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Tomographic Reconstructions of the Solar Wind from Heliospheric Remote Sensing Observations: Density and Velocity Predictions at Mars

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Abstract

Remote sensing observations of the solar wind over a large range of elongations provide a means for modeling the solar wind in the inner heliosphere, out to and beyond the orbit of Mars. We use interplanetary scintillation (IPS) data from meter-wavelength radio systems (from STELab, Univ. of Nagoya, Japan), and Thomson scattering brightness data (from the Solar Mass Ejection Imager, SMEI) in 3D reconstructions of the density and radial outflow velocity of the solar wind, both in corotating structures and in transient features such as coronal mass ejections (CMEs). The reconstruction technique relies on the changing perspective view of structures in the solar wind due to solar rotation and outward flow. We obtain estimates of solar wind density and velocity at specific heliospheric locations (*e.g.*, Earth, Mercury, Mars and deep space spacecraft such as Ulysses, and Stereo A and B) as a time series extracted from the 3D solutions. We discuss density and velocity obtained at Mars in comparison with the dynamic ("ram") pressure as modeled from magnetometer data from the *Mars Global Surveyor*[1] (MGS). We emphasize variations in ram pressure that are related to CMEs observed in the remote sensing data[2].

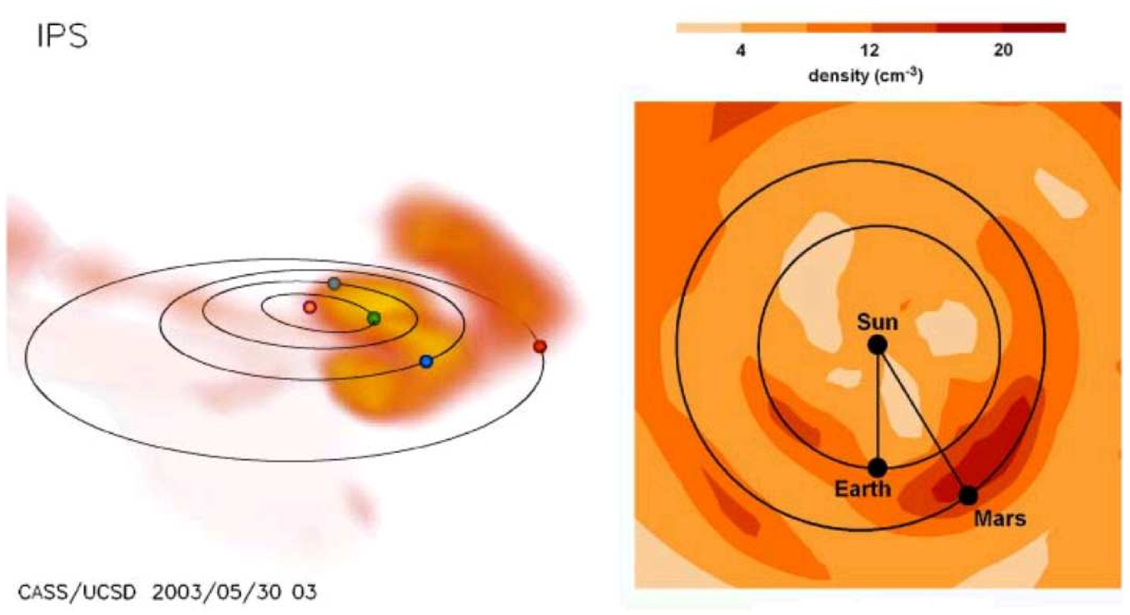

Figure 1: (Left) Density reconstruction of the halo CME of 27 May 2003, seen from 30° above the ecliptic and 30° east of the Sun. Shown are the four inner planets (Mercury, Venus, Earth and Mars). The density runs from 10 to 30 electrons cm^{-3} with an r^{-2} radial falloff removed. (Right) Earth and Mars locations superposed on the density in the ecliptic plane.

3D Reconstruction

The tomography reconstructs 3D solar-wind velocity and density by applying an inversion technique to the IPS data. When structures do not evolve significantly on a time scale of one solar rotation, rotation alone yields sufficient information for a reconstruction. The corotational model can be applied in this situation. For transient structure such as CMEs it is essential that they are observed moving across a large range of elongations, and are thus viewed from widely different directions. This changing perspective is exploited in the time-dependent tomography model.

Typically only a few thousand IPS observations are available for each solar rotation. This limits the resolution of the reconstruction to $10^\circ \times 10^\circ$ in latitude and longitude, and 0.1 AU in heliocentric distance for the corotating model, and $20^\circ \times 20^\circ$, 0.2 AU with a 1-day temporal cadence for the time-dependent model. Even though these reconstructions only allow modeling of the largest solar wind features (both corotating and transient), they do adquately provide gross spatial extent and temporal evolution of structures in the heliosphere. This provides, for instance, quantitative estimates for speed, mass content and total kinetic energy.

Ram Pressure

Once the 3D solar wind density and velocity are available, time series at Mars are extracted. Then the ram pressure is $P = m\,n\,V^2 = 2\times10^{-6}\,n\,V^2$. The effective mass per electron, m, is taken to be $2\times10^{-24}\,g$; P is in nPa, n is in $electrons\,cm^{-3}$, and V is in $km\,s^{-1}$. Several assumptions determine the accuracy of this conversion. The IPS-derived density depends on an set of emperical power laws relating small-scale electron-density fluctuations and bulk density, calibrated against the *in situ* proton density from the ACE spacecraft. In addition, the effective mass per electron assumes a 10% He abundance.

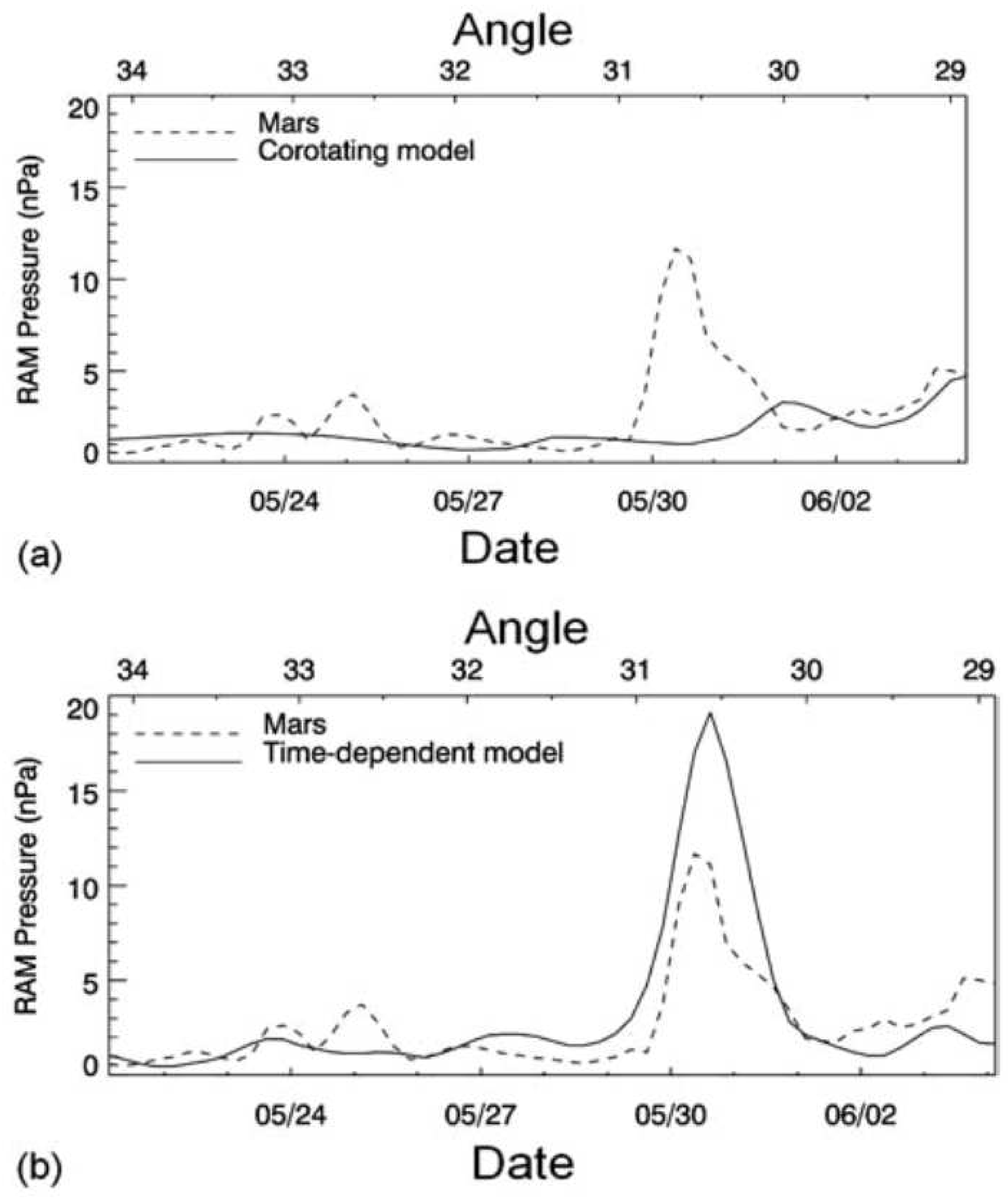

Figure 2: IPS-derived and in situ MGS-derived ram pressure at Mars for the time period from 21 May 2003 to 4 June 2003 covering the 27 May 2003 CME event. The MGS response to the event begins on 30 May 2003. The ecliptic longitude of Mars relative to Earth is given at the top. (a) Corotating. (b) Time-dependent.

We compare the IPS-derived data with ram pressures derived from magnetic field observations obtained by the magnetometer on MGS using a pressure balance model[1].

IPS-MGS comparison

This study focuses on the time period between 26 April 1999 and 7 December 2004, when both STELab IPS and MGS magnetometer are available. The MGS ram pressure data were smoothed with a one-day running mean, approximately matching the smoothing inherent in the low-resolution IPS reconstructions. Each peak above a threshold of 3.5 nPa in the smoothed MGS time series is identified as a "ram pressure event". These events were than compared with nearby peaks (within a 3-day window) in the IPS ram pressure time series.

47 events above 3.5 nPa are present in the MGS data at times where IPS data are also available; 20 events were above 5 nPa and 5 were above 10 nPa. 42 events could be associated with peaks in the corotating IPS model and 37 with peaks in the time-dependent model. To determine whether a match of an MGS and IPS event is valid, several additional factors were considered, including the event's proximity to other nearby events, the shape and relative levels of the nearby IPS peak values.

The very largest events observed in the MGS data have obvious solar manifestations associated with CMEs. Two of these are shown in Figs 1 and 3. Fig 1 shows a "frontside" halo CME observed at the Sun on 27 May 2003, when Mars was near opposition. Fig 3 shows a series of mostly West-limb CMEs observed in September 2002 when Mars was approaching conjunction. Fig 2 shows the MGS and IPS ram pressure time series for the 27 May event. This halo CME shows a clear response at Mars in both the MGS and time-dependent IPS ram pressure starting on 30 May, and (not surprisingly) is not evident in the corotating IPS model.

Results

The IPS modeling shows significant correlation in time with approximately the same amplitude when compared with the ram pressure events observed by MGS. This correlation persists even when Mars is in the hemisphere on the opposite side of the Sun from Earth.

The statistical comparisons of IPS and MGS events shows some interesting features. Most events are only just above the 3.5 nPa threshold. The few events with significantly higher peaks are associated with obvious CME-related peaks in the IPS data (such as the 27-May halo).

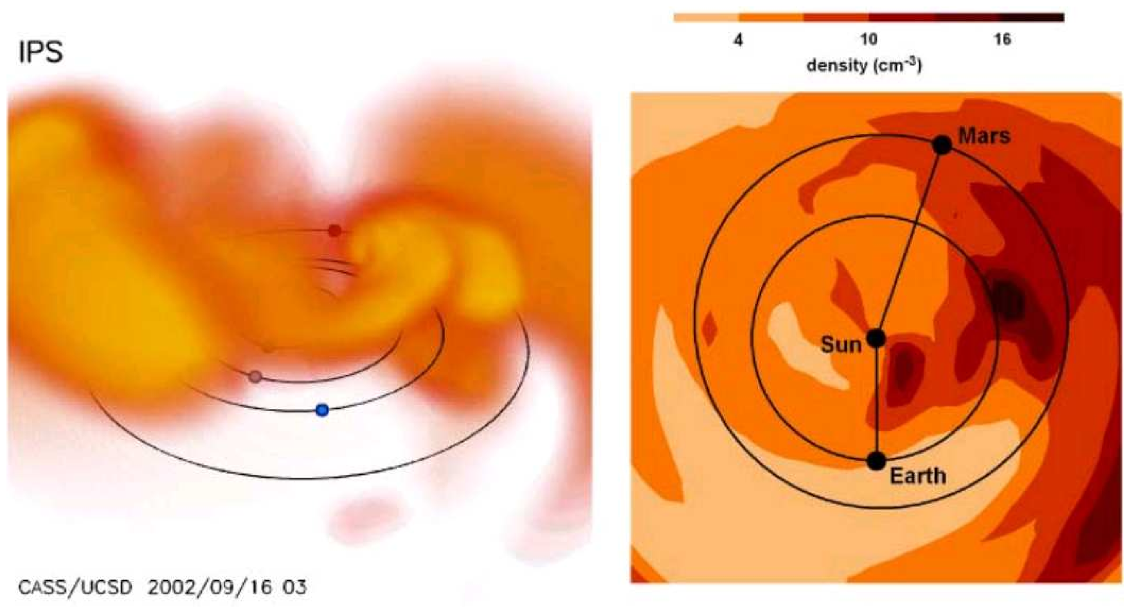

Figure 3: (Left) Density reconstruction for West-limb CMEs observed on 16 September 2002, as seen from 30° above the ecliptic and 5° east of the Sun. Earlier CMEs are seen to the solar northeast. Earth is in the front, Mars at the back of the view. The density scales from 5 to 15 electrons cm^{-3} with a r^{-2} falloff removed. The largest CME moves to the West as observed from Earth with material distributed over more than 180° in longitude. (Right) Earth and Mars locations superposed on the density in the ecliptic plane.

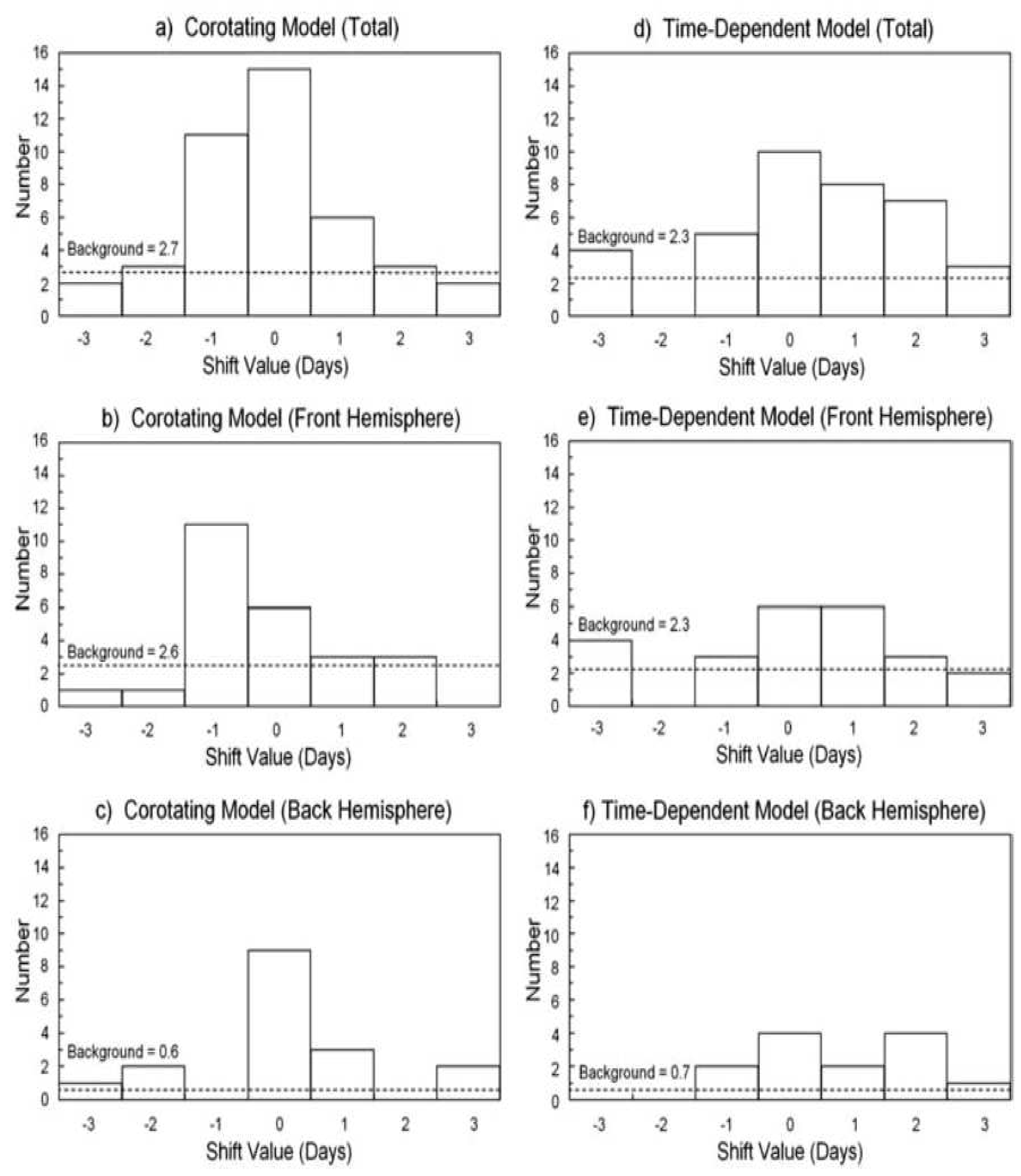

Figure 4: Histograms of time lags between ram pressure peaks observed at Mars by MGS and peaks observed in the tomographic IPS models. Positive/ negative shifts mean that the IPS peaks is later/earlier than the MGS peak. (a)-(c) are for the corotating model: (a) all events, (b) frontside events (toward Earth), (c) backside events (behind the Sun); (d)-(f) the same for the time-dependent model.

However, the peak amplitudes in general show only a weak correlation between MGS and IPS. IPS peaks tend to be lower (about 85%). Most of the MGS events have a matching IPS event within one day (Fig 4), especially for the time-dependent model (which is sensitive to transient events). This we consider acceptable given the approximations inherent in the tomographic technique. A significant number of events show time lags of 2 or 3 days, which in general cannot be explained by deficiencies in the tomography (such as the kinematic solar wind model that does not handle shock physics accurately). We currently do not have a convincing explantion for this (some may simply be mismatches between MGS and IPS events).

References

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