forsyth et al.* [1995].

Comparing this computation with that of Forsyth et al., the key difference appears to be their requirement that the convective electric field vanish in a frame corotating with the Sun, or equivalently, that it equal $(2\pi/T_S) r \sin(\Theta) B_R$ in the spacecraft frame. While this requirement is satisfied by the Parker model, we see no reason to impose it as a fundamental condition on all models of the IMF. Our approach, in contrast, views **B** and **V** as the dynamically significant quantities and models their evolution by basic laws such as conservation of magnetic flux and conservation of angular momentum. The electric field, in this approach, follows from **B** and **V** in accord with the frozen–in field condition and need not vanish in the corotating frame.

Acknowledgments. This work is supported by NSF grant ATM-9314683, NASA grant NAGW-3033, NASA Space Physics Theory Program grant NAG5-1573, and Jet Propulsion Laboratory contract 959167 to the Bartol Res. Inst.

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March 18, 1996; revised June 20, 1996; accepted July 12, 1996.