Evaluating the de Hoffmann-Teller cross-shock potential at real collisionless shocks

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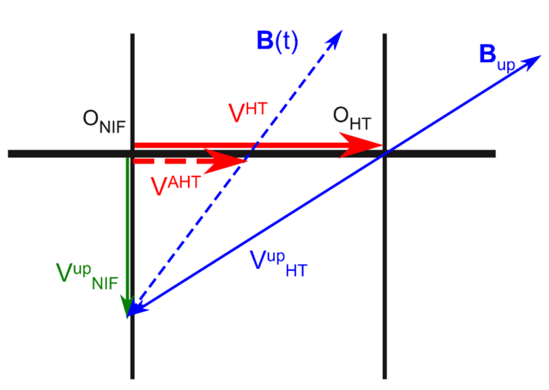
Background

- In deHoffmann-Teller (HT) frame, cross-shock potential is linked to ambipolar E-field
- Shock energy partition related to HT potential via electron "heating"
- Comisel et al, Marghitu et al, (C&M) introduced "adaptive" HT frame transformation for non-steady circumstances; tested in 1D PIC simulations

- **Q1: Does this work at real shocks?**
- **Q2: Can MMS do it?**

HT transformation

- Move along shock with $\mathbf{V}^{T,HT}$ to make $\mathbf{V} \parallel \mathbf{B}$
- $\mathbf{E} \rightarrow \mathbf{E} + \mathbf{V}^{T,HT} \times \mathbf{B}$
- Removes tangential motional $\mathbf{E}$
- $\mathbf{E}^{HT} = E_n\, \mathbf{n}$
- $\mathbf{V}^{T,HT} = -\,\mathbf{n} \times \mathbf{E} / B_n$
- For unsteady conditions C&M adaptive $\mathbf{V}^{T,AHT}$ follows $\mathbf{E}(t)$ (so $\mathbf{V}$ follows $\mathbf{B}$)



e- momentum & ϕ

$$\mathbf{E}^{ve} \equiv \mathbf{E} + \mathbf{V}_e \times \mathbf{B}$$
$$= -\frac{1}{en_e}\nabla \cdot \underline{\underline{\mathbf{P}}}_e + \text{inertial, frictional, ...}$$
$$= \mathbf{E}^{amb} + \text{other terms}$$

which yields

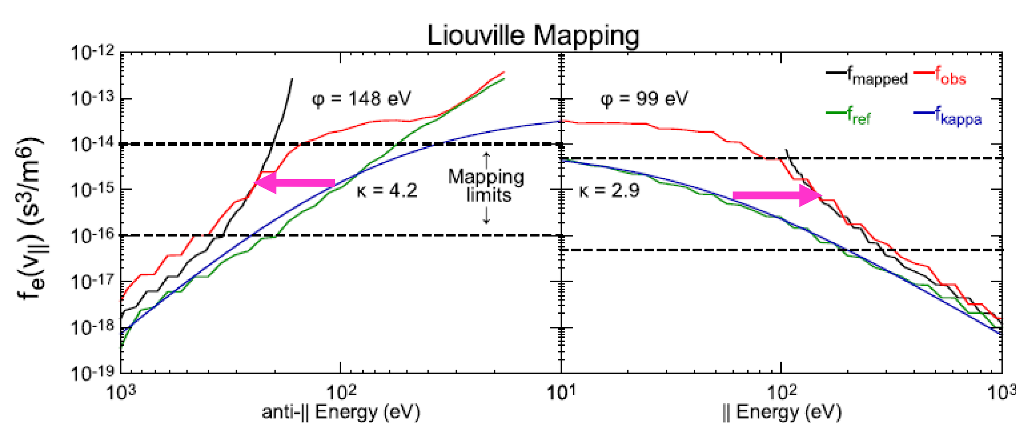
$$E_\parallel = -\frac{1}{en_e}\left(\nabla \cdot \underline{\underline{\mathbf{P}}}_e\right) \cdot \mathbf{B}/B$$

Shock potentials for est. HT $\mathbf{E}^\alpha$

$$\phi^\alpha(n) = -\int^n E_n^\alpha(t)\, dn$$
$$= -\int^\ell E_\parallel^\alpha(t)\, d\ell$$

Liouville Mapping

- Note $V_{flow} << v_{th,e}$ so magnetized electrons traverse shock in both directions
- Phase space "inflation" (aka heating) thus related directy to ϕ^{HT}
- Transform to ~ HT
- Identify upstream reference $f_{ref}(v_\parallel)$
- Find ϕ to map all other $f(v_\parallel)$
- Direct measure of $\phi(x)-\phi_{ref}$



ϕ estimators

1. $\phi^{HT} = V_n^{sh} \int E_n^{HT}(t)\, dt$
   $\equiv V_n^{sh} \int \left(\mathbf{E}^{NIF}(t) + \mathbf{V}^{T,HT} \times \mathbf{B}^{up}\right) \cdot \mathbf{n}\, dt$
   Static upstream values.
2. $\phi^{AHT} = V_n^{sh} \int \left(\mathbf{E}^{NIF}(t) + \mathbf{V}^{T,AHT}(t) \times \mathbf{B}(t)\right) \cdot \mathbf{n}\, dt$
   C&M's adaptive HT, B_n = constant.
3. $\phi^{AHTt} = V_n^{sh} \int \left(\mathbf{E}^{NIF}(t) + \mathbf{V}^{T,AHTt}(t) \times \mathbf{B}(t)\right) \cdot \mathbf{n}\, dt$
   uses $B_n(t)$
4. $\phi^{\parallel} = -\int E_\parallel(t)\, d\ell \equiv V_n^{sh} \int E_\parallel(t) B^{up}/B_n^{up}\, dt$
   Direct; no down-sampling of E
5. $\phi^{ve} = V_n^{sh} \int (\mathbf{E}(t) + \mathbf{V}_e(t) \times \mathbf{B}(t)) \cdot \mathbf{n}\, dt$
   Left hand side of the e- momentum; no frame transf.
6. $\phi^{amb} = \int \frac{1}{en_e} \frac{dP_{e,nn}}{dt}\, dt$
7. ϕ^{Lvl0},
   Liouville-mapped determination

References

- Schwartz et al, 2021, JGR (submitted)
- Comisel et al, 2015, AnnGeo, doi: 10.5194/angeo-33-345-2015
- Marghitu et al, 2017, GRL, doi: 10.1002/2017GL073241

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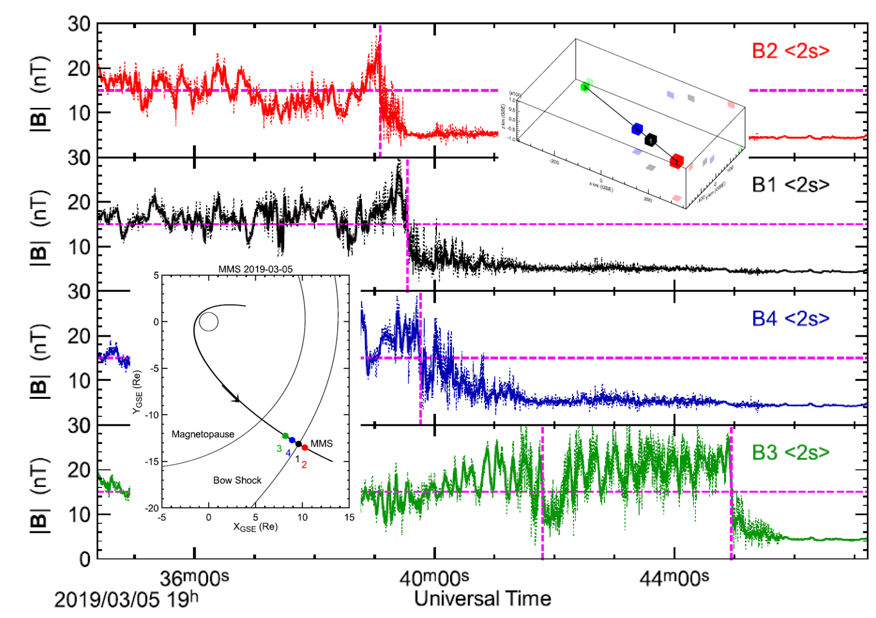
Bow Shock

- M_A = 6.0; M_f = 4.9; θ_{Bn}=76; β~0.6
- V_{shock}~7.6 km/s [steady until MMS3]

MMS Pearls

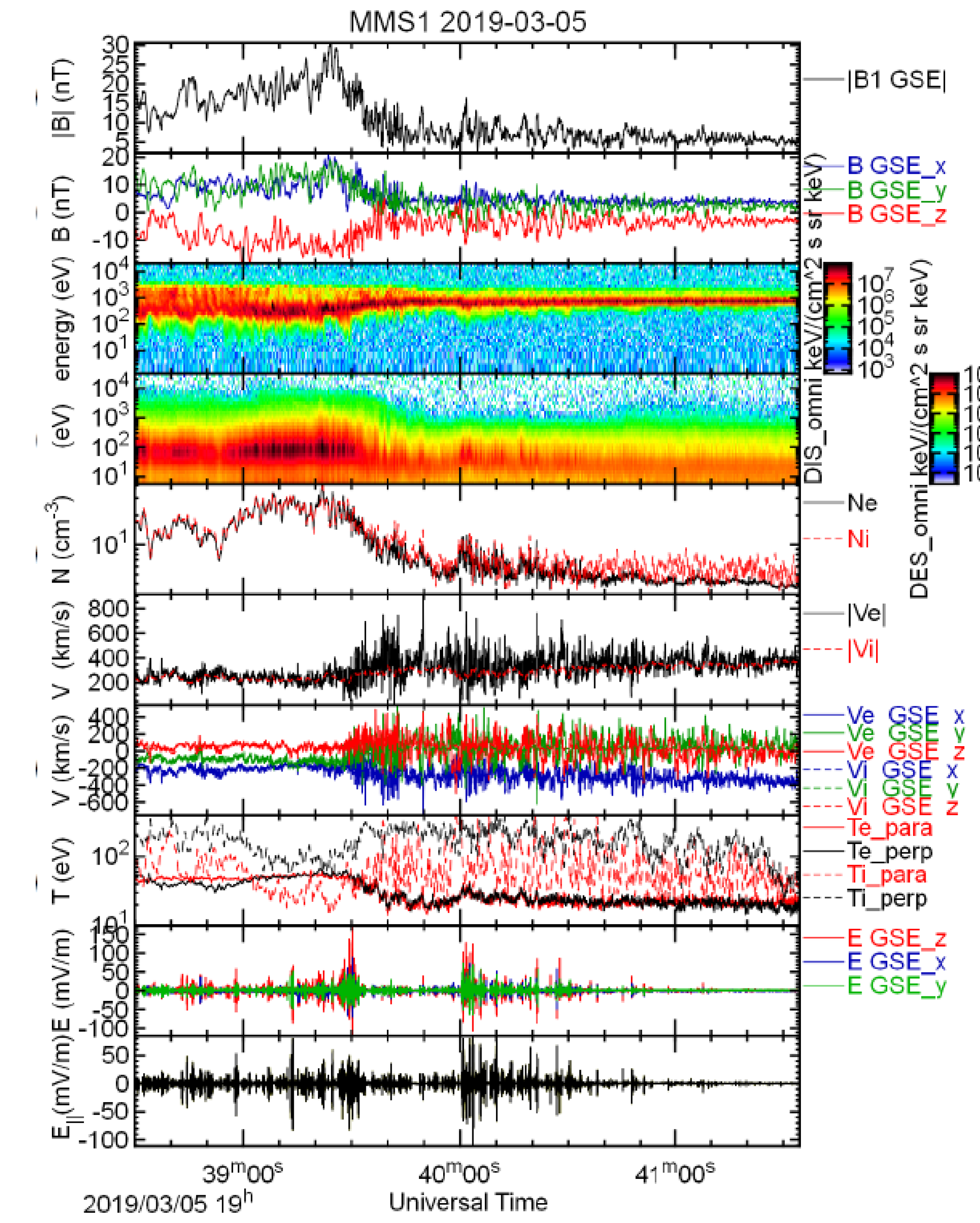


Results (colors)

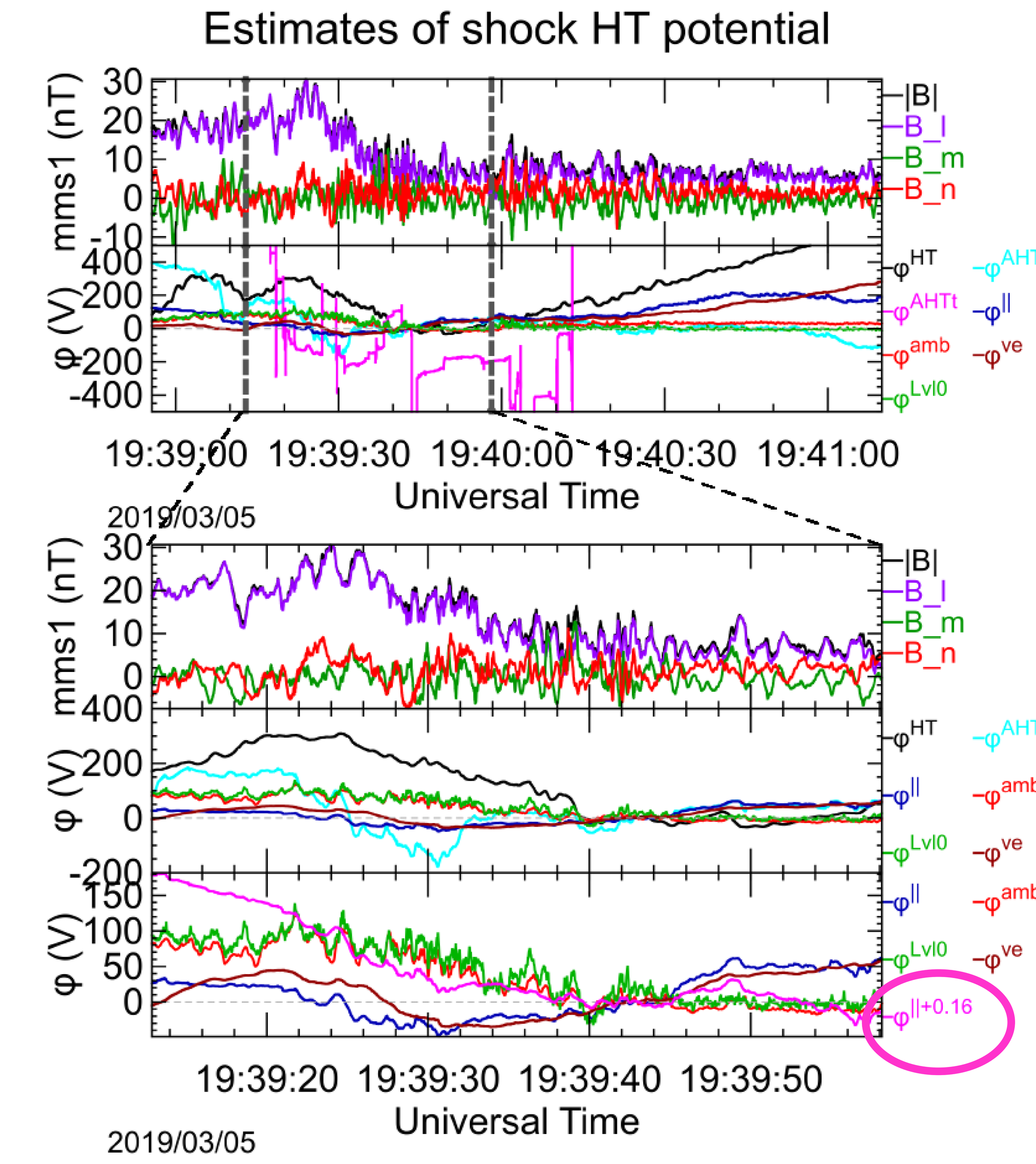
- ϕ^{amb} & ϕ^{Lvl0} agree & are gold standard, relying on e- physics
- Adaptive forms problematic due to non-constant B_n and/or **n** in >1D
- $\phi^{\parallel}$ & ϕ^{ve} similar – neither uses frame transformation
- $\phi^{\parallel}$ & (ϕ^{ve}) can be made ≈ ϕ^{amb} if add 0.16 mV/m offset to $E^{\parallel}$ through shock

Conclusions

- Q1: No. Unsolved problem of $B_n(t)$ or **n**(t) in 3D non-stationary shocks
- Q2: Almost! Manipulations get to within uncertainty in dc **E**
- That we get this close is testament to MMS quality of fields and particles
- Direct approaches, e.g., $E_\parallel$, better than frame transformations
- Electron (ϕ^{amb} or ϕ^{Lvl0}) good.
- No real independent determination of ϕ^{HT} directly from E-fields

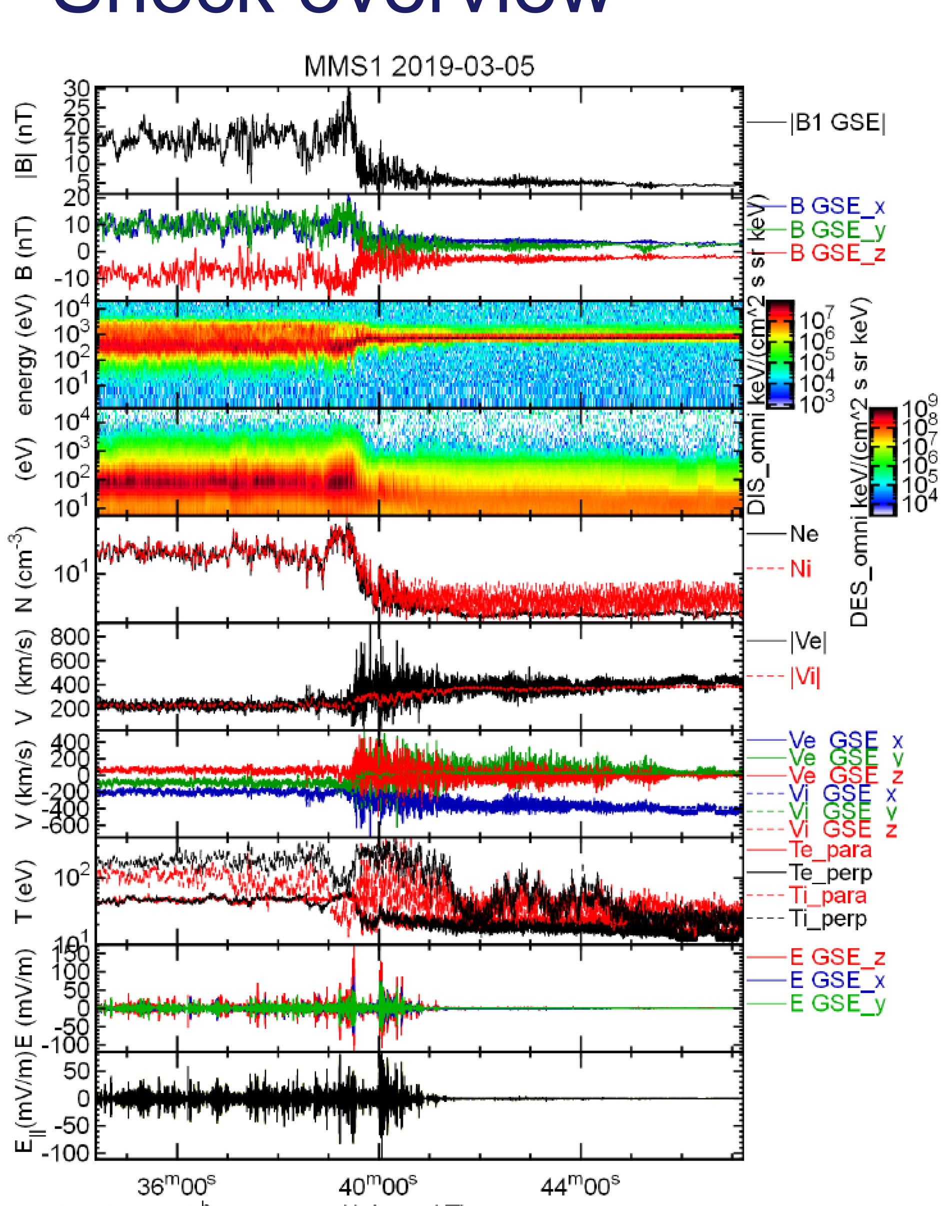


Estimates of shock HT potential



Extras

Shock overview



Liouville mapping ϕ

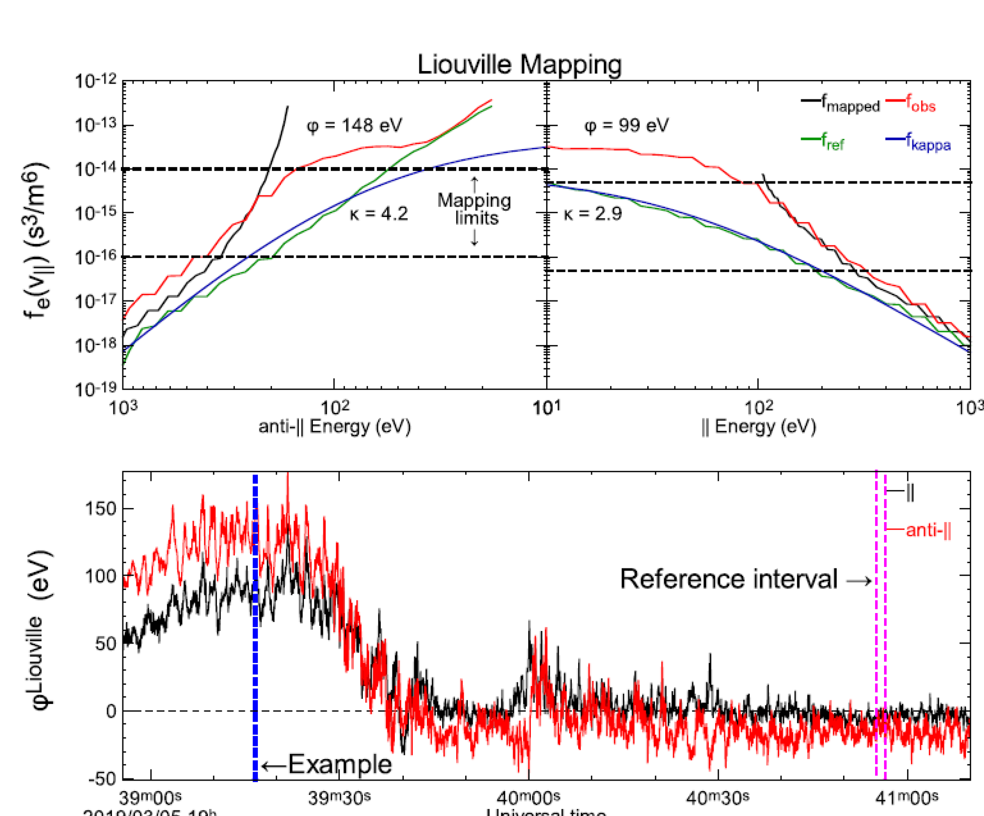


Table 1: Solar wind and shock parameters

Parameter	Value	Units	Comments
MMS2 Shock Crossing Time	2019-03-05 19:39:05	UT	
MMS2 Location	(10.1, -13.4, 6.85)	GSE R_e	
Upstream field $\mathbf{B}_{up}$	(3.45, 2.47, -2.46)	GSE nT	MMS2 19:43:57–19:44:47
Proton density $n_{p,up}$	3.5	cm^{-3}	Wind 3DP†
Proton velocity $V_{p,up}$	(-402, 14, -5)	km/s	Wind 3DP
Proton temperature $T_{p,up}$	5.9	eV	Wind 3DP
Electron temperature $T_{e,up}$	4.4	eV	Wind 3DP
Plasma beta β_{up}	0.6		total
Shock normal **n**	(0.847, -0.482, 0.226)	GSE	[?]
θ_{Bn}	76	deg	
Inflow speed along **n**: V_n	-341	km/s	In shock rest frame
Shock Alfvén Mach M_A	6.0		
Fast Magnetosonic Mach M_f	4.9		
Spacecraft separations:			$\mathbf{r}_{21} \equiv \mathbf{r}_1 - \mathbf{r}_2$, etc.
$\mathbf{r}_{21} \cdot \mathbf{n}$	-201	km	
$\mathbf{r}_{14} \cdot \mathbf{n}$	-104	km	
$\mathbf{r}_{43} \cdot \mathbf{n}$	-407	km	
Shock motion along **n**:			$\mathbf{r}_{21} \cdot \mathbf{n}/(t_1 - t_2)$, etc.
$V_{shkn,2\rightarrow1}$	-7.4	km/s	
$V_{shkn,1\rightarrow4}$	-7.8	km/s	
$V_{shkn,4\rightarrow3}$	-1.3	km/s	First encounter

†All Wind parameters are 20 minute averages lagged 65 minutes.