The Evolution of Interplanetary Coronal Mass Ejections in the Heliosphere

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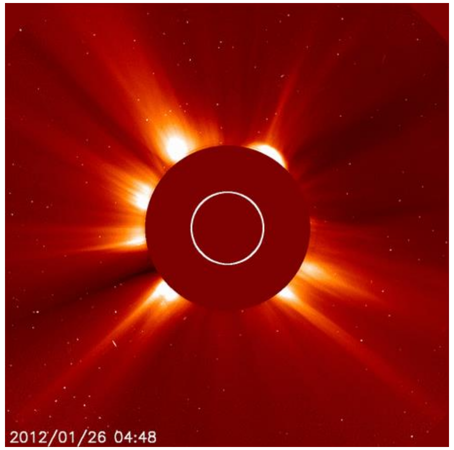
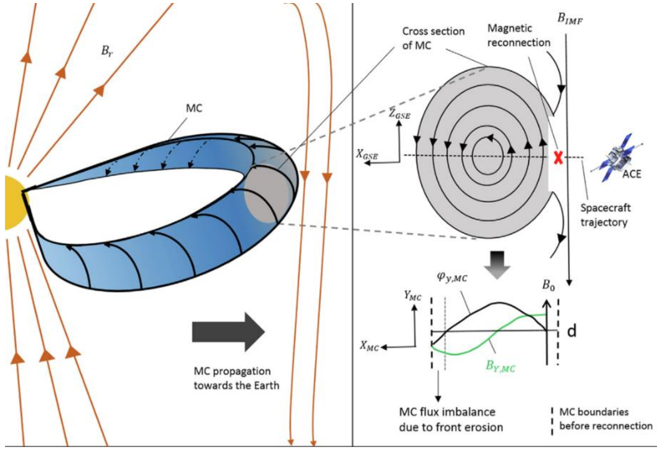
Background

Coronal Mass Ejections（CMEs/ICMEs） are huge eruptions of plasma, magnetic field, and energy that are expelled from the lower solar corona into interplanetary space.

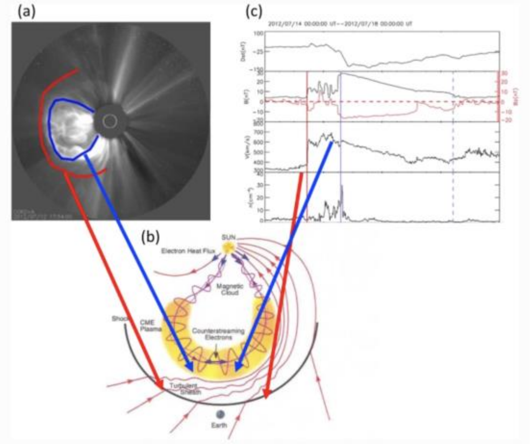
Earth: ICMEs have been recognized as major drivers of severe space weather (e.g. Gosling et al. 1991; Zhang et al. 2007; Shen et al. 2017), which can cause geomagnetic storms and trigger a wide array of undesirable consequences, including anomalies in satellite systems, damage to the ground-based electric power grids, and interference with radio communications and satellite navigation systems (e.g. Cannon et al. 2013).

Mars or Venus: ICMEs can also change the plasma environments of Venus and Mars and increased ion escape rates on those planets (Curry et al. 2015;Dimmock et al.2018; Zhang et al. 2021)。

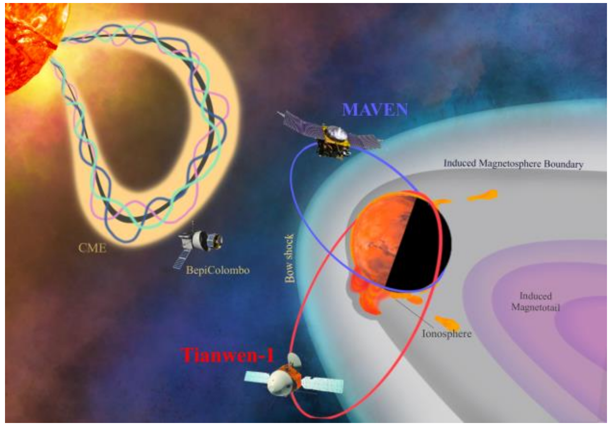




Pal et al. (2022)



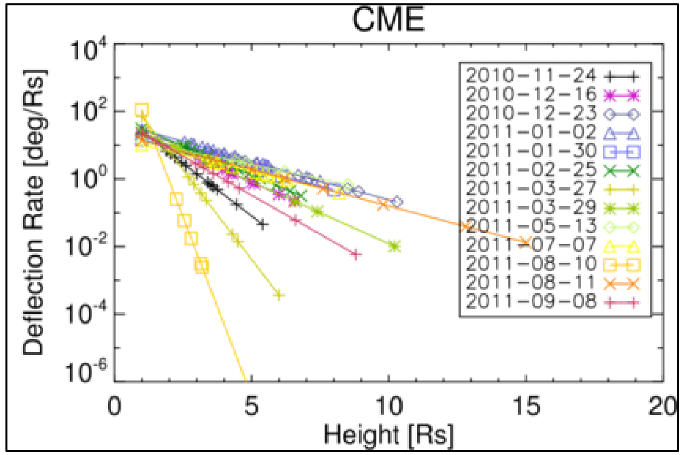
Zhang et al. 2021



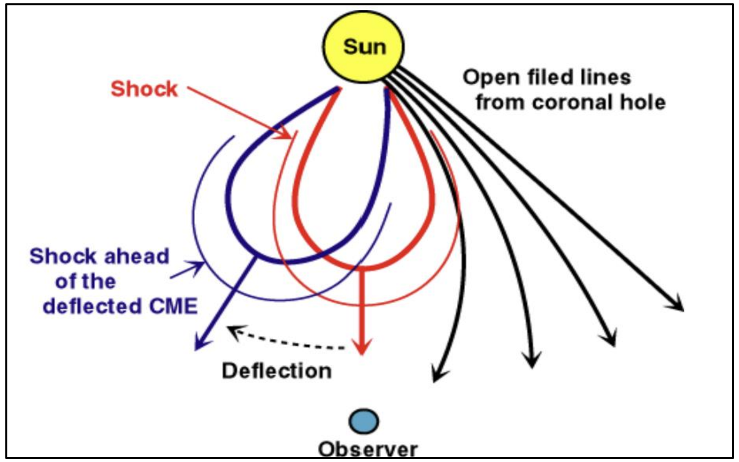
Yu et al. 2023

Background Deflection of CMEs

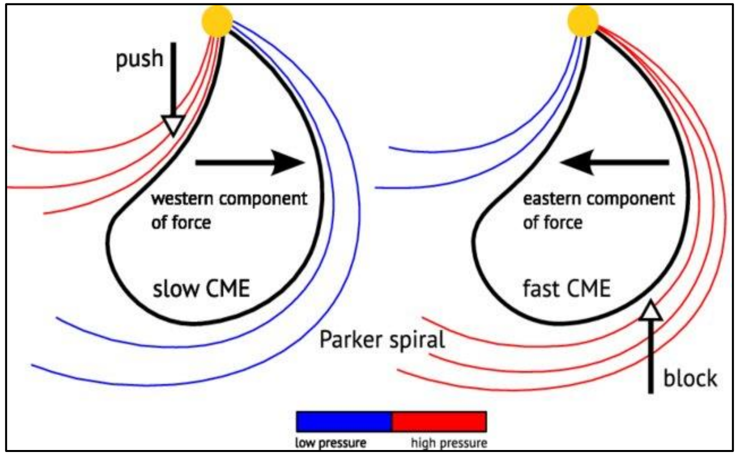
➢ **Predict the arrival time and the magnetic field configuration** of CMEs is difficult, as they **are rotated, deformed, deflected, and disguised** during their propagation in the heliosphere by interacting with ICMEs or solar wind.



Deflection rate vs. height for CMEs (Sieyra et al. 2020)



CME deflection caused by nearby coronal hole (Gopalswamy et al. 2010)



Deflection of CMEs in the heliosphere(Wang et al. 2003)

The deflections of CMEs can be attributed to three primary causes:

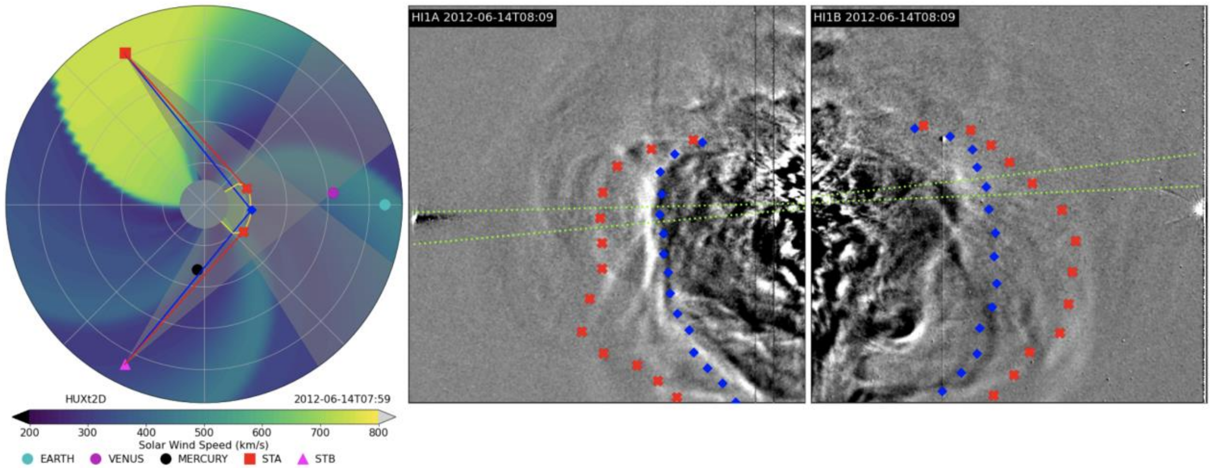
- **magnetic forces produced by the background corona (e.g., MacQueen et al. 1986; Kilpua et al. 2009; Shen et al. 2011)**
- **The coronal holes near the CME (e.g., Gopalswamy et al., 2010)**
- **the background solar wind flow pattern (e.g., Wang et al. 2004;Manchester et al. 2017).**

Background Distortion of CMEs

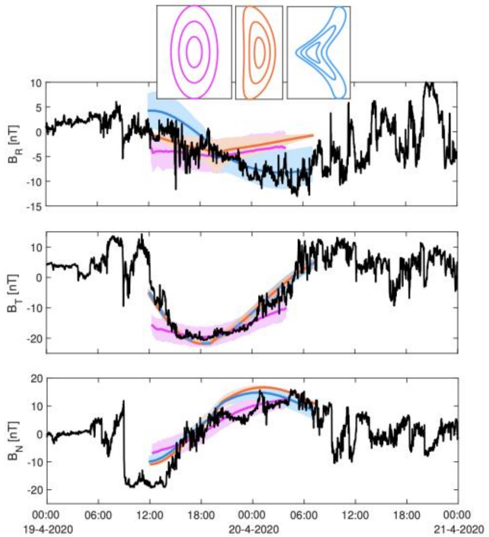
CMEs is not **coherent magnetohydrodynamic structures** after propagate beyond 0.3 AU of the Sun (Owens et al 2017).

Savani et al. 2010 reported the CME passed through the field of view of the STEREO-B Heliospheric Imagers where the leading edge was observed to **distort into an increasingly concave structure**.

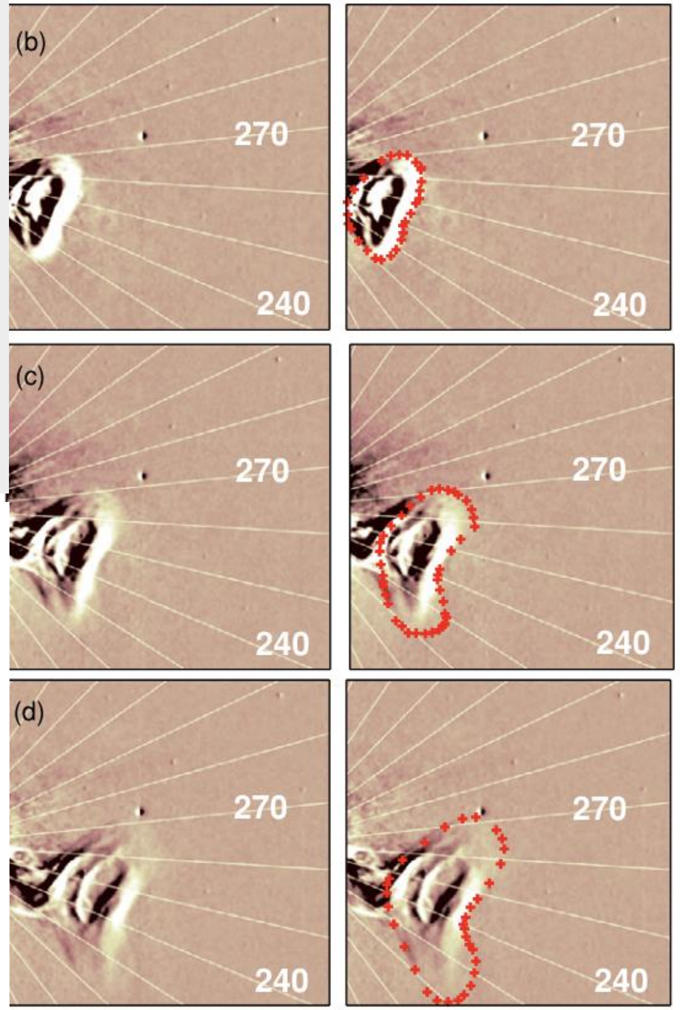
Chi et al., 2021 used the **HUXt model** to simulate the distortion of CME frontal shape and shown that the **latitudinal structure in the ambient solar wind speed** can cause the distortion of CMEs.



Chi et al., (2021)



Davies et al. 2021

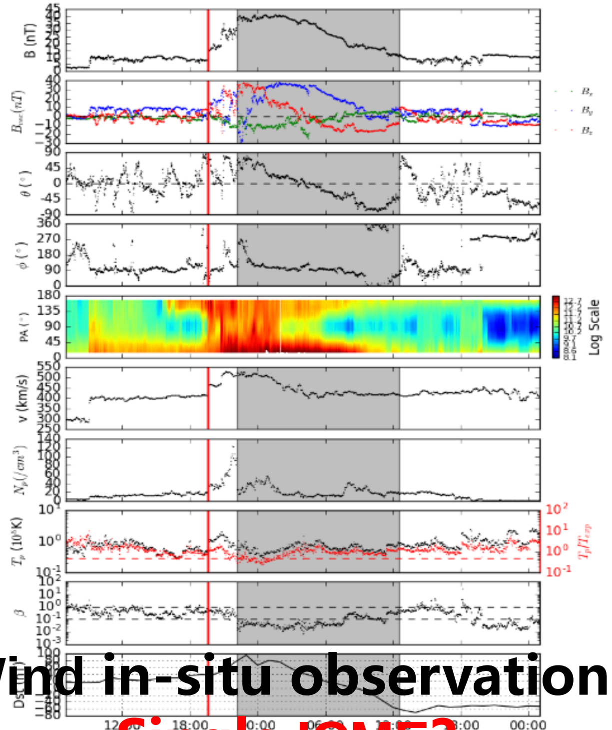


Savani et al. 2010

Background Interaction between CMEs

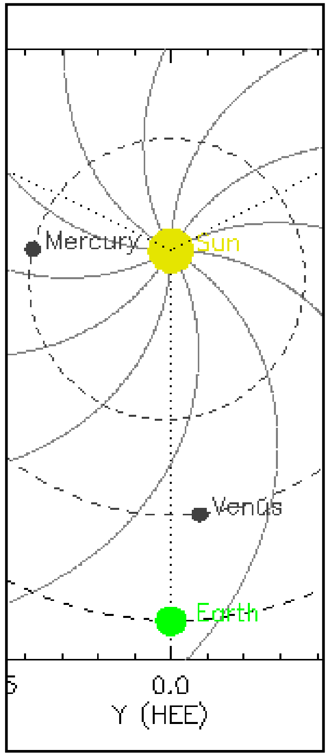
If a slow CME and a fast CME erupt continuously from the adjacent positions, then the fast CME will approach and interact with the slow CME during propagation. The complex structures caused by multiple CME interactions are frequently observed in a variety of forms, including

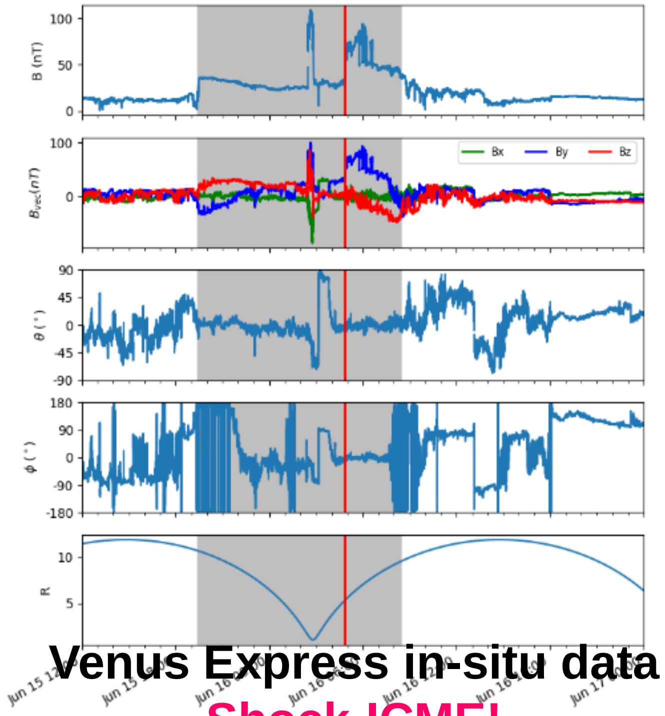
- complex ejecta (Burlaga et al. 2002)
- multi-magnetic clouds (multi-MC) (Wang et al. 2003a)
- **shock- interplanetary CMEs (S-ICMEs) (Wang et al., 2002, Lugaz et al., 2013, Shen et al 2017)**



Wind in-situ observations

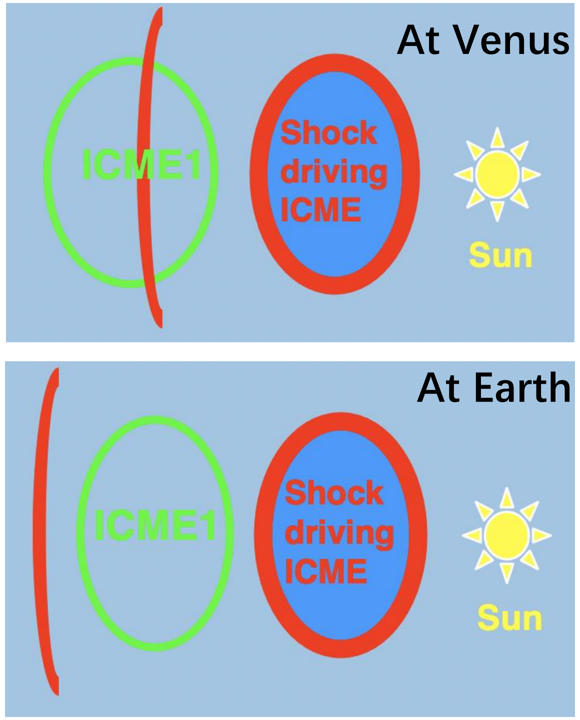
Single ICME?





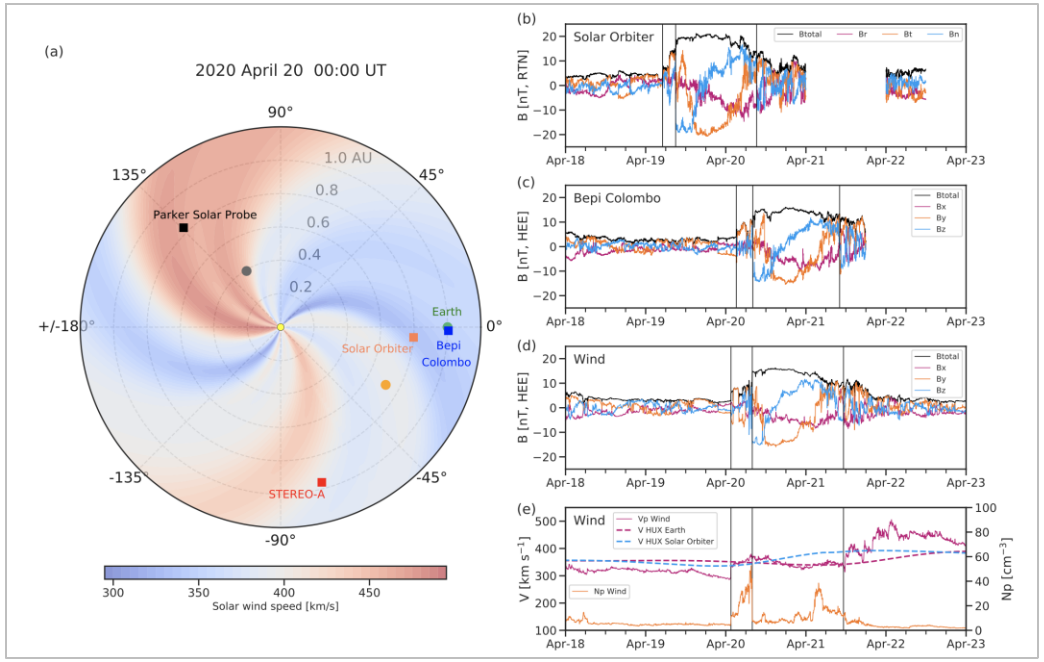
Venus Express in-situ data

Shock-ICME!

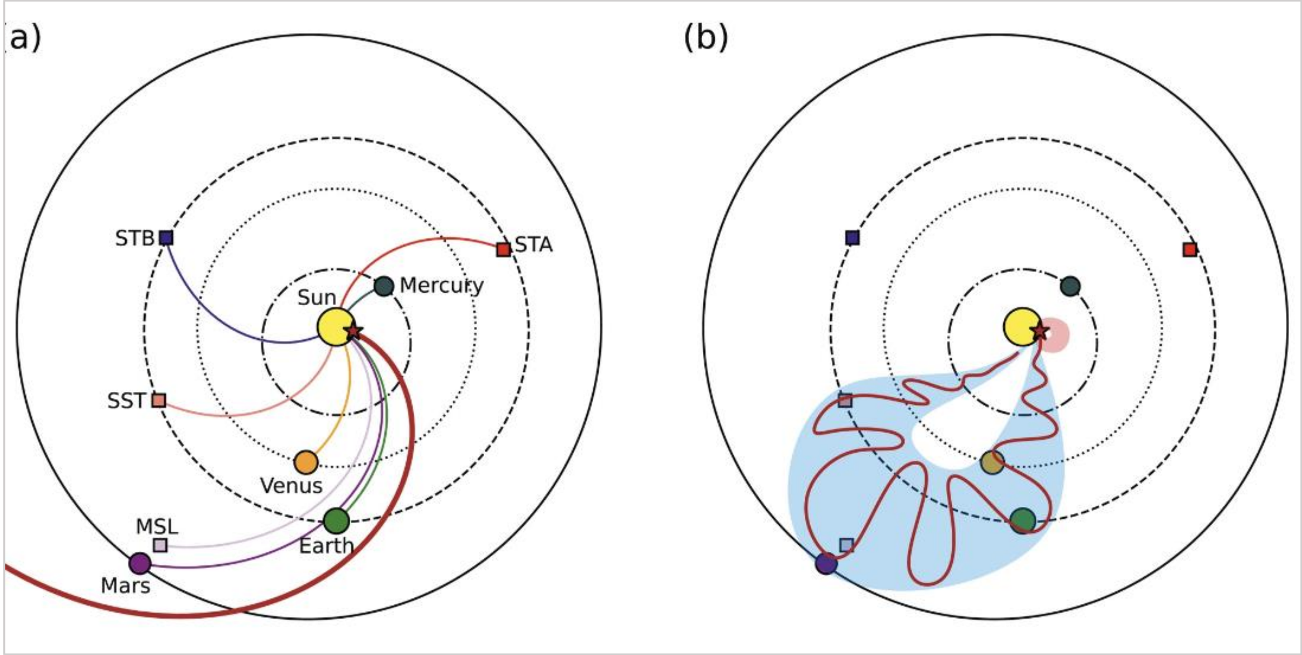


Background

- **Single in-situ observations** **can not** reflect the magnetic field evolution and dynamic evolution of the CME
- To better understand the structure and evolution of ICMEs, analyzing the ICMEs that are detected by **multiple spacecraft** (Palmerio et al. 2019; Kilpua et al. 2019; Chi et al. 2020, 2021; Weiss et al. 2021; Salman et al. 2020).



Davies et al. (2021)

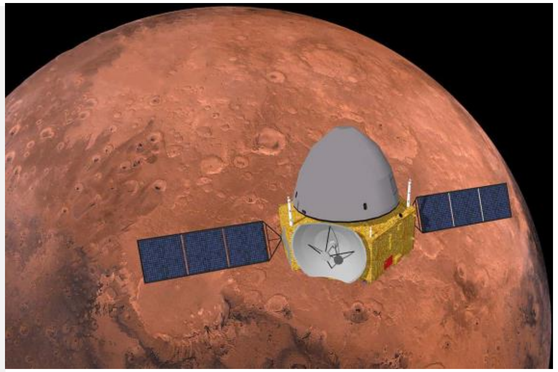


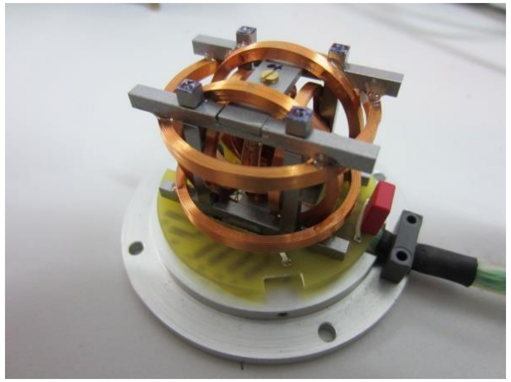
Palmario et al. (2021)

Mission

China's first Mars exploration mission-- Tianwen-1 spacecraft

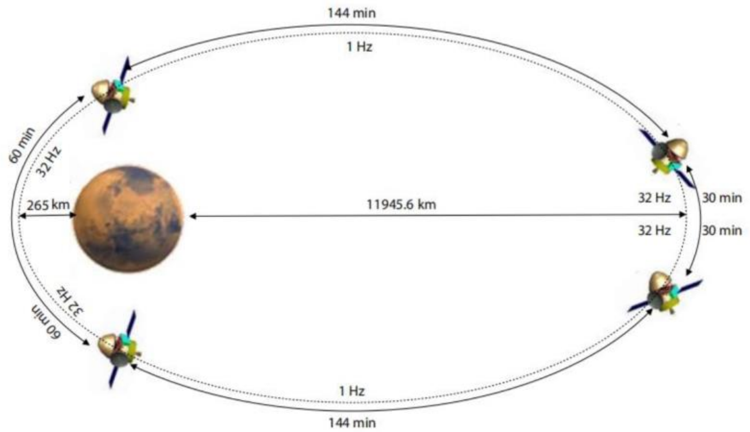
- launched on July 23, 2020
- Since November 16, 2021, the **Mars Orbiter Magnetometer (MOMAG)** (Liu et al. 2020) on board the Tianwen-1 spacecraft has been continuously measuring the local magnetic field conditions around Mars.
- **MOMAG science data from Tianwen-1 （2021-2022） has been released.**





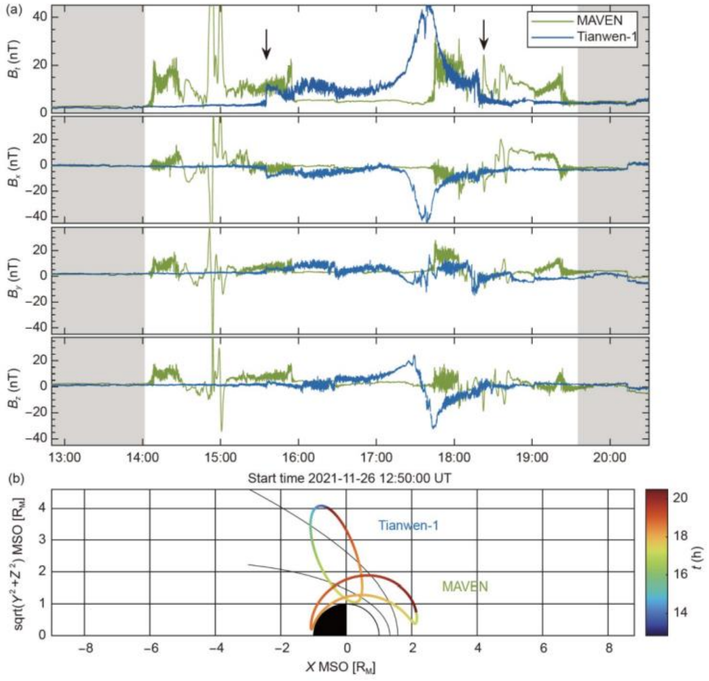
Download the Data from the Planet Exploration Program Scientific Data Release System
http://202.106.152.98:8081/marsdata/

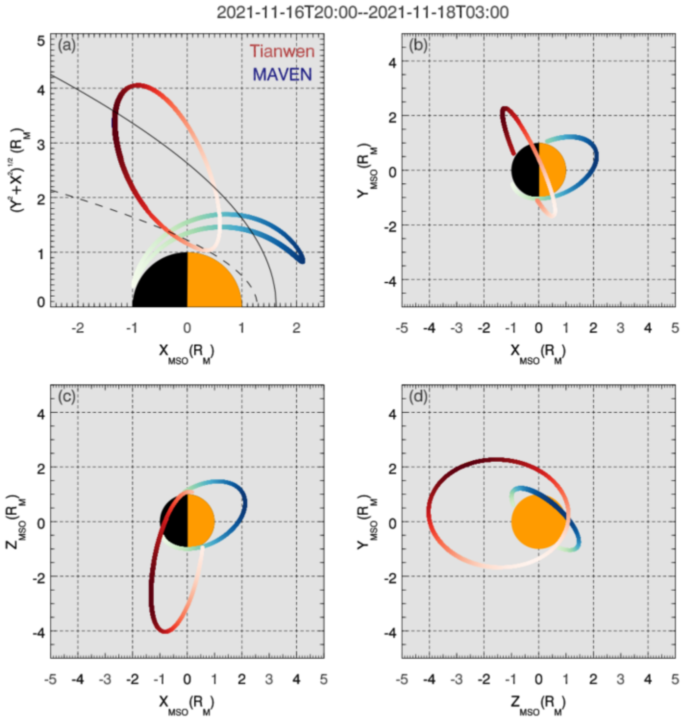
Contact mail： Ytchi@mail.ustc.edu.cn
Ymwang@ustc.edu.cn

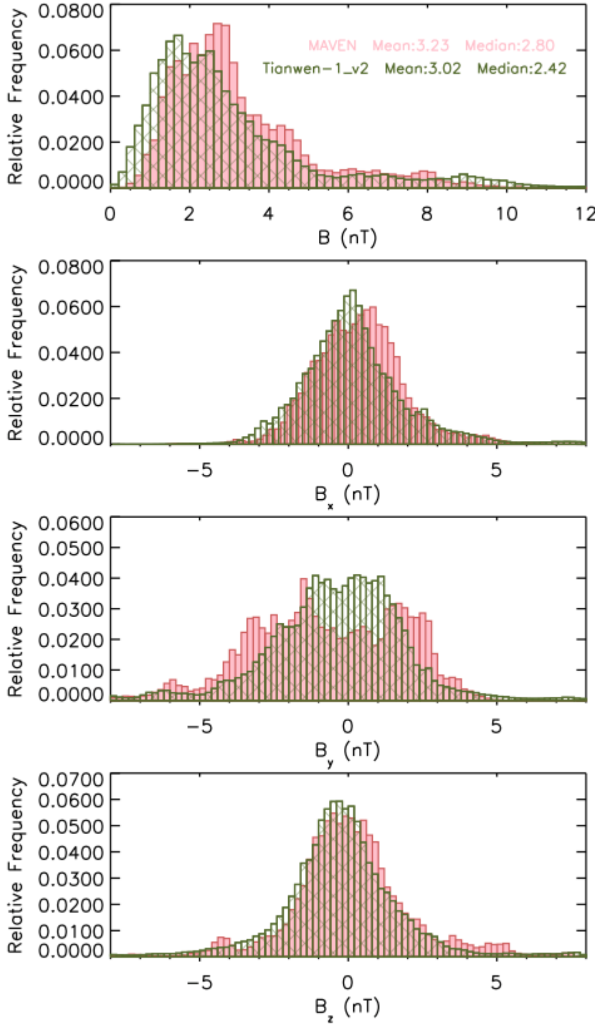


Mission

- The magnetic field detected by Tianwen-1 is comparable to Maven in the solar wind.
- Tianwen-1 spacecraft is a good complement to MAVEN to monitor the interplanetary magnetic field and to record the passage of huge solar transient structures like **ICMEs and SIRs.**







Chi +2023, ApJL

Zou+2023, Science China Technological Sciences

In-situ data

ICME criteria

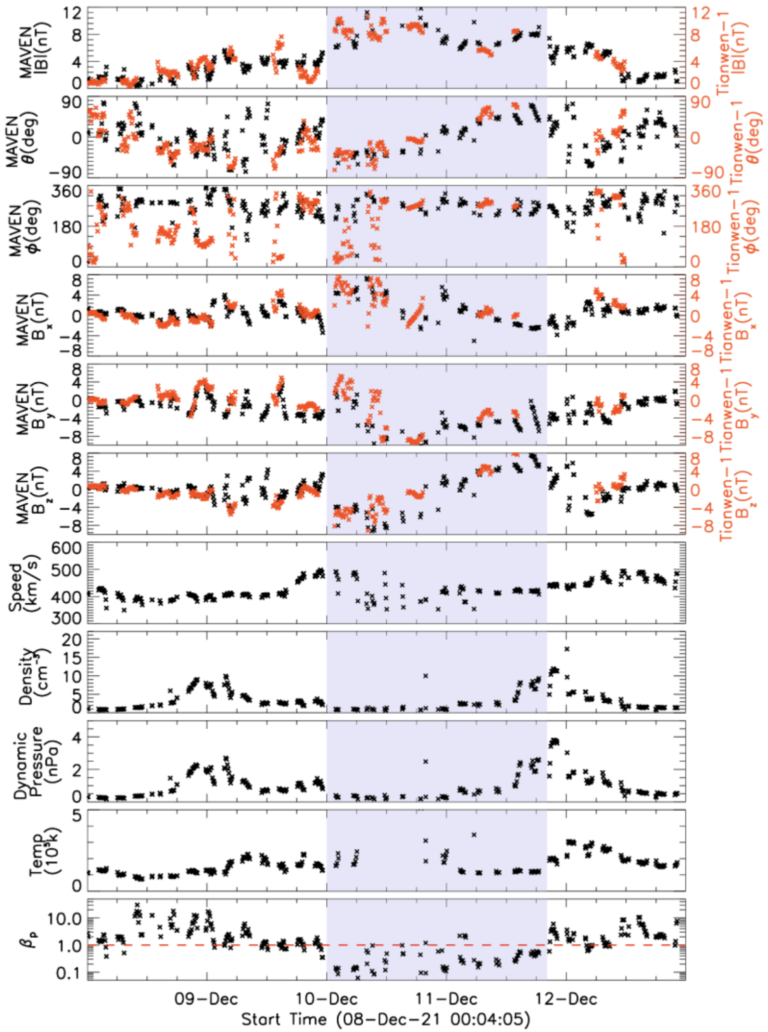
- higher magnetic-field strength compared to its surroundings;
- reasonably monotonic, smooth rotating magnetic field direction;
- abnormally lower proton temperature;
- decreasing plasma velocity;
- lower plasma beta (β)

[Shen+2017, Chi+2016]

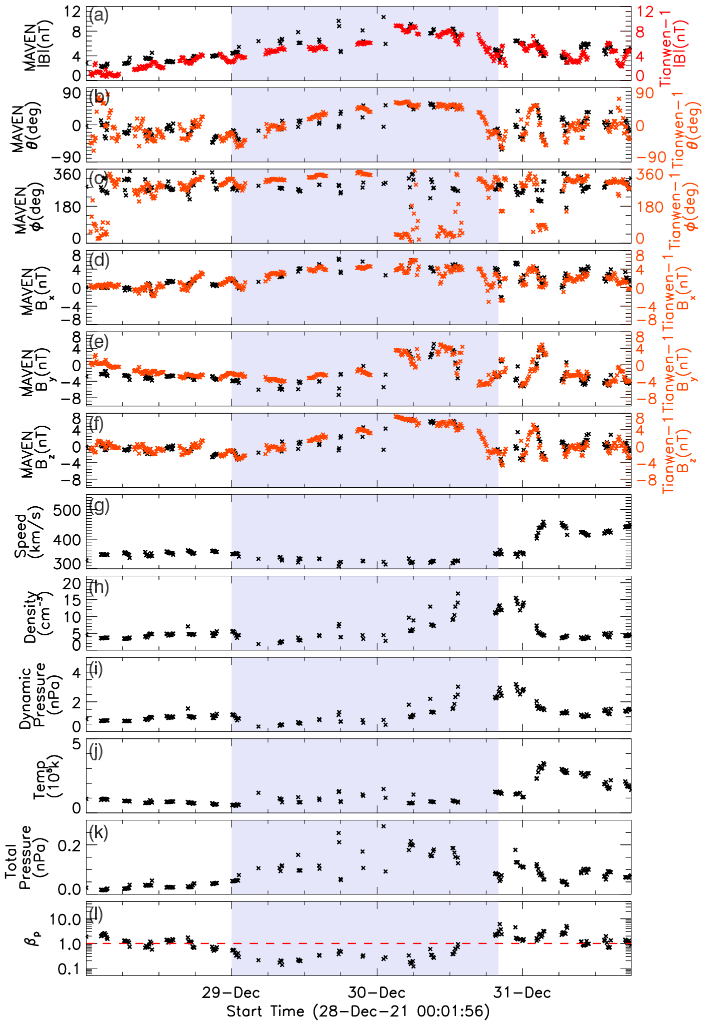
No.	Shock Time (UT)	Begin Time of the Ejecta (UT)	End Time of the Ejecta (UT)
1	——	2021-12-10T00:00	2021-12-11T14:10
2	——	2021-12-29T00:00	2021-12-30T20:00

[Chi+2023, ApJS]

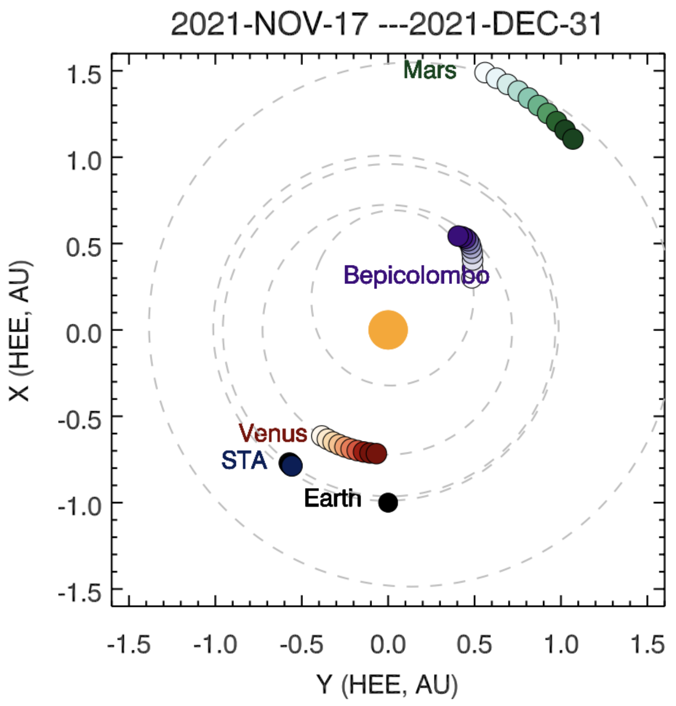
ICME-1



ICME-2

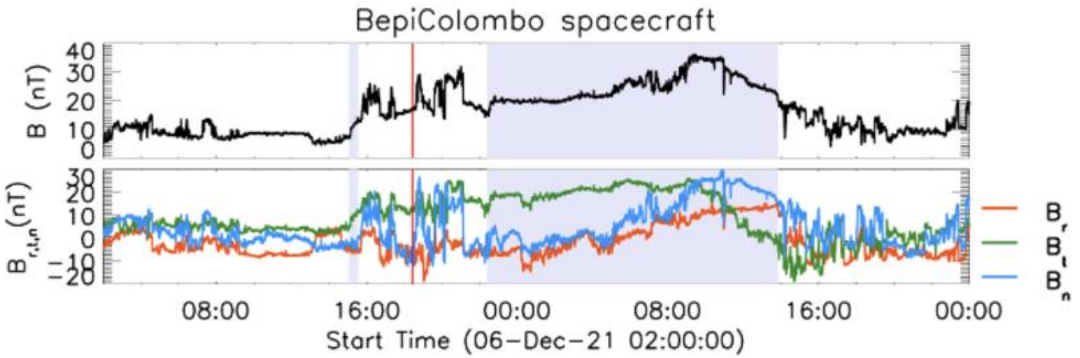


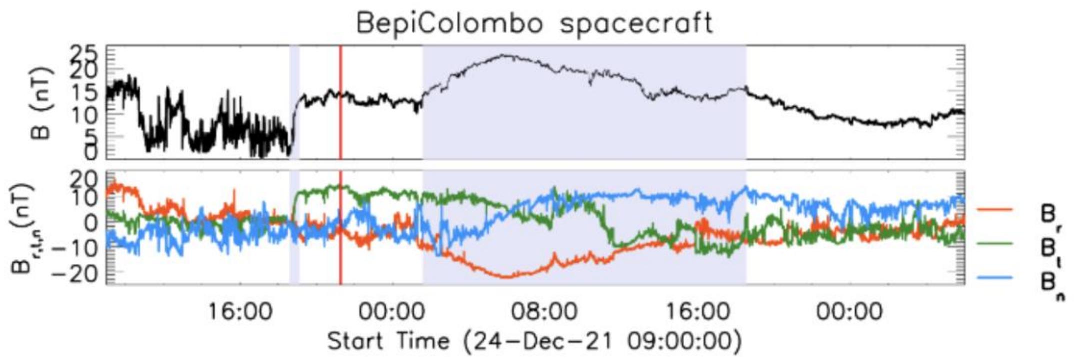
BepiColombo in-situ observations



- BepiColombo spacecraft
- BepiColombo :0.56~0.67 AU
- Mars: 1.55 ~ 1.66 AU
- the heliocentric separation angle between BepiColombo and Mars changed from approximately -16.5◦ to 7◦.

An excellent opportunity to study the dynamic evolution, expansion, and interaction of the ICMEs with the background solar wind by Tianwen-1, MAVEN, and BepiColombo spacecraft.

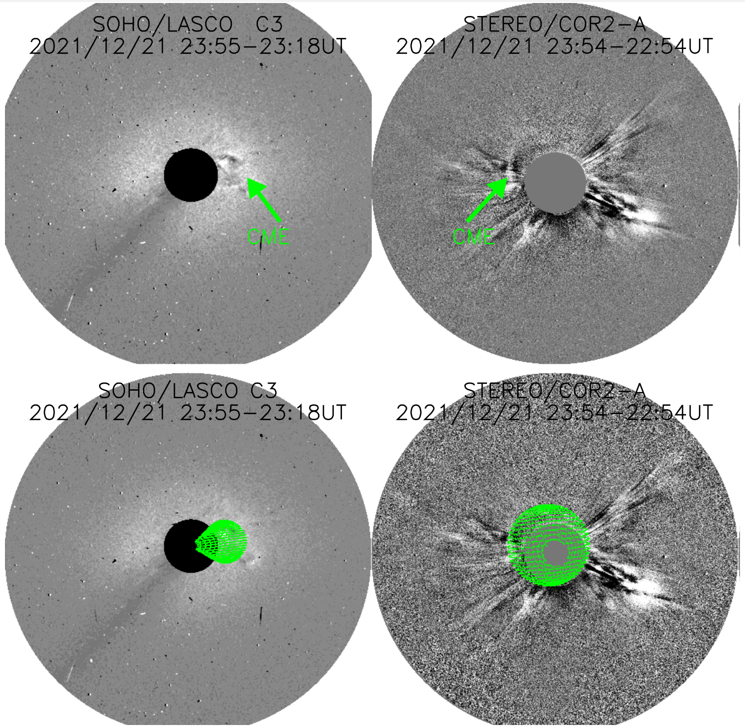




SLOW CME

2021/12/21 SLOW CME EVENT

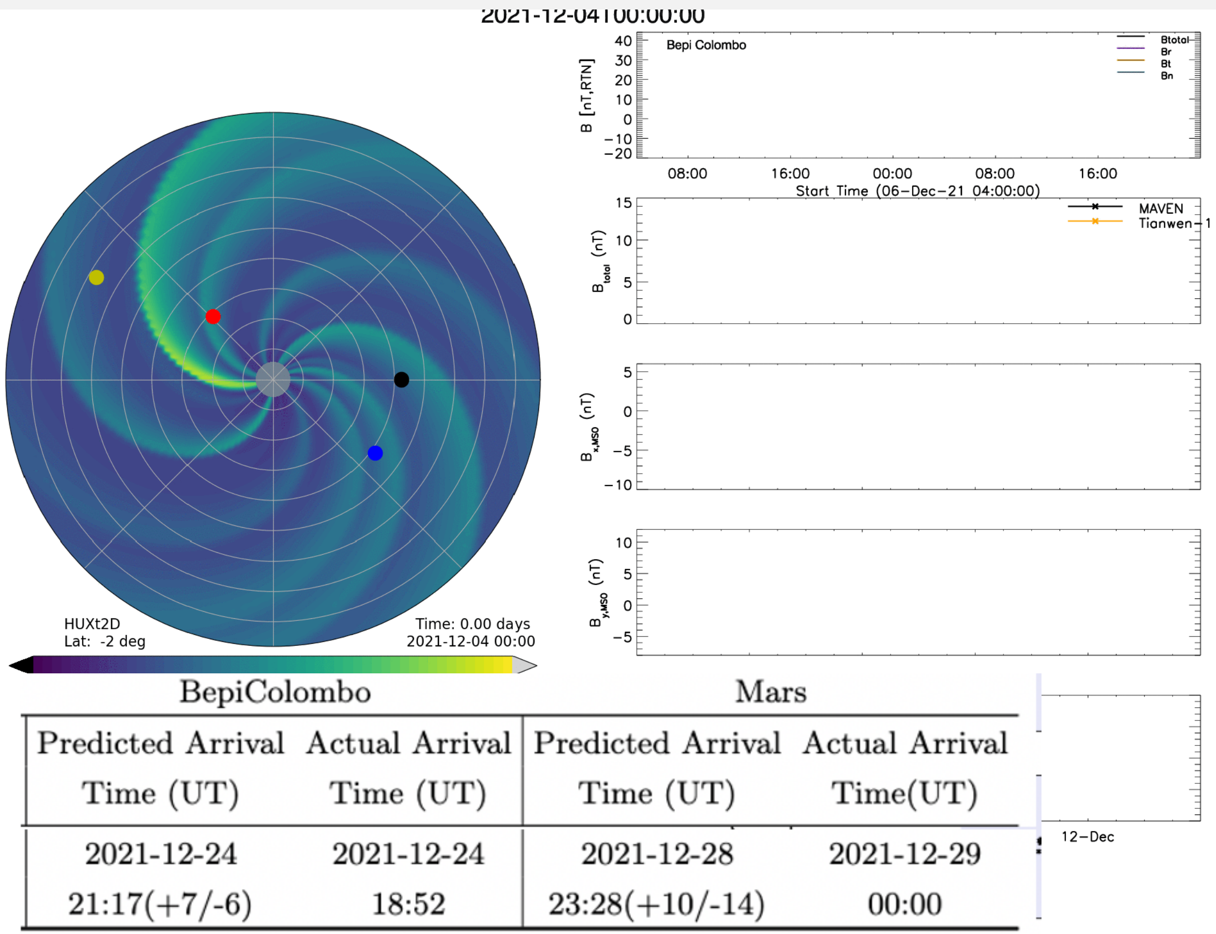
Using GCS model to obtain the parameters of the CME



CME Initial Parameteres

Time (UT)	Longitude (°)	latitude (°)	Half angle (°)	Height ($R_\odot$)	Speed (km/s)
2022-12-22 00:38	148(±5)	1.8(±5)	36.5(±10)	15.91(±2)	390.7(±50)

HUXt model to predict the arrival time of the CME at BepiColombo and Mars



BepiColombo		Mars	
Predicted Arrival Time (UT)	Actual Arrival Time (UT)	Predicted Arrival Time (UT)	Actual Arrival Time(UT)
2021-12-24 21:17(+7/-6)	2021-12-24 18:52	2021-12-28 23:28(+10/-14)	2021-12-29 00:00

[Chi+2023]

FAST CME

2021/12/04 FAST CME EVENT

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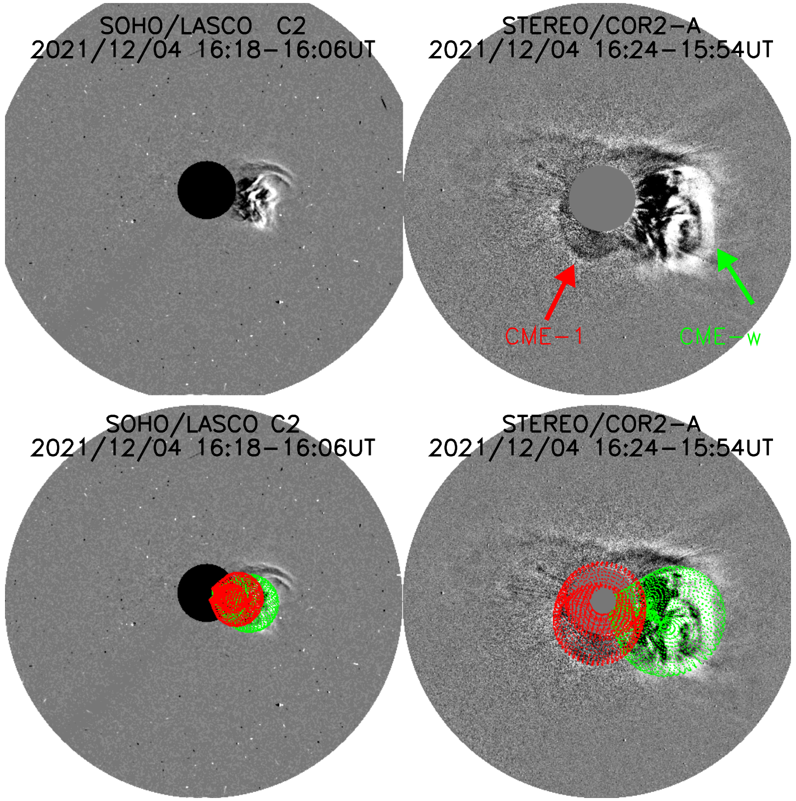
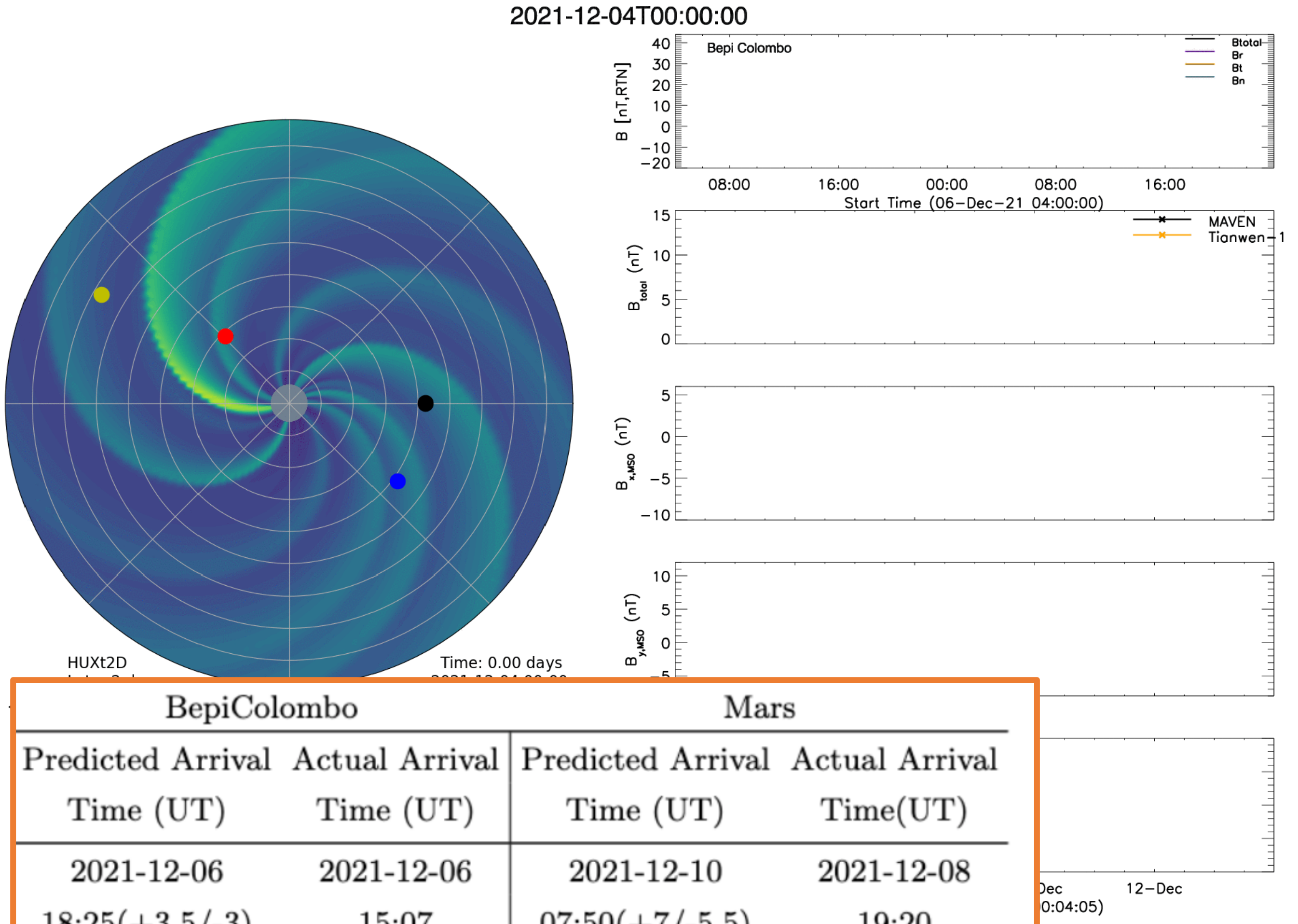
GCS MODEL



CME Initial Parameteres

Time (UT)	Longitude (°)	latitude (°)	Half angle (°)	Height ($R_\odot$)	Speed (km/s)
2021-12-04 17:39	149(±5)	-11(±5)	43.6(±10)	17.55(±2)	761.2(±50)

HUXt MODEL



BepiColombo		Mars	
Predicted Arrival Time (UT)	Actual Arrival Time (UT)	Predicted Arrival Time (UT)	Actual Arrival Time(UT)
2021-12-06 18:25(+3.5/-3)	2021-12-06 15:07	2021-12-10 07:50(+7/-5.5)	2021-12-08 19:20

[Chi+2023]

3DCORE model

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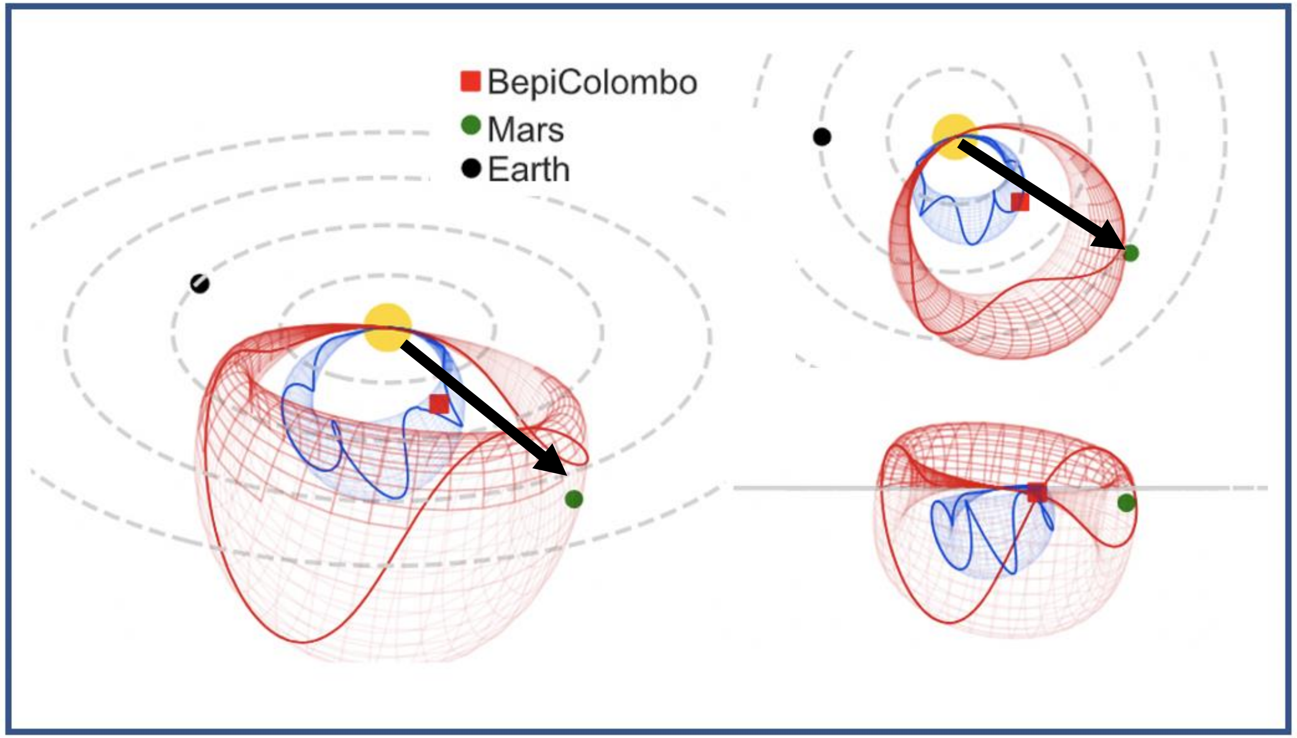
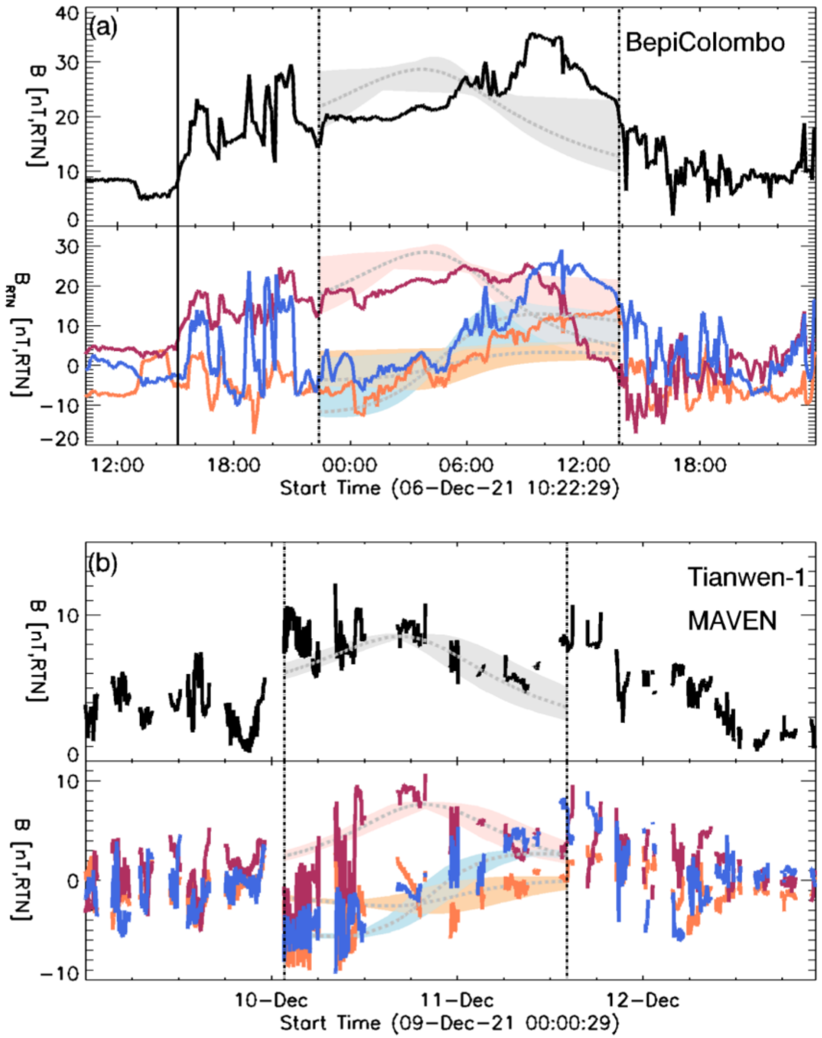




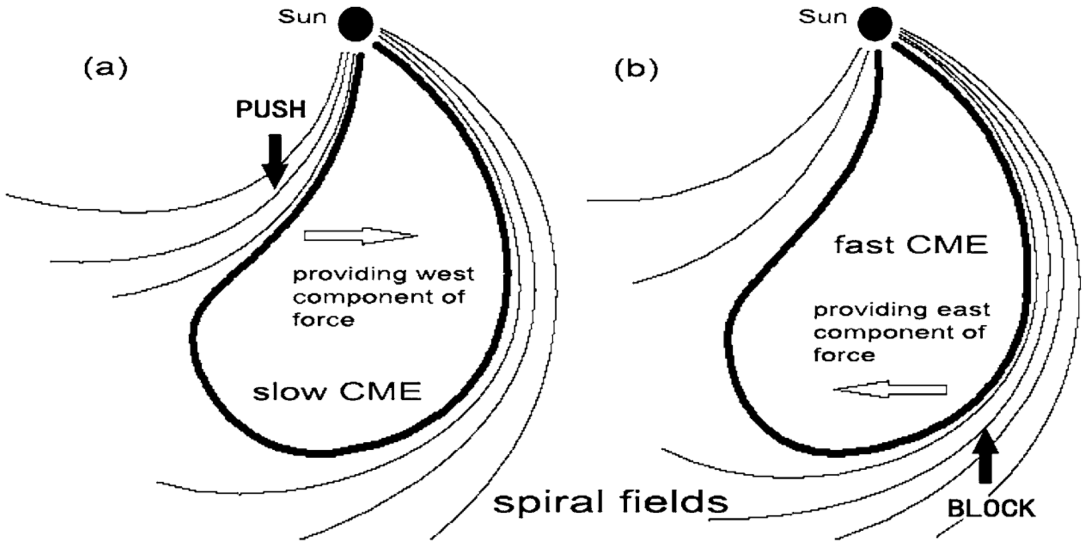
The fast CME undergoes clear deflection (～40°) and rotation (～16.5 °) during its propagation.

Mostl + 2017

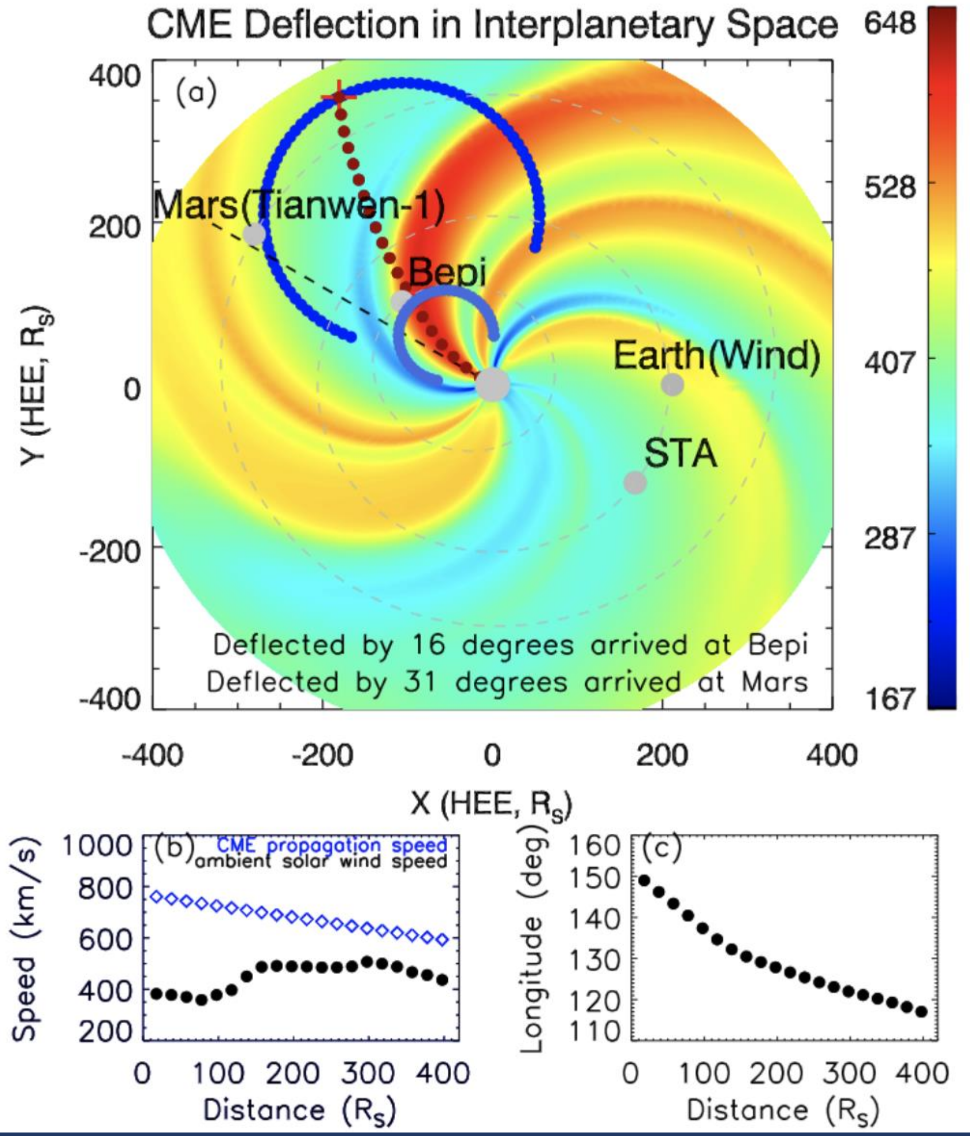
Chi et al 2024 in prepare

FAST CME

CME deflection model



Wang et al. (2014)



The propagation longitude of the CME event changes about 16◦ at BepiColombo, and changes about 31◦ at Mars.

FAST CME

MC-fitting model

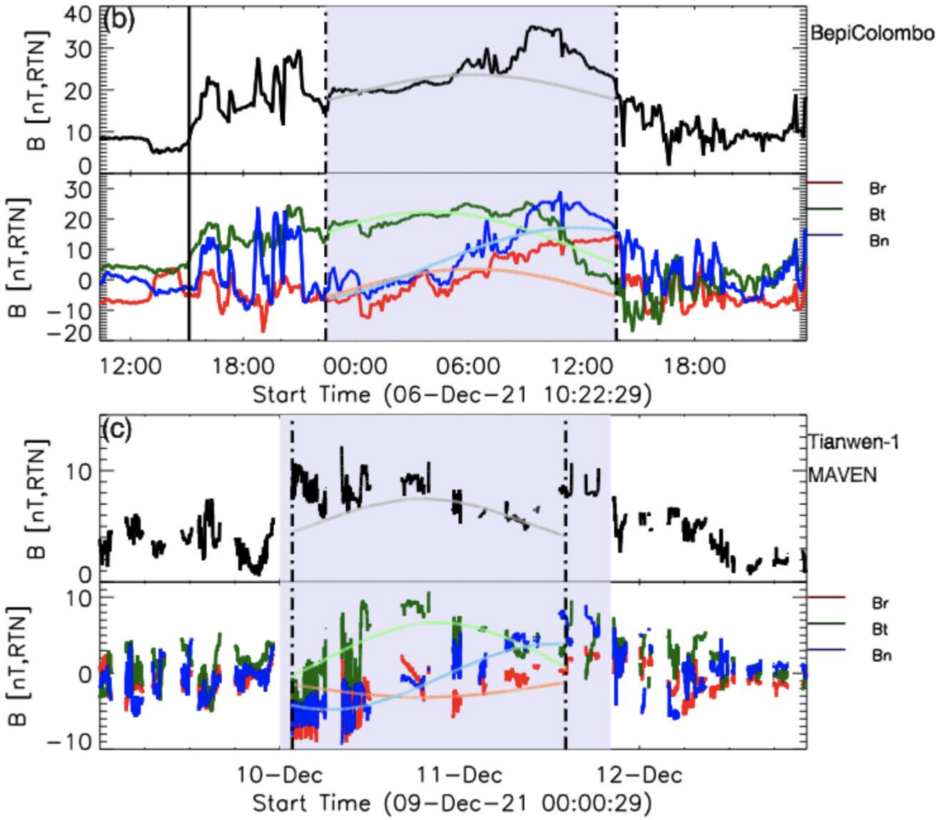


Table 1. CME input parameters specified for the HUXt model and predicted arrival times at the BepiColombo and Mars

		BepiColombo	Tianwen-1/MAVEN	Ratio	
ICME	r (AU)[a]	0.67	1.57	0.427	$\propto r^{1.00}$
	Lon, Lat (HEEQ)[b]	134.5°, -2.4°	146.9°, -3.3°	—	—
	T_{begin}[c]	2021-12-06T22:32	2021-12-10T01:40	—	—
	T_{end}[d]	2021-12-07T13:50	2021-12-11T14:10	—	—
	Δt (hr)[e]	15.3	36.5	0.419	$\propto r^{1.02}$
	B_{max} (nT)[f]	36.12	14.57	2.48	$\propto r^{-1.07}$
	B_{mean} (nT)[g]	24.73	8.25	3.00	$\propto r^{-1.29}$
	B_0 (nT)[h]	34.02	7.64	4.45	$\propto r^{-1.78}$
	Axis direction (θ, ϕ)[i]	10.27°, 202.63°	-12.45°, 284.6°	—	—
	R_{MC} (AU)[j]	0.072	0.14	0.51	$\propto r^{0.79}$
	D (R_{MC})[k]	0.717 (0.05AU)	0.16 (0.02AU)	2.5	—
	F_z (10^{20} Mx)[l]	5.29	4.55	1.16	—
	H_m (10^{40} Mx^2)[m]	257.00±85.08	226.21±50.23	1.14	—
	h_m (10^{40} Mx^2)[n]	149.25	56.06	—	—
	$h_{m,AU}$ (10^{40} Mx^2)[o]	100.00	88.01	1.14	—
	τ (Turns/AU)[p]	5.47	2.75	—	—
	τ_{AU} (Turns/AU)[q]	3.66	4.31	0.85	—

- **The relationship of the axial field strength and the distance is $B_0 \sim r^{-1.78}$**
- **The axial magnetic flux of the flux rope F_z and the total magnetic helicity of the flux rope H_m are nearly invariant**
- **The number of turns (twist) at 1 .5 AU τ increased about 17%**

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Conclusion

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- ✓ The version MOMAG scientific data has been released to the public from 2021 November 15 to 2022 November 4.
- ✓ This is the first time that BepiColombo is used as an upstream solar wind monitor ahead of Mars and that Tianwen-1 is used to investigate the magnetic field characteristics of ICMEs.
- ✓ The fast CME event show clearly rotation, deflection, and distortion by ambient solar wind structure.
- ✓ The axial magnetic field strength (B_0) derived from the force-free flux rope model decreases with heliocentric distance as $r^{-1.78}$, showing a self-similar manner in expansion.
- ✓ The axial magnetic flux and helicity of the magnetic cloud decreased approximately 13% and twist increased 17% from BepiColombo spacecraft to Mars, which implies that the CME event was eroded by the ambient solar wind.

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Thanks For Your Attention!