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Determination of Solar Wind Angular Momentum and Alfvén Radius from PSP Observations

Ying D. Liu, Chong Chen, Michael L. Stevens, and Mingzhe Liu
(Correspondence: National Space Science Center, Chinese Academy of Sciences, Beijing, China; liuxying@swl.ac.cn)

1. Abstract

As fundamental parameters of the Sun, the Alfven radius and angular momentum loss determine how the solar wind changes from sub-Alfvenic to super-Alfvenic and how the Sun spins down. We present an approach to determining the solar wind angular momentum flux based on PSP observations. A flux of about 0.15×10^{30} dyn cm sr^{-1} near the ecliptic plane and 0.7:1 partition of that flux between the particles and magnetic field are obtained by averaging data from the first four encounters within 0.3 au from the Sun. The angular momentum flux and its particle component decrease with the solar wind speed, while the flux in the field is remarkably constant. A speed dependence in the Alfven radius is also observed, which suggests a "rugged" Alfven surface around the Sun. Substantial diving below the Alfven surface seems plausible only for relatively slow solar wind given the orbital design of PSP. Uncertainties are evaluated based on the acceleration profiles of the same solar wind streams observed at PSP and a radially aligned spacecraft near 1 au. We illustrate that the "angular momentum paradox" raised by Reville et al. can be removed by taking into account the contribution of the alpha particles. The large proton transverse velocity observed by PSP is perhaps inherent in the solar wind acceleration process, where an opposite transverse velocity is produced for the alphas with the angular momentum conserved. Preliminary analysis of some recovered alpha parameters tends to agree with the results.

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2. Derivation of Alfven Radius and Angular Momentum Flux

In previous studies, the solar wind angular momentum per unit mass and the Alfven radius are calculated from

$$L = rv_\phi - \frac{rB_rB_\phi}{\mu\rho v_r} = \Omega r_{\rm A}^2,$$

and the angular momentum flux per steradian near the ecliptic plane is

$$F = \rho v_r v_\phi r^3 - \frac{B_rB_\phi r^3}{\mu}.$$

The first term often involves complications, such as uncertainties in the measurements of the transverse velocity and density, and lack of accurate measurements of the alpha particles that may be a significant factor in modifying the angular momentum flux. Here we present an approach in an attempt to avoid some of those complications. The Alfven radius can be reasonably approximated as

$$r_{\rm A} \simeq \frac{r}{M_{\rm A}}$$

and the angular momentum flux can be derived using

$$F = \rho v_r r^2 \Omega r_{\rm A}^2 \simeq \frac{\Omega r^4 B_r^2}{\mu v_r}$$

An advantage is that Equation (4) only requires the radial components of the velocity and magnetic field, which avoids various complications associated with the measurements of the transverse velocity, density, and alpha parameters. The field component of the angular momentum flux can be calculated using the second term of Equation (2), which is independent of the particle parameters.

3. Effects of Alpha Particles

Alpha particles may carry a significant negative angular momentum flux. In the presence of the alpha particles, the angular momentum flux of the wind plasma can be written as

$$F_w \simeq n_p m_p r^3 (v_{pr}v_{p\phi} + 0.2v_{\alpha r}v_{\alpha\phi})$$

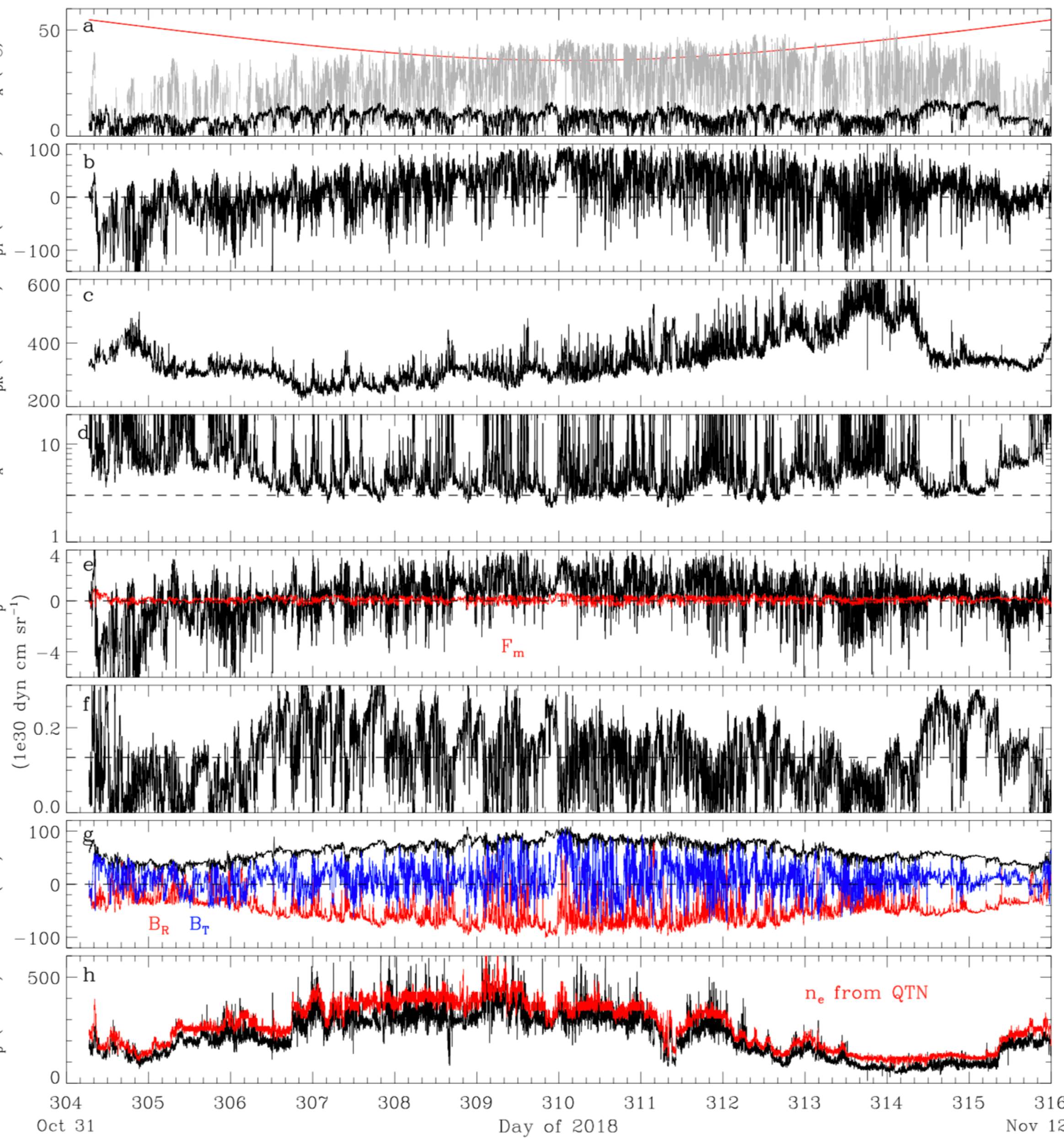
We construct the alpha velocity based on observations between 0.3-1 au:

$$\boldsymbol{v}_\alpha = \boldsymbol{v}_p - {\rm sign}(B_T)\frac{\boldsymbol{B}}{\sqrt{\mu\rho}}.$$

We aim at illustrating if the alphas can offset a considerable amount of the angular momentum flux in the protons, not to the exact value one may expect.

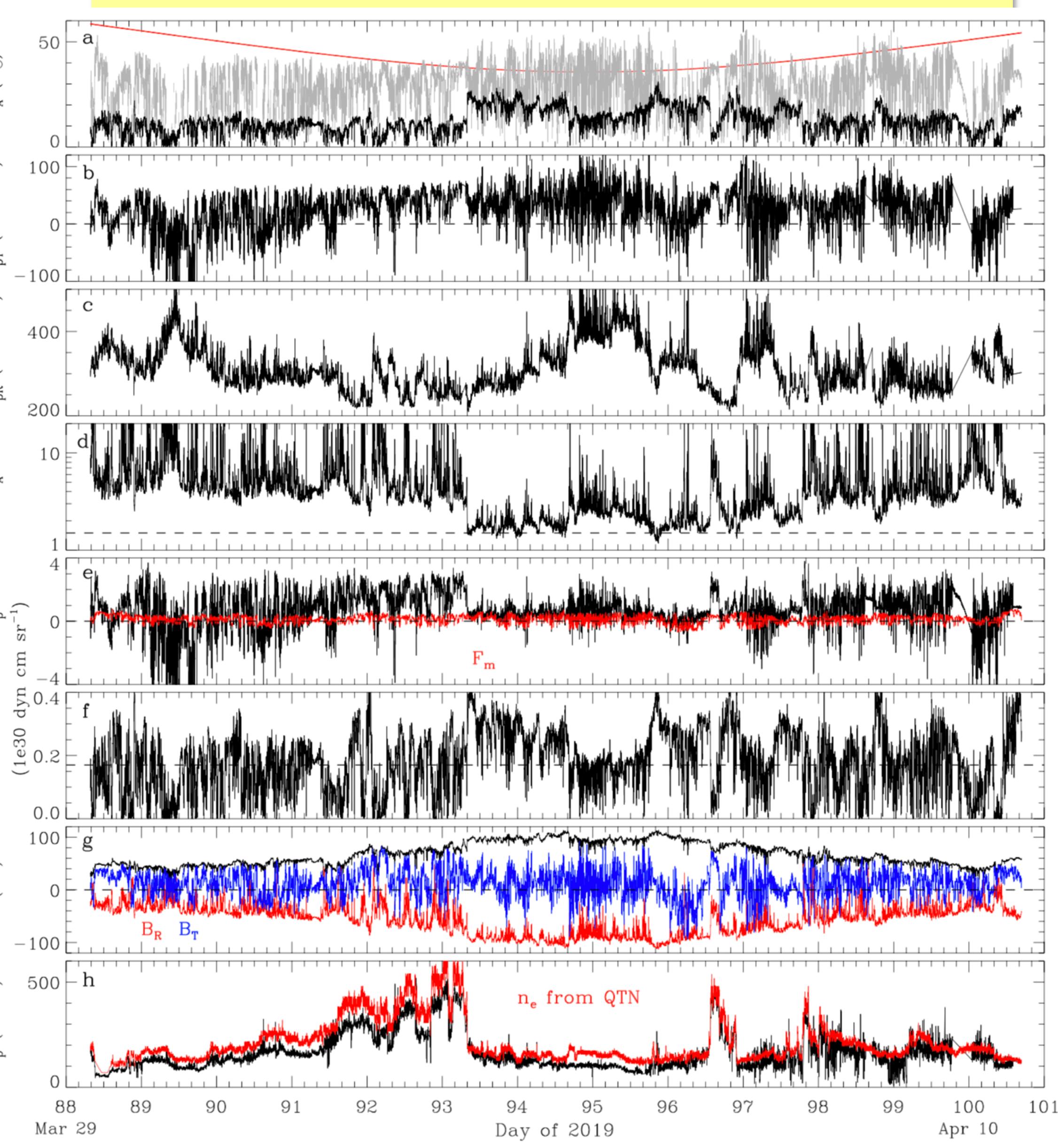
4. Observations and Results

Fig. 1. PSP measurements at the first encounter



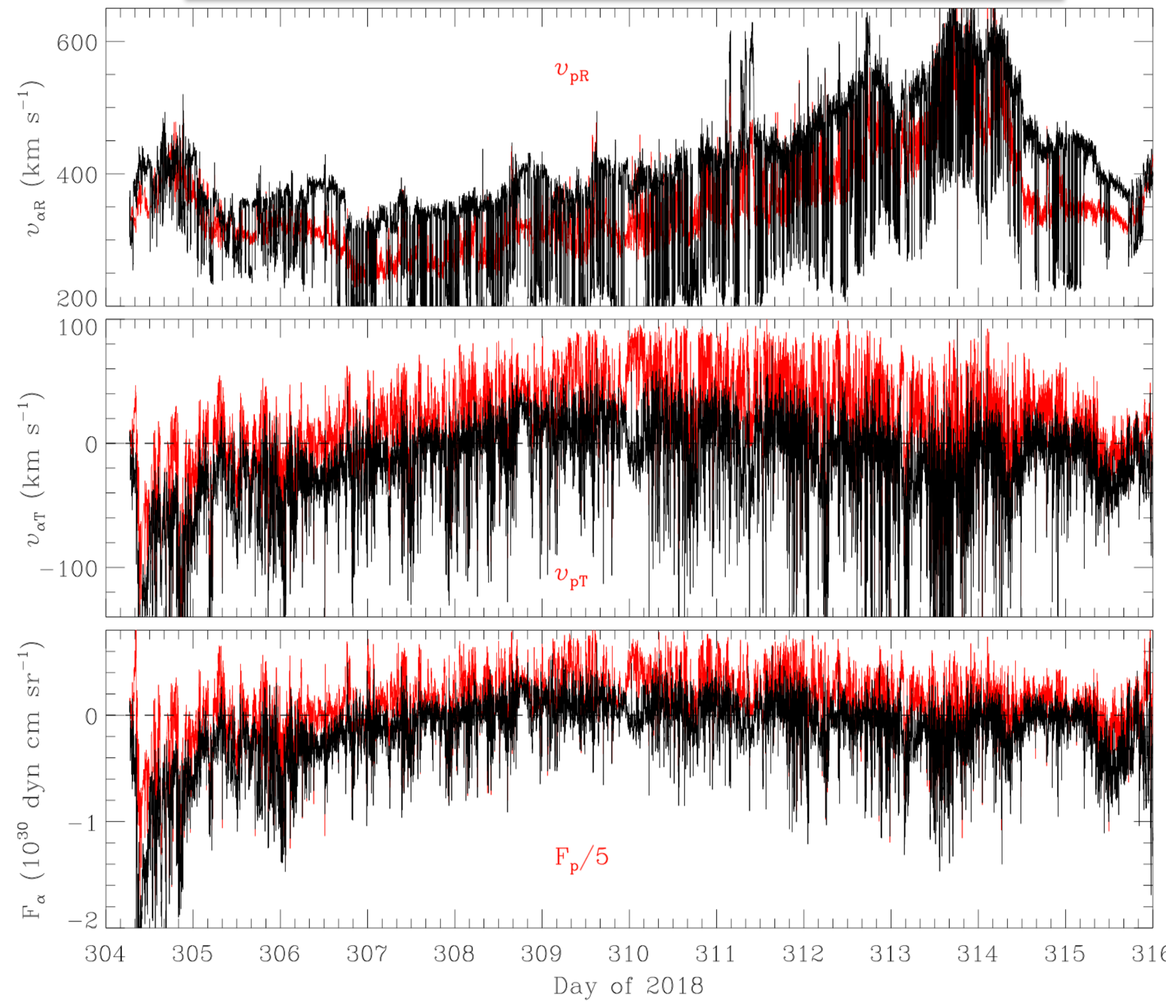
- Previous approach gives Alfven radii above the PSP distances;
- The Alfven radius from Equation (3) is well below the PSP distances;
- Negative transverse flows are seen for enhanced radial speeds, which may indicate stream-stream interactions even for encounter distances;
- The field AMF is relatively invariant compared with the proton AMF;
- An anticorrelation is visible between the total AMF and the radial velocity;
- The SPC proton density is systematically smaller than the electron density from QTN.

Fig. 2. PSP measurements at the second encounter



- The situation is generally similar to that of the first encounter;
- We see elevated Alfven radii corresponding to an interval of reduced densities, with M_A as low as about 1.5;
- The third and fourth encounters are also generally similar.

Fig. 3. Constructed alpha velocity and AMF



- Alpha radial velocity is generally larger than that of the protons, but similar values between the two species are also seen for slower wind;
- Persistent negative transverse velocities are obtained for the alphas, as expected;
- Alphas are indeed capable of canceling a significant amount of the AMF carried by the protons.

Table 1. PSP Measurements of Alfven Radius and Angular Momentum Flux

Encounter	$r_{\rm A}$ ($R_\odot$)	F[a]	F_m	F_w[b]	F_p	F_α[c]
		(10^{30} dyn cm sr^{-1})				
1	8.1	0.13	0.08	0.05	0.37	−0.19
2	11.8	0.17	0.13	0.04	0.66	−0.08
3	9.7	0.15	0.07	0.08	0.47	−0.13
4	9.0	0.13	0.08	0.06	0.82	−0.01
Average	9.7	0.15	0.09	0.06	0.58	−0.10

- The AMF of magnetic stresses is relatively invariant compared with the flux in protons;
- Averaging the whole data yields r_A = 9.7 solar radii, F = 0.15 × 10^{30} dyn cm sr^{-1}, and about 0.7:1 partition of the flux between the particles and field;
- The alpha particles, in principle, could cancel a considerable amount of the flux in the protons, but we find this more difficult as we move closer to the Sun;
- On average, the alphas are anticipated to carry an angular momentum flux of about −0.5 × 10^{30} dyn cm sr^{-1} in order to bring down the protons' flux to the level of the plasma.

Table 2. Alfven Radius and Angular Momentum Flux as a Function of Speed

Speed[a] (km s^{-1})	Percentage	$r_{\rm A}$ ($R_\odot$)	F	F_m	F_w[b]	F_p
			(10^{30} dyn cm sr^{-1})			
$v_p \leqslant 250$	4.5%	12.3	0.22	0.08	0.14	0.86
$250 < v_p \leqslant 350$	62.3%	10.2	0.16	0.09	0.07	0.65
$350 < v_p \leqslant 450$	27.8%	9.1	0.12	0.09	0.03	0.42
$v_p > 450$	5.4%	7.9	0.09	0.10	−0.01	0.50

- The field component of the flux is remarkably constant over the solar wind speed;
- The total flux decreases with speeds, and so does the flux in the wind plasma;
- We see a predominance of the plasma contribution over the field's for speeds less than 250 km/s, a near equipartition for speeds between 250 and 350, and a reversal for speeds larger than 350 km/s (the solar wind may be still accelerating at encounter distances);
- The wind plasma carries zero or even negative AMF when the speed exceeds 450 km/s;
- Substantial diving of PSP below the Alfven surface is plausible only for the solar wind with speeds below 350 km/s.