Verification and Validation of the Updated WSA-ENLIL-Cone Modeling System

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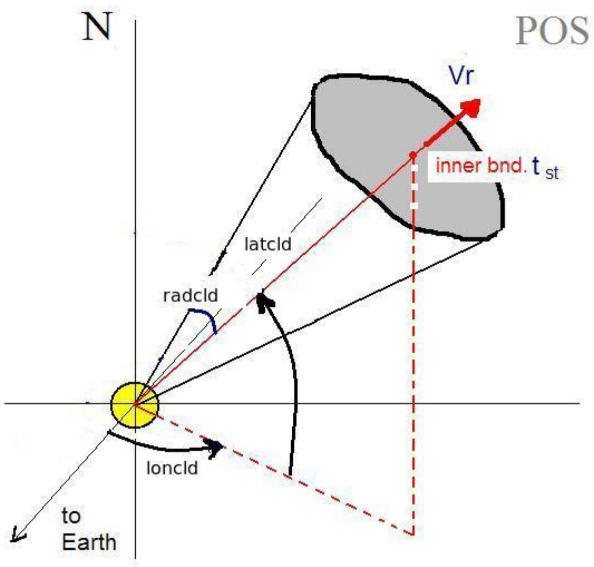
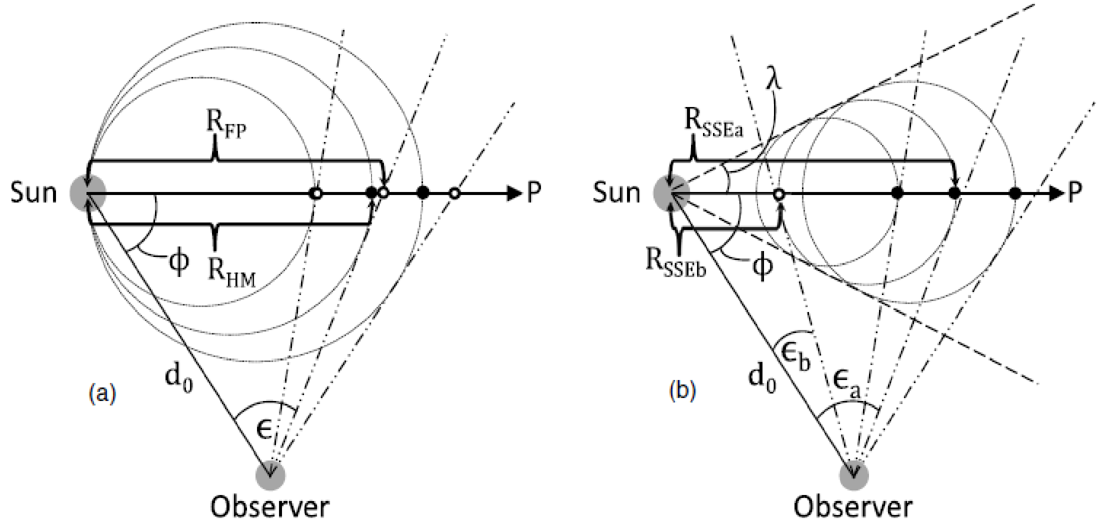
Introduction of the Modeling System

- The global 3D MHD WSA-ENLIL model provides a time-dependent description of the background solar wind plasma and magnetic field (e.g., Odstrcil et al., 1996; Odstrcil and Pizzo, 1999a, 1999b; Odstrcil et al., 2004)
- The ENLIL model at CCMC has been gradually evolving for run-on-request, but has been kept as v2.7 for the predictions at NOAA/SWPC
- The WSA-ENLIL model does not simulate CME initiation but uses kinematic properties of CMEs inferred from coronal and/or heliospheric observations to launch a CME-like **hydrodynamic** structure at **21.5 Rs** (Arge and Pizzo, 2000; Arge et al., 2004; Odstrcil et al., 2005)
- The geometrical CME properties are commonly approximated by the Cone model (Zhao et al., 2002; Xie et al., 2004) which assumes isotropic expansion, radial propagation, and constant CME cone angular width



Courtesy of CCMC

Methods to Fit CMEs



Davies et al. (2012)

Several different ways to fit CMEs from remote-sensing observations

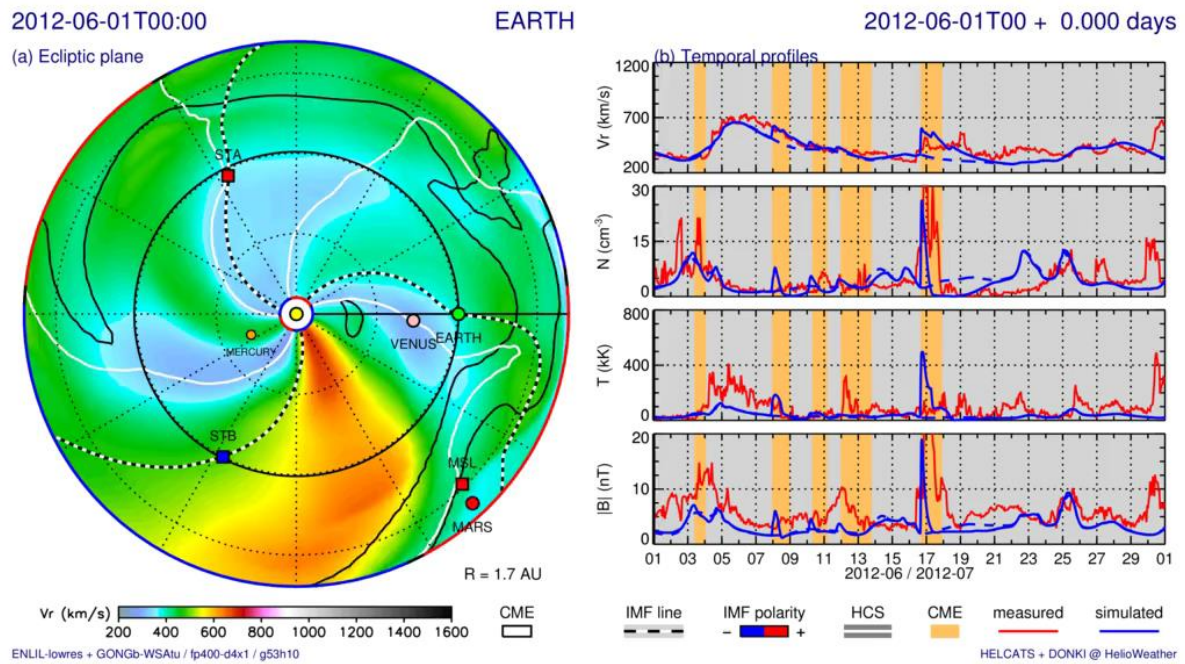
- Single s/c
  - CME is point-like → fixed-phi fitting (Rouillard et al., 2008)
  - CME is a wide circle → harmonic mean fitting (Lugaz, 2010)
  - CME with a varying width → self-similar expansion fitting (Davies et al., 2012)
- Multiple s/c
  - Geometric triangulation (Liu et al., 2010)
  - Tangent to a sphere (Lugaz et al., 2010)
  - Stereoscopic self-similar expansion (Davies et al., 2013)

CME Parameters Used as Model Input

- At CCMC, CME parameters are determined using
  - Stereoscopic CME Analysis Tool (StereoCAT) based on tracking specific CME features (Pulkkinen et al., 2010)
  - Since about 2014, CME Analysis Tool (CAT) to capture the volumetric structure of CMEs (Pizzo and Biesecker, 2004; Millward et al., 2013)
- The CME parameters and simulation graphic outputs since 2010 are publicly available at the CCMC Space Weather Database of Notifications, Knowledge, Information (DONKI) (http://kauai.ccmc.gsfc.nasa.gov/DONKI)
- The ENLIL simulation results including graphic outputs in 2007-2016 are archived at **Helioweather** (http://helioweather.net/)
- In this project joint with the Heliospheric Cataloguing, Analysis and Techniques Service (HELICATS), CME parameters are from fixed-phi fitting

Cone	date lat lon radcld vcld dcld tcld	Leading edge at 21.5 Rs at this time (yyyy-mm-ddThh:mm) Heliographic latitude of the cone axis (deg) Heliographic longitude of the cone axis (deg) Half-width of the cone (deg) Velocity of the cone (km/s) Density of the cone as factor of mean stream value Temperature of the cone as factor mean stream value
Cavity if radcav > 0	radcav dcav tcav	Radius of the cavity as factor of radcld Density of the cavity as factor of mean stream value Temperature of the cavity as factor of mean stream value

Execution of the WSA-ENLIL-Cone Model

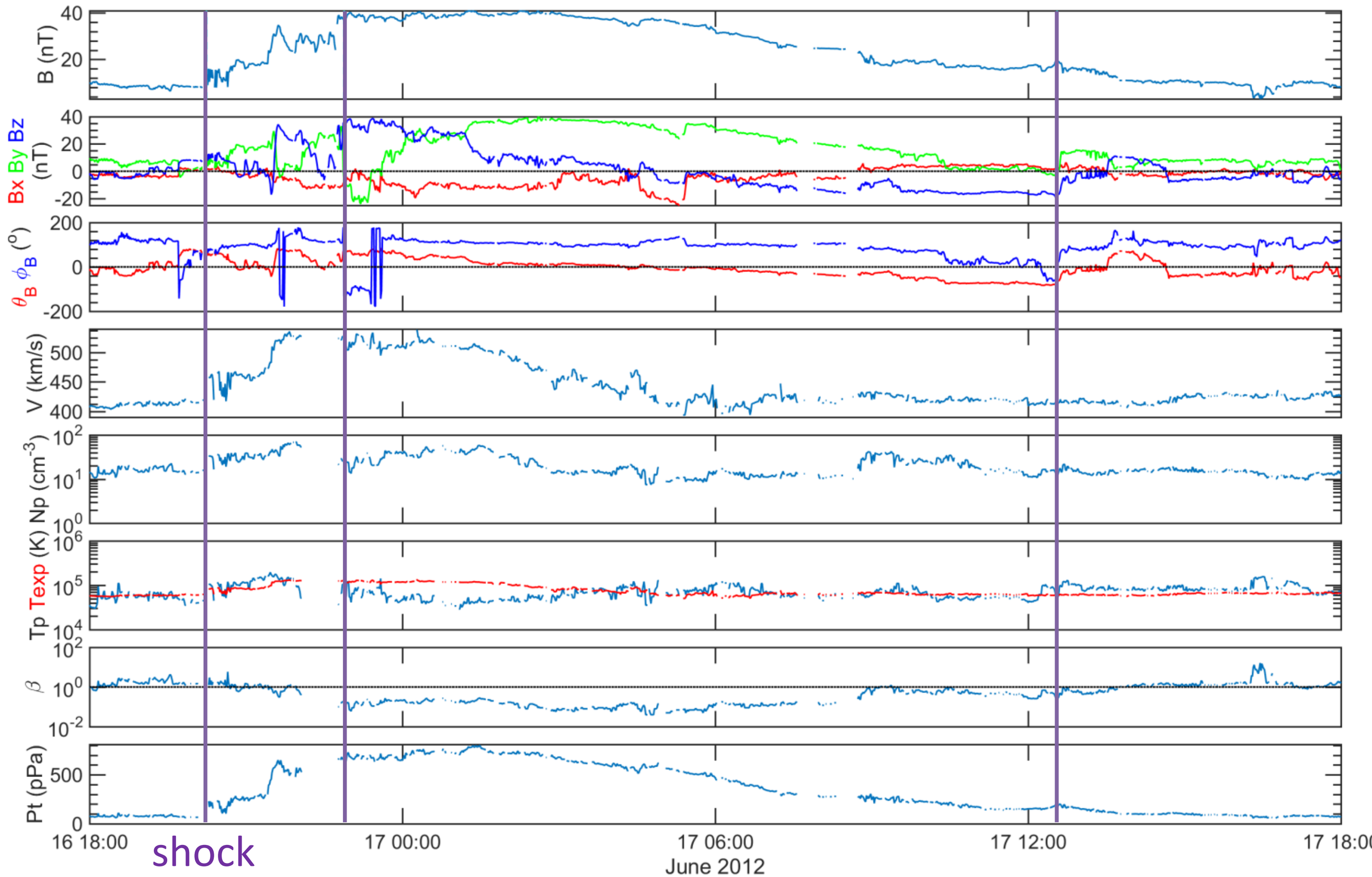


helioweather.net

- Main new features used in the present **v2.9** of ENLIL model
  - Evolving background solar wind
  - Using a sequence of the WSA maps computed from the closest GONG daily synoptic magnetogram
  - More reliable identification of disturbances by multi-grid computations
  - Revised the volumetric heating that is independent on the numerical time step variations
  - Updated model free parameters based on the calibration runs for 2007-2016 (so-called “a6b1” settings)

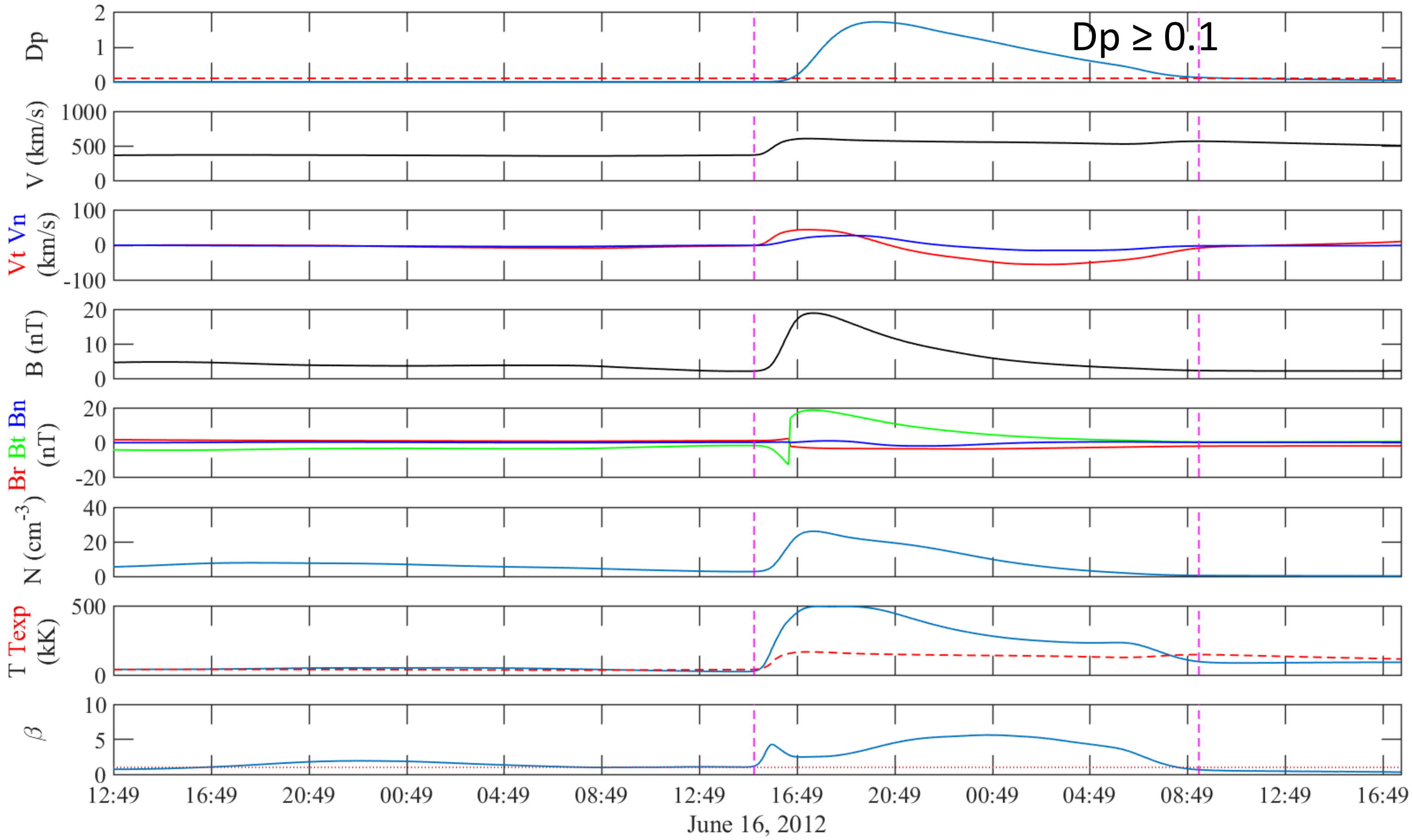
- The simulations use a spherical grid size of 256×30×90 (r, θ, ϕ) to cover 0.1-2.1 AU in radius, ±60° in latitude, and 360° in longitude. Output is of 4-min cadence at Earth

A Survey of Interplanetary CMEs (ICMEs)



- **ICMEs = Magnetic Clouds (MCs) + ICMEs without well-defined flux ropes**
- Multiple (not all) criteria are used: increased magnetic field, field rotations over a large scale, lower than expected proton temperature, low β, bidirectional suprathermal electron strahls, speed decrease, increase of total pressure (Pt), etc.
- ICMEs at L1 are surveyed using 1-min OMNI data for 2007-2016. The ICME/MC catalogs from Richardson and Cane, Nieves-Chinchil, Wu and Lepping are used as references

Identification of Simulated ICMEs



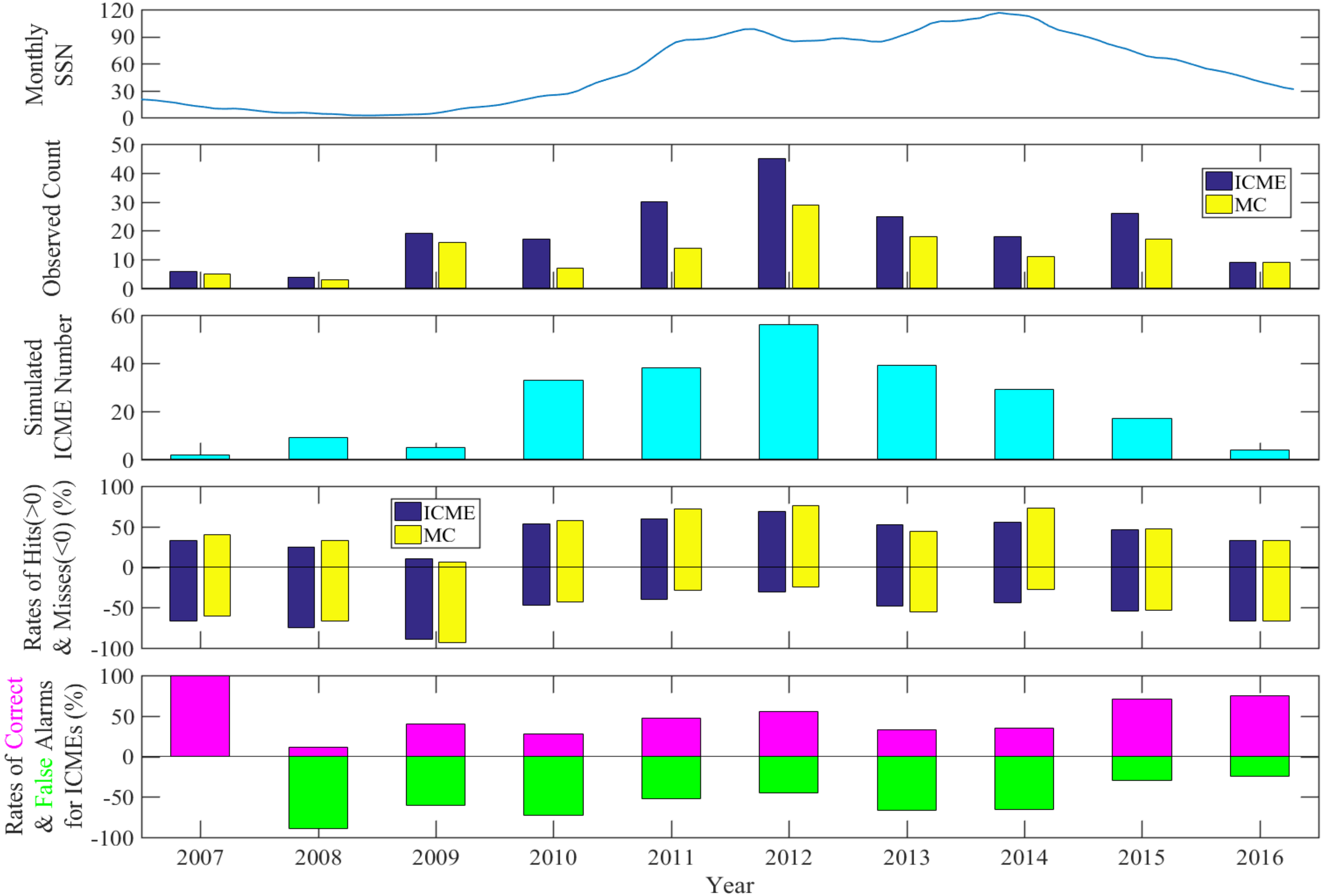
- ICMEs in simulations are identified by requiring Dp ≥ 0.1
- ICME start time
  - The closest time when V and/or B increases sharply, earlier than Dp ≥ 0.1
  - If there is no sharp increase of V or B, choose the time when V and/or B starts to increase
- ICME end time: at the end time of Dp ≥ 0.1 or when solar wind parameters return to ambient, whichever comes last

Statistics of ICME Prediction in 2007-2016

	Observed	Captured	Rate of Hits (%)	Rate of Misses (%)	Simulated	Rate of Correct Alarms (%)	Rate of False Alarms (%)	Absoulte Offset of Arrival Time (hr)
ICME	199	101	50.8	49.2	232	43.5	56.5	13.8±1.2
MC	129	67	51.9	48.1	N/A	N/A	N/A	13.3±1.4
ICME with shock	106	72	67.9	32.1	N/A	N/A	N/A	11.4±1.2

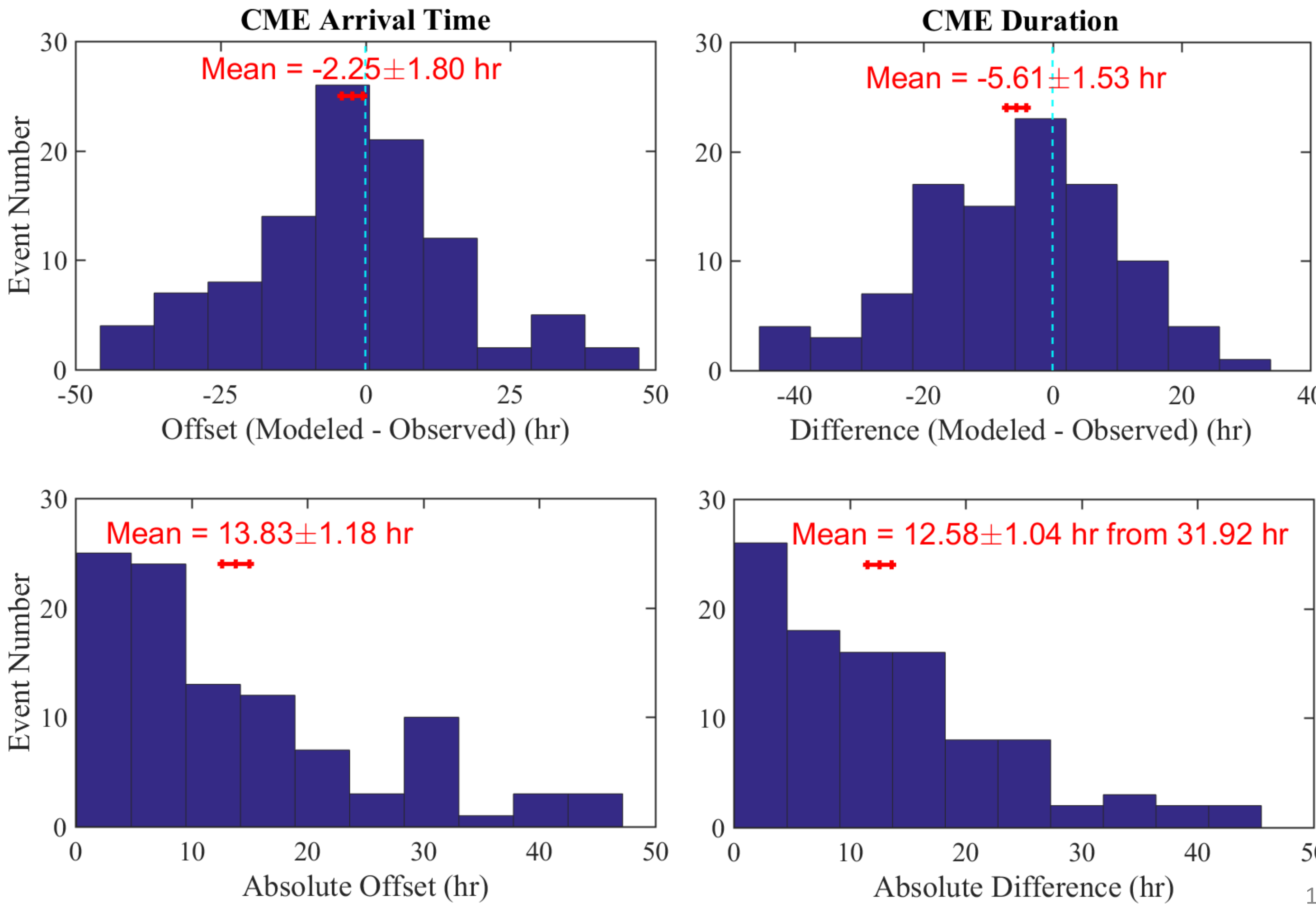
- During the 10 years, 2180 CMEs with an initial speed > 400 km/s are simulated, only a fraction of them propagating toward the Earth
- At Earth, 232 ICMEs are identified in the simulated data

Annual Variations of ICME Prediction

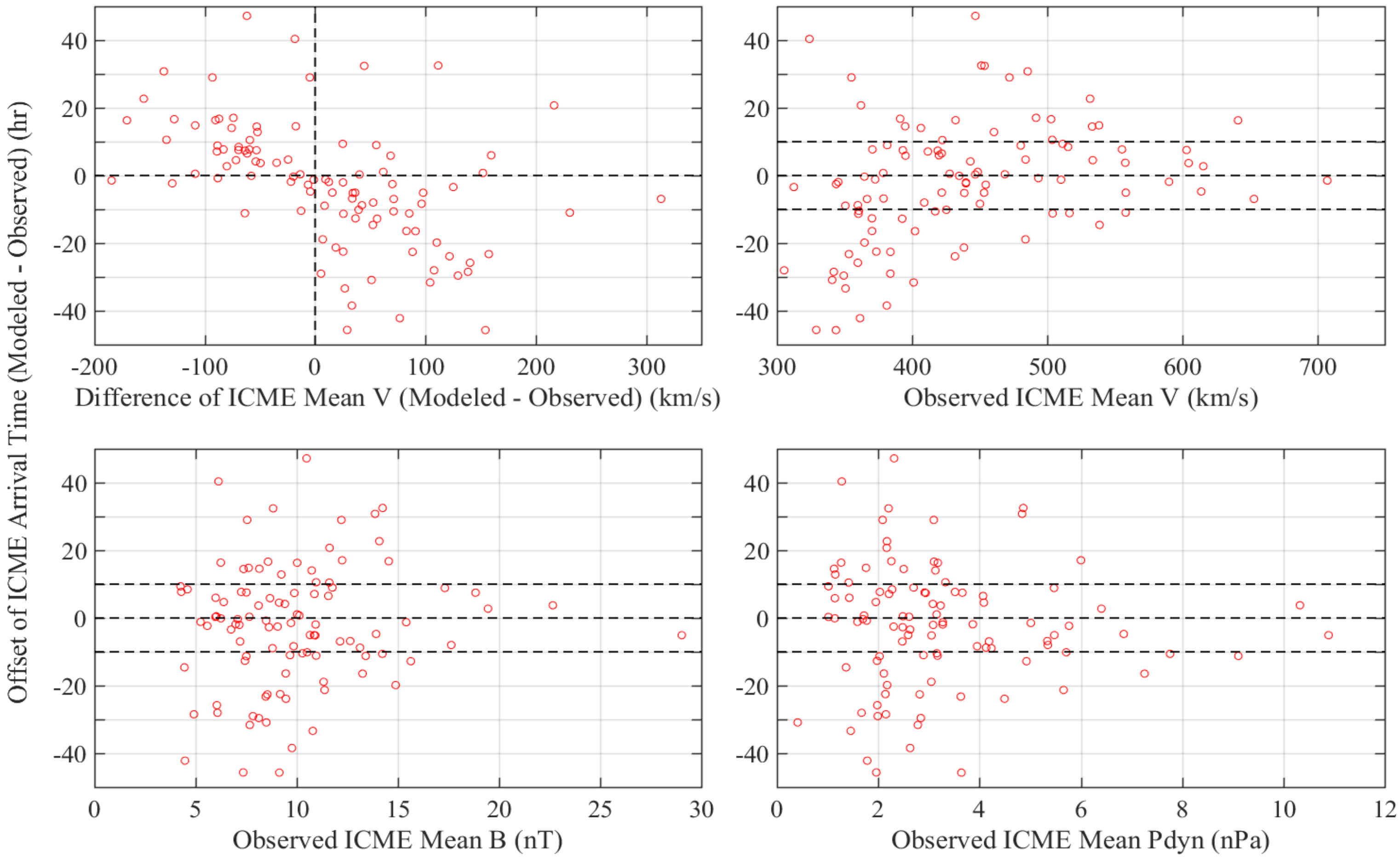


- The rates of hits are higher around solar maximum than at other time
- The rates of correct alarms are higher in the declining phase of solar cycle

Predicting ICME Arrival Time and Duration

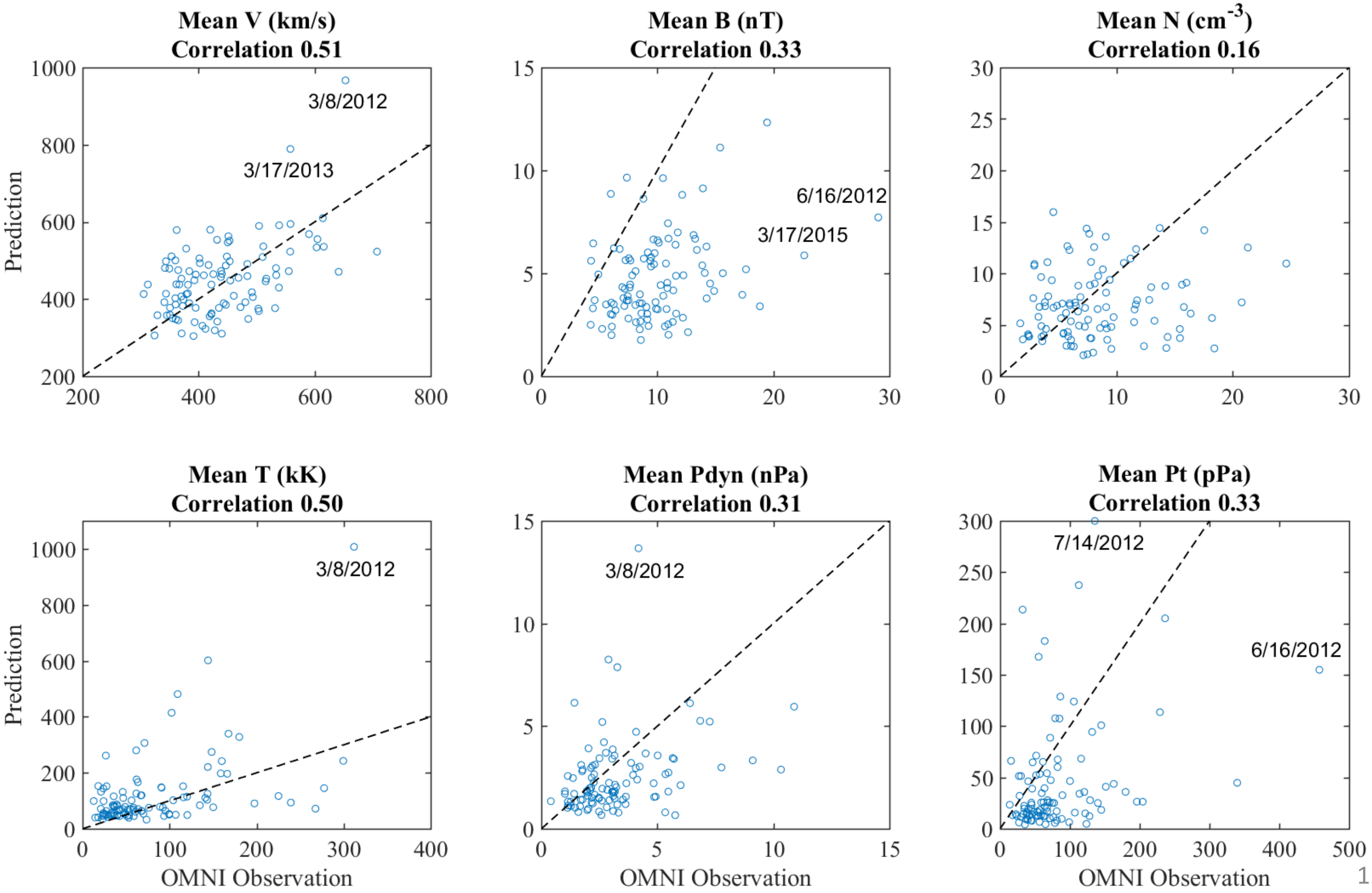


Factors Affecting the ICME Arrival Time

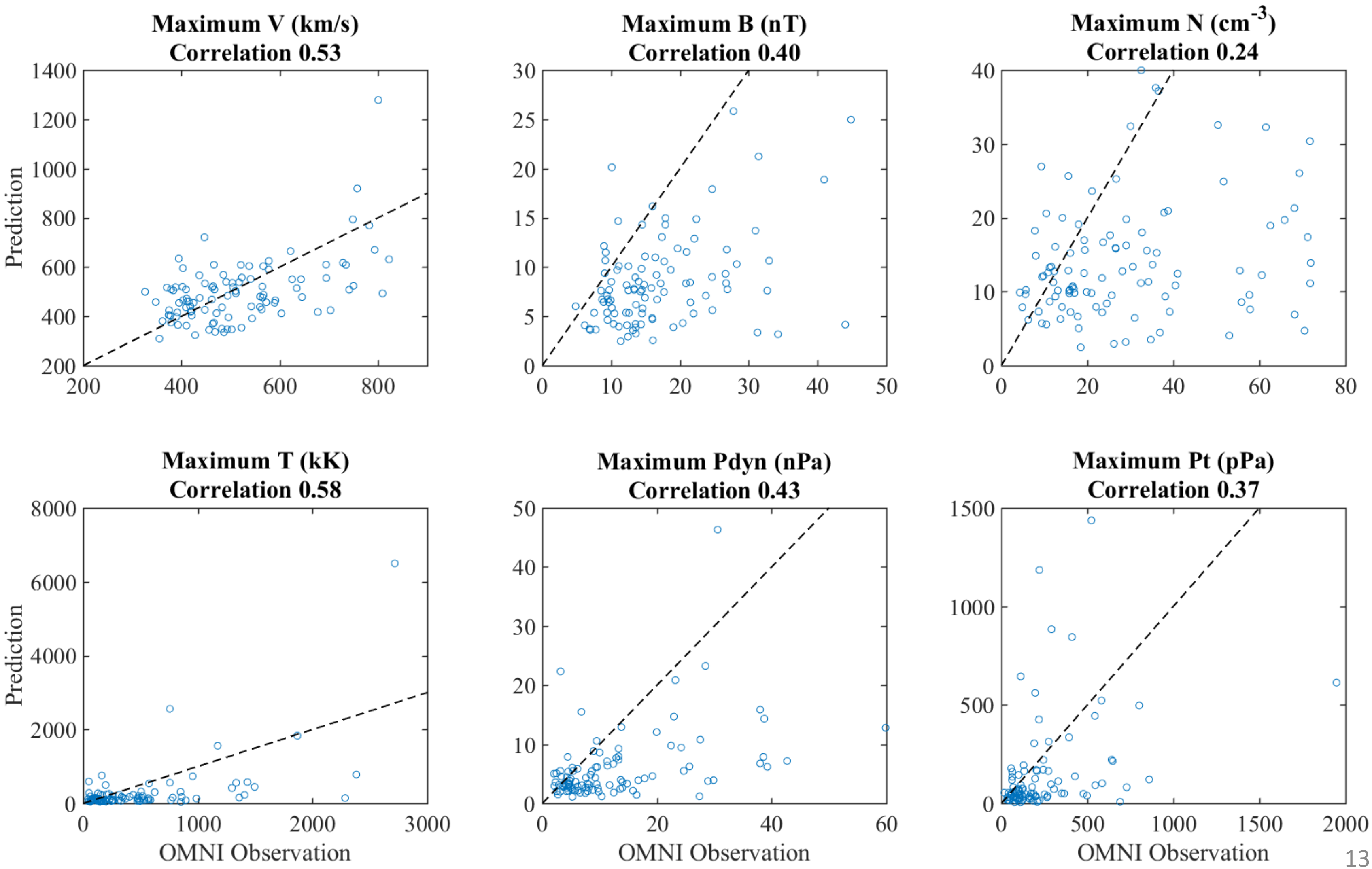


- ✓ As expected, the faster the predicted ICME speed than the observed speed, the earlier the ICME arrives at 1 AU than observed
- ✓ For fast and strong ICMEs, their arrival time is predicted within an error of ±10 hr
  - mean V > 550 km/s, B > 15 nT, Pdyn > 8 nPa

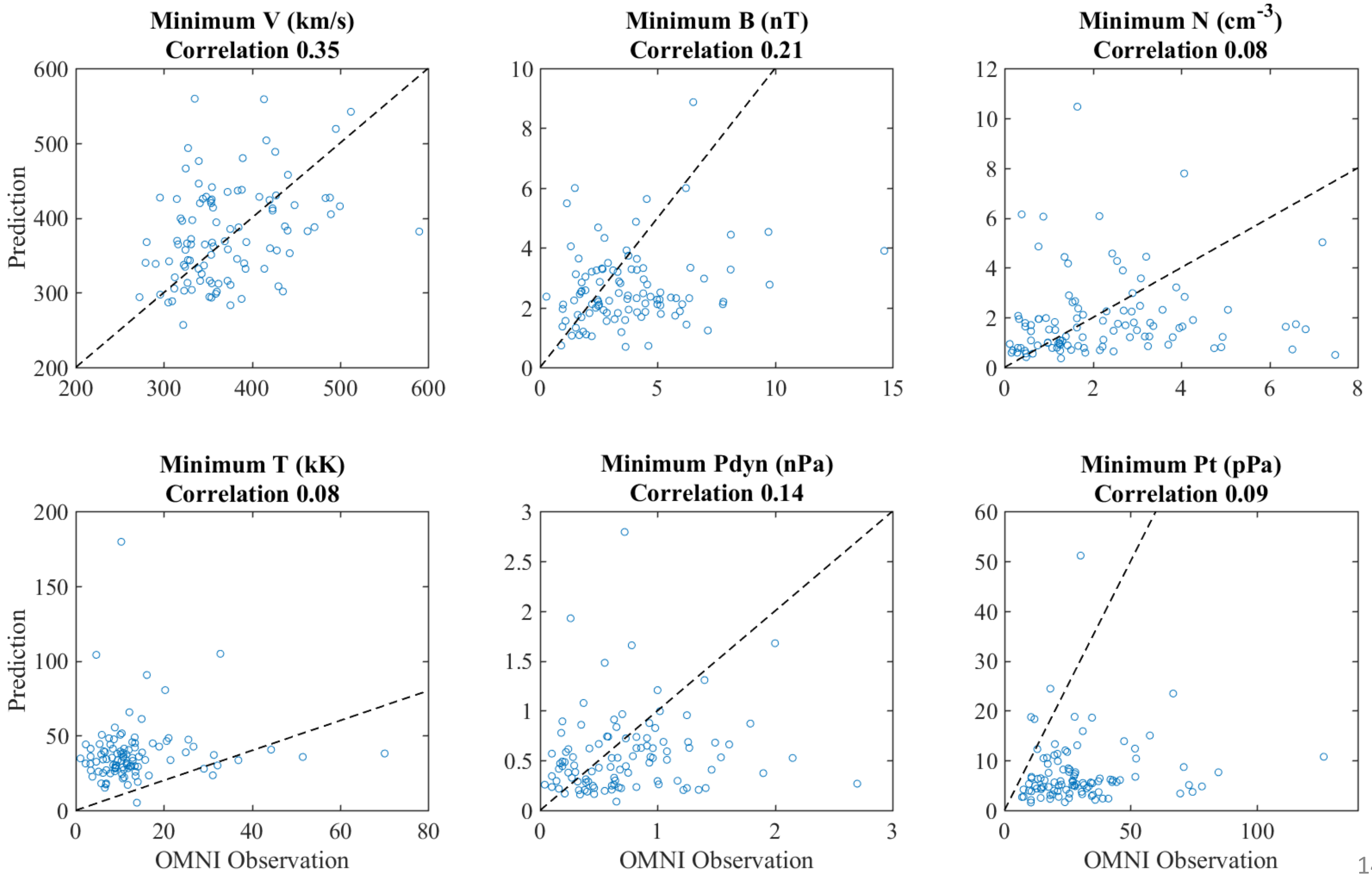
Simulated vs. Observed Mean Parameters of ICMEs



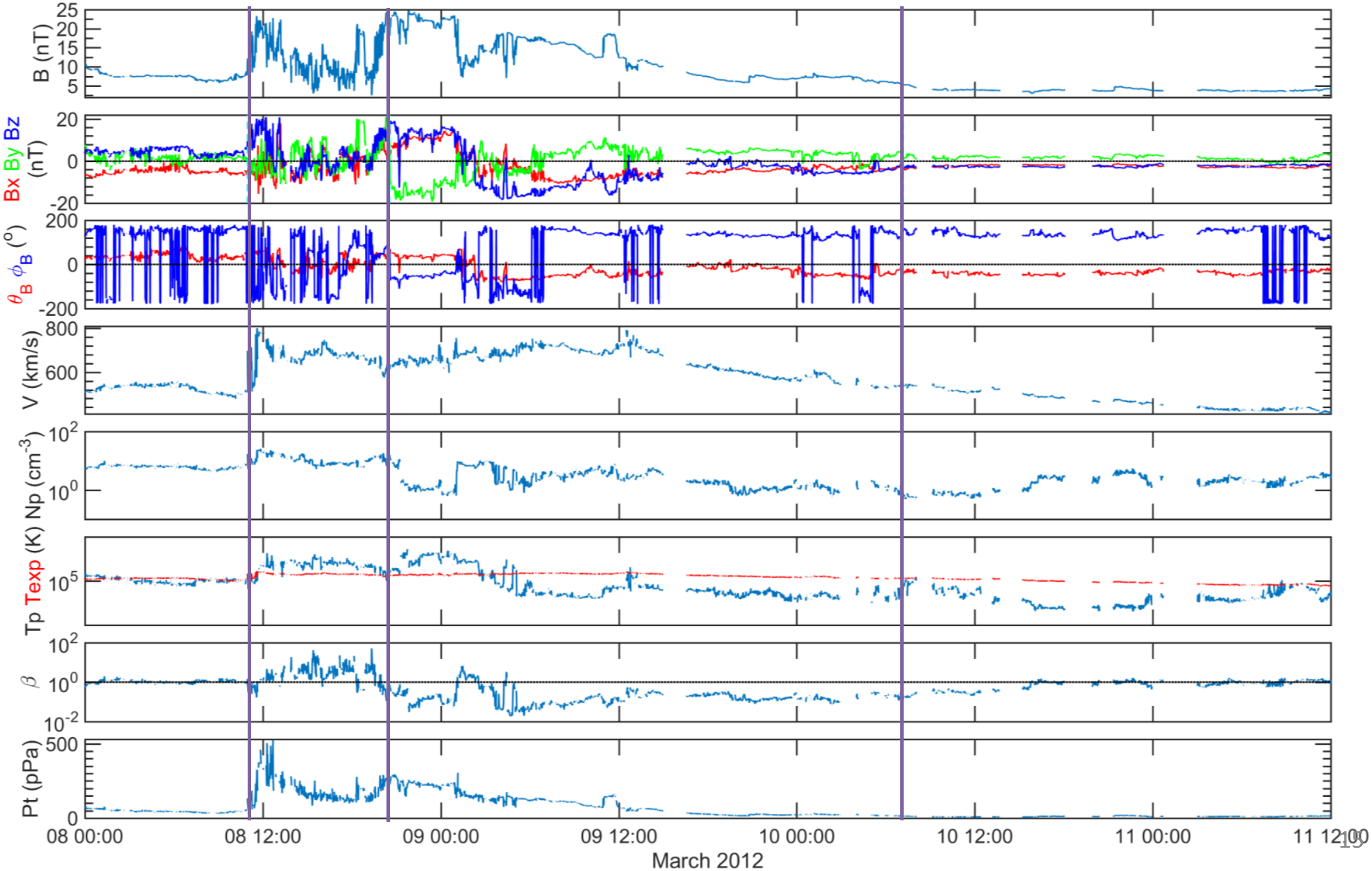
Simulated vs. Observed Maximum Parameters of ICMEs



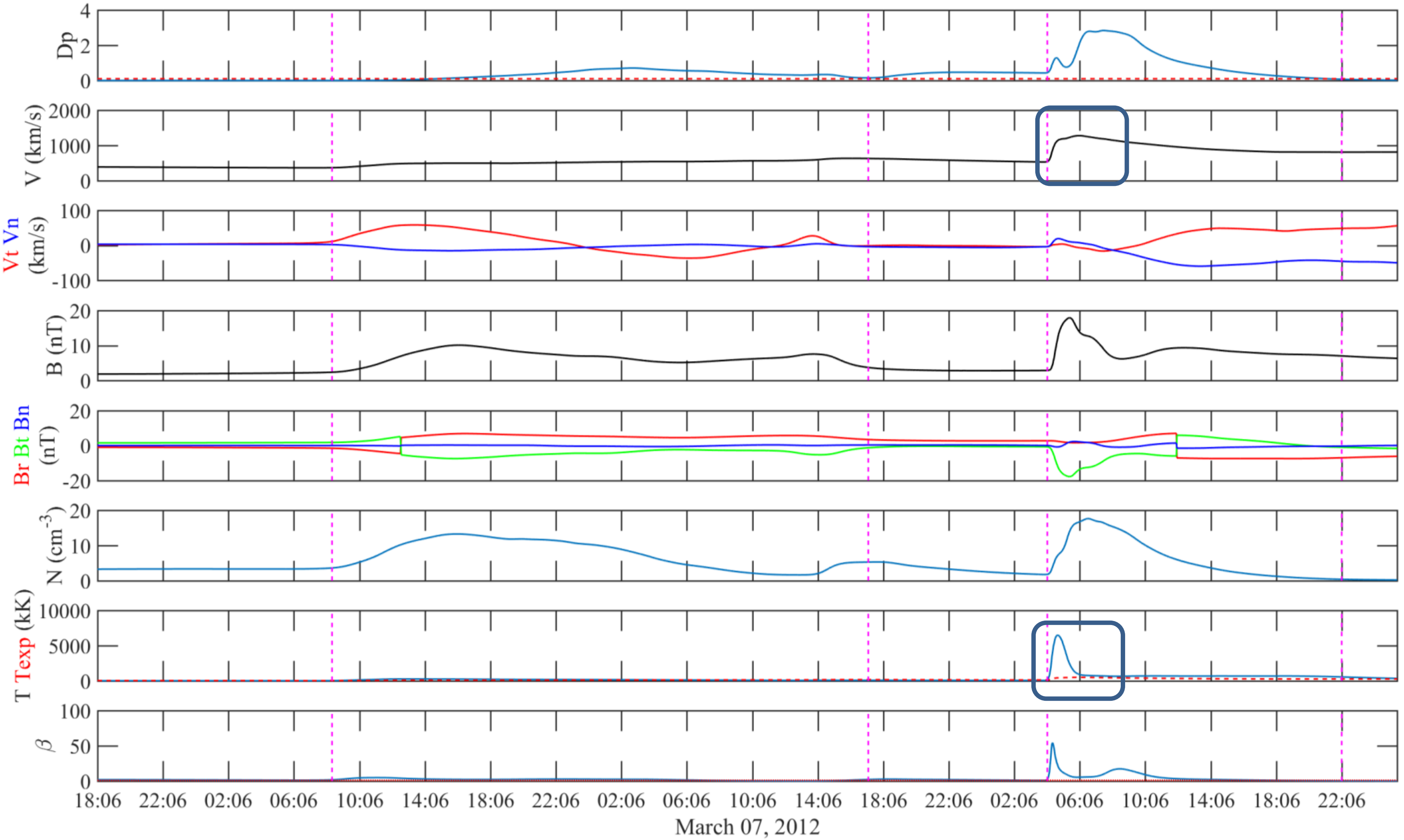
Simulated vs. Observed Minimum Parameters of ICMEs



An Example of the Large Discrepancy between Observation and Simulation



An Example of the Large Discrepancy between Observation and Simulation (cont.)

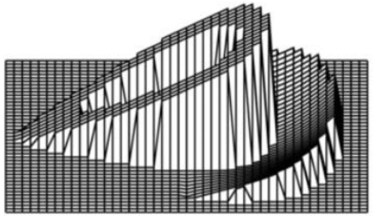


The simulated Tp and β are much higher than observed

Adding Additional Features

- Self-correcting model free parameters based on monthly-averaged in situ measurements at 1 AU
- Extended “cone” specification of CMEs by **enabling tail and surrounding shock/waves**, to investigate the effect of post-eruption flow and to compare with heliospheric imager observations, respectively
- Computations in sidereal (25.38-day) frame (present in synodic frame)
- Solving the “blended” thermal and total energy equations
- Enhanced post-processing
  - Extracting observer-connected IMF lines with shock parameters (if intersected) for SEP models (used by Janet’s SEPMOD)
  - Calculating synthetic white-light images (from the density) and making J-maps

Tail if ntail > 0	vtail dtail ttail ntail	Speed of the cone tail (km/s) Density at the cone tail as factor of mean stream value Temperature at the cone tail as factor of mean stream value =1,2 for trailing, complete interpolation from leading edge to tail
Shock if radsho > 1	radsho vsho dsho tsho	Radius of the shock as factor of radcld Speed of the shock (km/s) Density at the shock as factor of mean stream value Temperature at the shock as factor of mean stream value



Future Work

- Analyze the effect of CME input parameters on the model performance
  - Large statistics based on the current used parameters
  - Trying input parameters from different fitting methods
  - Focusing on the cases in which the simulated and observed parameters have large discrepancy
  - Focusing on the CMEs which are well observed remotely and in situ
- The simulated Tp and β are generally higher than observed. Is the expansion of ICMEs well simulated?
- The simulated B is generally weaker than observed. Adding the magnetic field structure in CMEs → long-term goal