First determination of 2D speed distribution within the bodies of Coronal Mass Ejections

Beili Ying [1], Alessandro Bemporad [2], Silvio Giordano [2], Paolo Pagano [3], Li Feng [1] yingbl@pmo.ac.cn

[1]Purple Mountain Observatory, CAS, China; [2]INAF-Turin Astrophysical Observatory, Italy; [3]School of Mathematics and Statistics, University of St. Andrews, UK

The determination of the speed of Coronal Mass Ejections (CMEs) is usually done by tracking brighter features (such as the CME front and core) in visible light (VL) coronagraphic images and by deriving unidimensional profiles of the CME speed as a function of altitude or time. Nevertheless, CMEs are usually characterized by the presence of significant density inhomogeneities propagating outward with different radial and tangential speeds, resulting in a complex evolution eventually resulting in the Interplanetary CME. In this work, we demonstrate for the first time how coronagraphic images can be analysed to derive 2D maps of the almost instantaneous plasma speed distribution within the body of CMEs. This is done both with the analysis of synthetic data, and real observations. Results from this work will allow to characterize the distribution of kinetic energy inside CMEs and the distribution of the Doppler dimming factor. In the future, CMEs can be observed by two channels (VL and UV Ly-alpha) coronagraphs, such as Metis on-board ESA Solar Orbiter mission (launch in 2020) and Lyman-alpha Solar Telescope (LST) on-board Chinese Advanced Space-based Solar Observatory (ASO-S) mission (launch in 2022). These future observations and our results could help to estimate the CME plasma temperature, while taking into account Doppler dimming effect.

1. Simulation

Method:
We use three VL images (at T_{n-1}, T_n, T_{n+1} moments) of CME to measure the radial velocity of the CME at the T_n moment.

- Converting VL images from Cartesian to polar coordinates.
- For each fixed latitude, extracting the radial VL intensity distribution of the three moments.
- Forward step (FS): We determined pixel by pixel the radial shift maximizing the cross-correlation between the signal in the actual frame (at T_n moment) extracted in a symmetric radial window and the signal in a shifted radial window extracted in the next frame (at T_{n+1} moment).
- Backward step (BS): the same procedure as the FS, but just determined the maximal cross-correlation between the frame at the T_n moment and the frame at the T_{n-1} frame.
- Average step (AS): The average of the results from forward and backward steps.

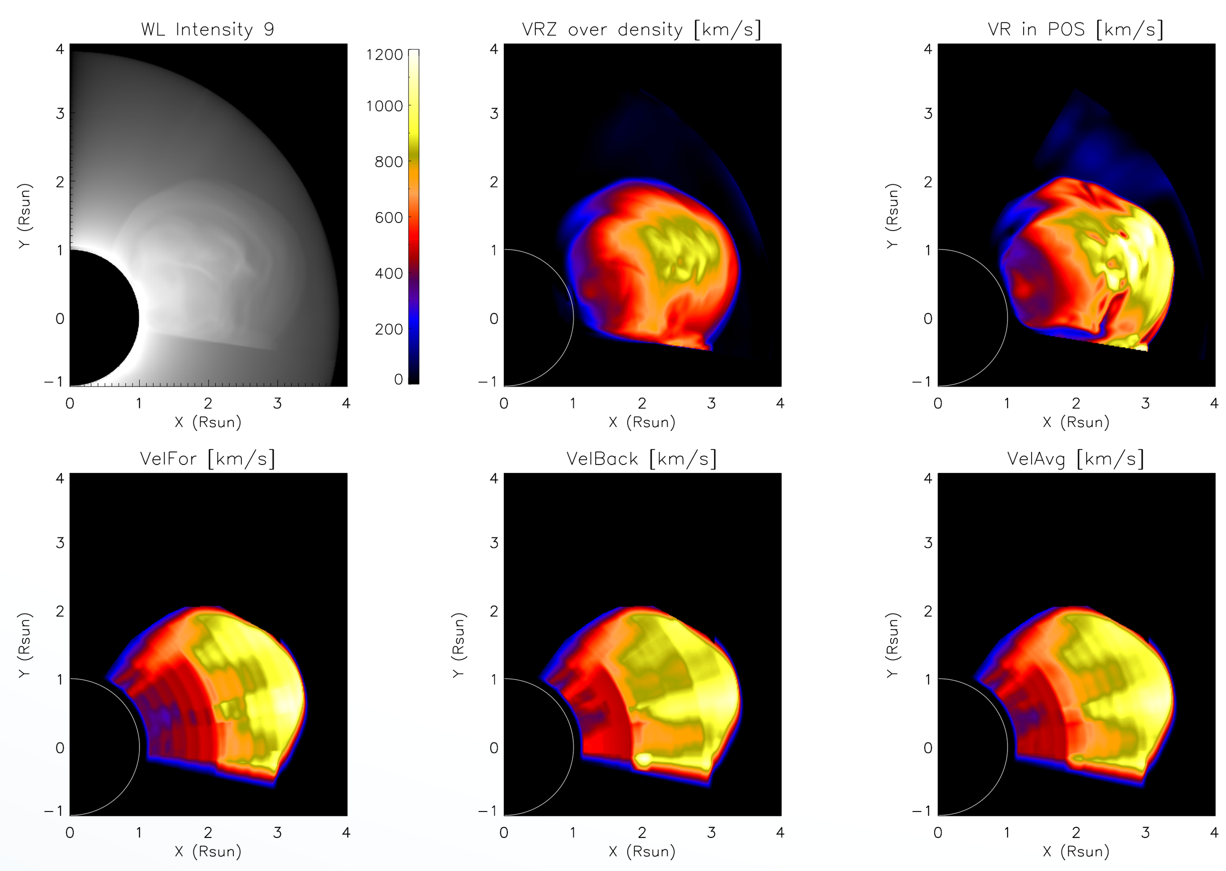

Fig 1. Top: left: resulting simulated intensities of a CME in coronagraphic image acquired in the VL channel. Middle: 2D image of the simulated radial velocity averaged with density (obtained by integrating along the line of sight). Right: the cut of radial velocity in the plane of the sky (POS). **Bottom**: 2D images of the measured radial velocities of the CME from the VL images by FS, BS and AS.

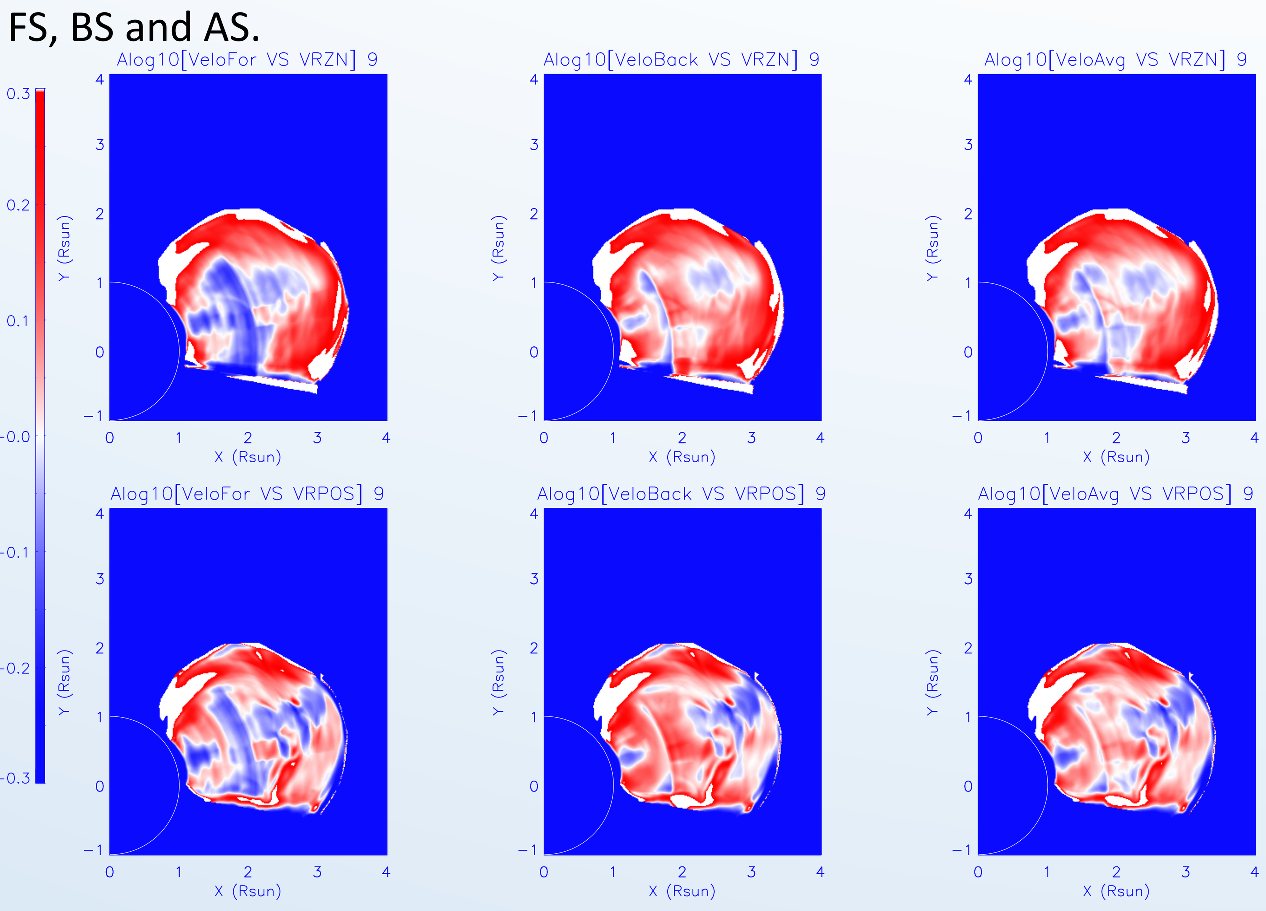

Fig 2. Top: comparison (in logarithmic scale) between the measured radial velocities from the VL images and the simulated radial velocities averaged with density (FS,BS and AS, respectively). **Bottom**: comparison (in logarithmic scale) between the measured radial velocities and the simulated radial velocities in the POS (FS,BS and AS, respectively).

2. Real event

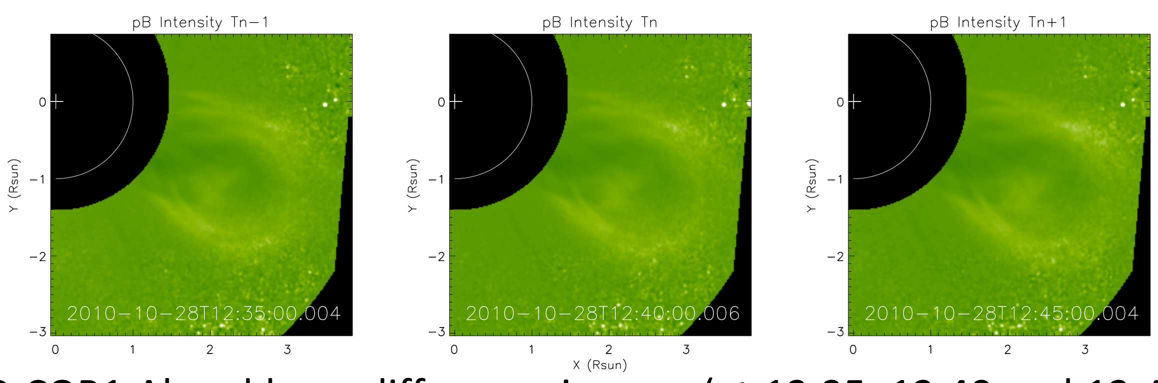

Fig 3. STEREO COR1 Ahead base-difference images (at 12:35, 12:40 and 12:45 UT), obtained from subtracting a previous image at 10:30 UT.

2.1 The measured radial velocities

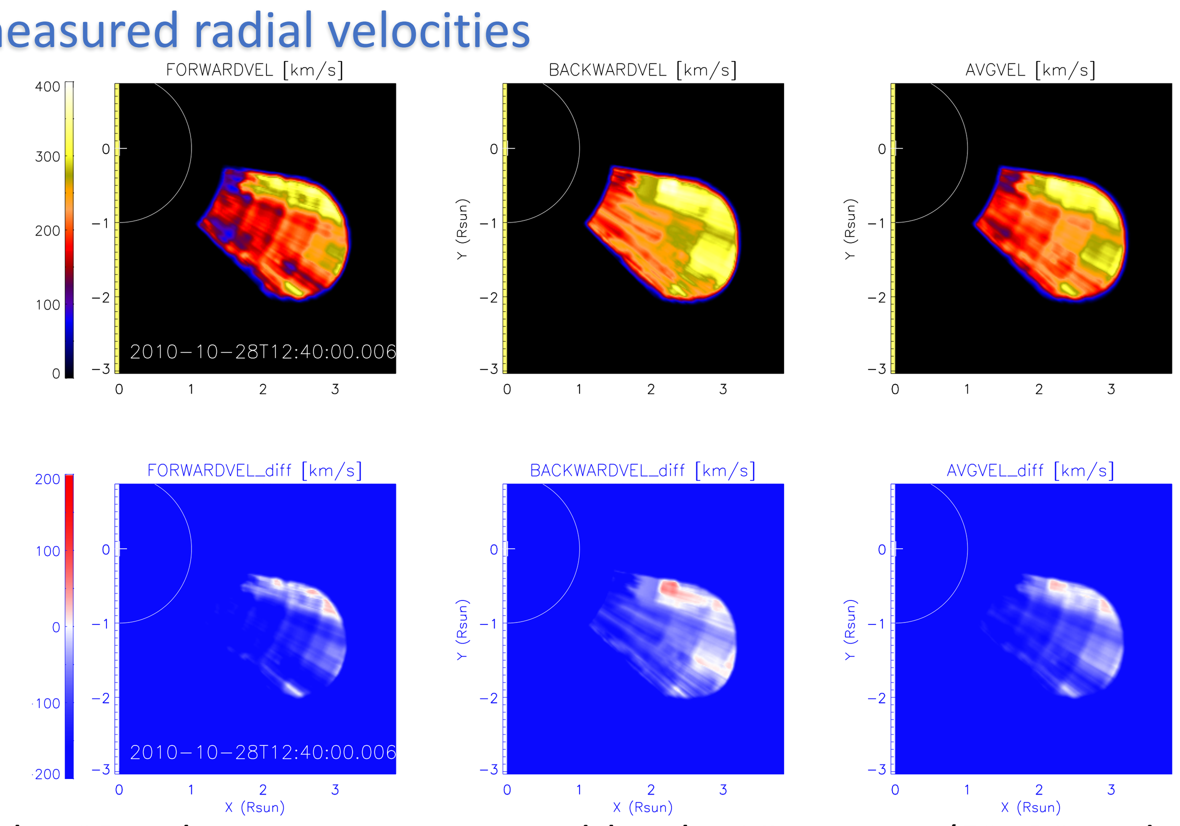

Fig 4. Top: the 2D velocity maps measured by the VL images (FS, BS and AS). Bottom: 2D maps showing the differences between the 2D radial speed map measured from the analysis of VL images in the CME body and the speed value measured at the CME nose.

2.2 The Doppler dimming factor

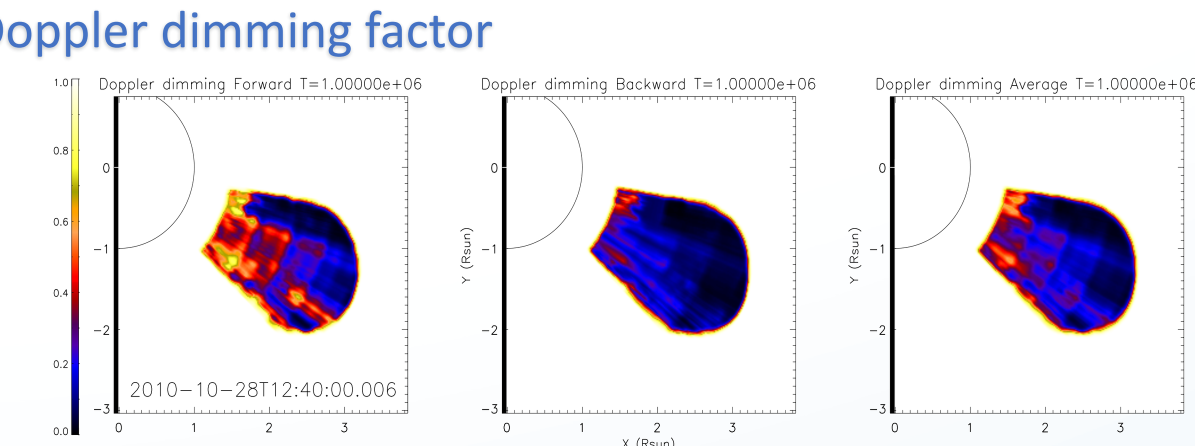

Fig 5. The distribution maps of the Doppler dimming factors (FS, BS and AS).

2.3 The energy distributions

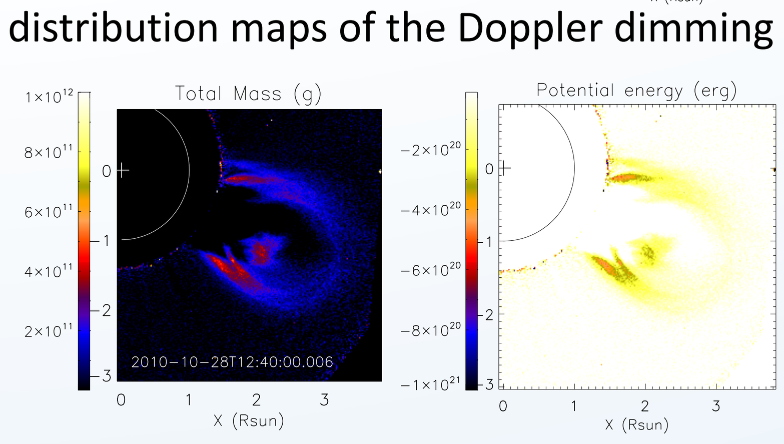

Fig 6. 2D images of the total mass and the potential energy of the CME at 12:40 UT.

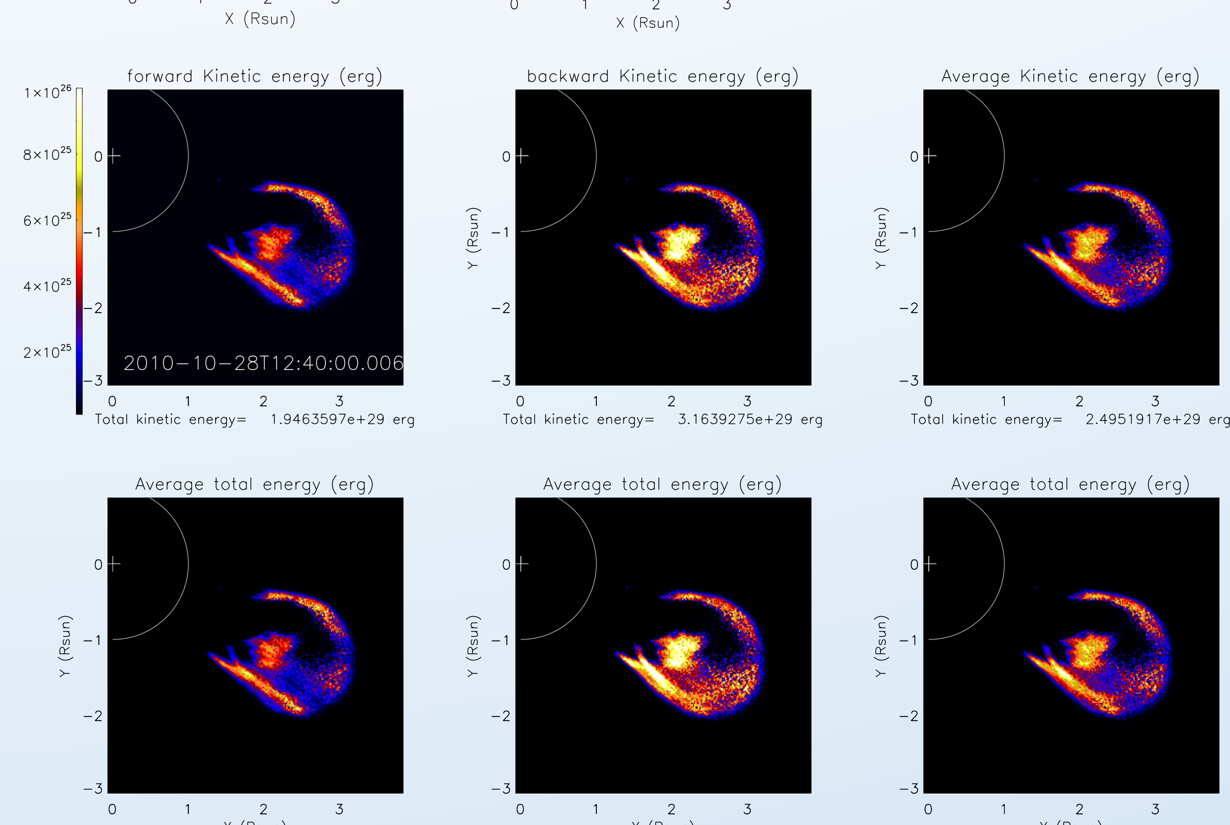

Fig 7. Top: 2D images of the kinetic energy of the CME (FS, BS and AS) at 12:40 UT. Bottom: 2D images the total mechanical (kinetic plus potential) energy of the CME (FS, BS and AS) at 12:40 UT.

3.Conclusions

Part 1

- The analysis of VL synthetic coronagraphic images allowed to us to successfully test the diagnostic method. Results show that the average between the forward and the backward radial speed maps provide a good estimate (within 30% of uncertainty on average) of the plasma speed distribution on the plane of the sky all over the CME body, with larger errors (up to about 100%) near the flanks of the simulated CME.

Part 2

- The application of the same diagnostic technique for the analysis of a real event observed by STEREO/COR1 allowed us to derive the first ever 2D map of kinetic energy distribution in the CME body. Results show that the CME front contains approximately 60% of the total CME kinetic energy, while the CME core contains 40% of the same energy. Hence, the larger fraction of CME kinetic energy is dragged by the front.
- The derived 2D speed maps have been employed also to derive the expected 2D distribution of Doppler dimming coefficients for UV Lyman-alpha intensity due to radiative excitation, confirming that (as recently shown by Bemporad et al. 2018) the UV intensity in the CME front will be severely attenuated due to the larger plasma radial speed.