Using In-Situ Juno Observations to Understand the Evolution of Interplanetary Coronal Mass Ejections

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Motivation

- **Interplanetary coronal mass ejections, ICMEs, are the main drivers of space weather at Earth which can have severe effects to systems both in space and on the ground. ICMEs with a strong southward magnetic component are the most geo-effective[1], thus the strength and orientation of an ICME is important in forecasting space weather severity. Understanding their evolution as they propagate through the heliosphere is therefore essential.**
- **Relatively few studies have used multi-spacecraft observations to analyse ICME evolution[2] as alignments between spacecraft are rare. Juno cruise phase data provides a new opportunity to study ICME evolution over greater distances.**

Outline

- **We present 7 magnetic clouds observed by both Wind and Juno. For each event, the arrival times of the magnetic cloud at Juno and the flux rope boundaries have been given, along with the radial, longitudinal and latitudinal separations between Wind and Juno.**
- **We present observations of the magnetic field of two events in particular, where spacecraft were close to radial alignment (longitudinally separated by 3.6° and 1.0°, respectively). We find that even small longitudinal separations of a few degrees between spacecraft can still result in significantly different observations and event properties.**
- **We also find the relationship between the mean magnetic field and heliocentric distance for the 7 events is in good agreement with previous relationships found between 1 and 5 AU.**

1. Magnetic Clouds Identified

- We've identified magnetic clouds observed by Juno throughout its cruise phase between 1 and 5 AU, using the magnetic criteria detailed by Burlaga et al. (1981): an enhanced magnetic field, with low variance, and a smooth rotation.[3]
- 7 of the magnetic clouds identified at Juno (<2 AU) were also observed at Wind. The corresponding ICMEs at Wind have been identified in the HELCATS ICME catalogue. (https://www.helcats-fp7.eu/catalogues/wp4_icmecat.html)
- Table 1 lists the times of the start of the ICME sheath, and the leading and trailing edges of the magnetic cloud observed at Juno that correspond to the boundaries defined by the HELCATS catalogue at Wind. We also note the radial separation in heliocentric distance (Δr_H), and the longitudinal/latitudinal separations between the spacecraft.

	JUNO r_H [AU]	ICME START TIME	MC START TIME	MC END TIME	Δr_H [AU]	ΔLONG [°]	ΔLAT [°]
1	1.07	2011-09-17 06:31	2011-09-17 19:58	2011-09-18 13:31	0.07	6.6	0.0
2	1.24	2011-10-25 14:23	2011-10-26 00:40	2011-10-26 13:36	0.26	3.6	0.1
3	1.60	2013-04-15 18:22	2013-04-17 02:25	2013-04-18 14:07	0.61	1.0	0.0
4	1.51	2013-05-02 03:33	2013-05-02 09:44	2013-05-03 06:05	0.52	7.6	0.0
5	1.36	2013-12-02 03:05	2013-12-03 11:12	2013-12-04 13:00	0.38	0.3	3.6
6	1.96	2014-02-06 23:41	2014-02-07 03:38	2014-02-08 00:23	0.98	34.8	4.5
7	1.99	2014-02-08 00:44	2014-02-09 14:53	2014-02-11 03:59	1.00	36.2	4.5

Table 1: Summary of each ICME observed by both Wind and Juno. The heliocentric distance, arrival time of the ICME and the magnetic ejecta boundary times observed Juno are given. The radial, longitudinal and latitudinal separations between Wind and Juno are also listed for each event.

- Table 1 shows that the radial separations between Wind and Juno range between 0.1 AU to 1.0 AU, and the longitudinal separations range between 0.3 and 36.2°. At greater heliocentric distances we note that the latitudinal separation also becomes greater as Juno is raised out of the ecliptic plane.
- ICMEs are generally considered in radial alignment if separated by less than 10° in longitude.[4] The observations of the ICMEs with the smallest longitudinal (and latitudinal) separations are shown in Section 2.

2. Wind and Juno Observations

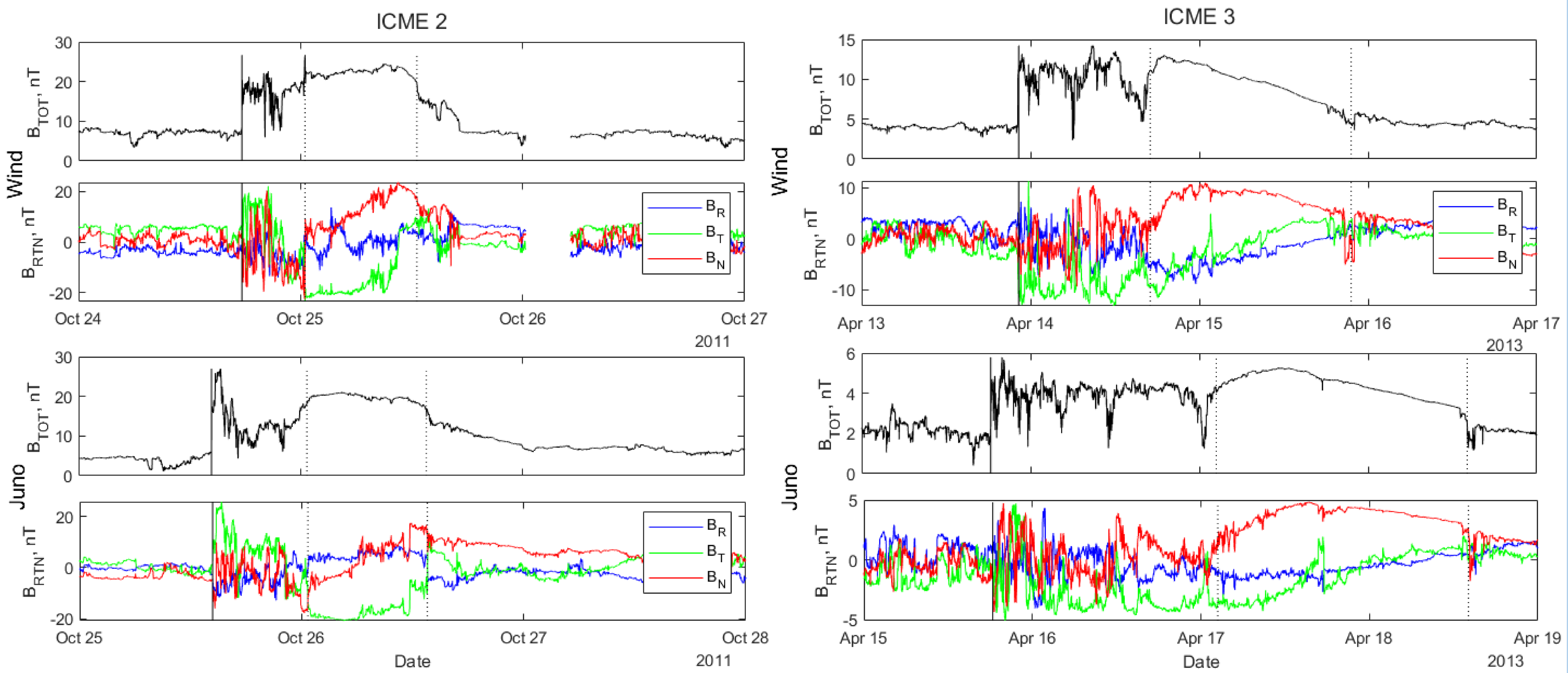

Figure 1: The detailed magnetic field data of ICME 2 (left) and ICME 3 (right) observed at Wind and Juno. The solid line marks the start of the ICME and the dotted lines constrain the flux rope. The top panel displays the magnetic field magnitude, the bottom panel displays the field components in RTN co-ordinates.

- Figure 1 shows the evolution of the magnetic field signatures of ICME 2 and ICME 3, listed in Table 1. ICME 2 has a radial separation of 0.26 AU and a longitudinal separation of 3.6° between Wind and Juno, in comparison to ICME 3 which has a longer radial separation of 0.61 AU and smaller longitudinal separation of 1.0°.
- The observations of ICME 3 look very similar between Wind and Juno: each of the magnetic field components have very similar profiles, although lower in magnitude and duration, as on would expect as the ICME has propagated between observations. Performing MVA on the flux rope, we find that there is a difference of θ = 10.8° and ϕ = 60.5° in flux rope orientation between spacecraft.
- The observations of ICME 2 (analysed in detail by Davies et al. (in prep.) [5]) are also very similar between the spacecraft, however, there are some differences in the magnetic field components: the radial component looks very dissimilar, and also the normal component is similar in profile, it is shifted lower in magnitude. The transverse component is the most similar between spacecraft. Another significant difference is the compressed magnetic field following the flux rope, indicative of faster solar wind running into the back of the event, that is present at Wind but not at Juno. Performing MVA on the flux rope, we find that there is a difference of θ = 22.7° and ϕ = 83.0° in flux rope orientation between spacecraft.
- We suggest that the significant differences between spacecraft observations and properties of ICME 2 are not necessarily due to the radial evolution of the ICME, but more so due to the longitudinal separation of the spacecraft. Caution should therefore be exercised in radial alignment studies.

3. Statistical Relationships

- Figure 2 presents the relationship of the observed mean magnetic field strength with heliocentric distance for the 7 events registered at both Wind and Juno.
- We find that $B_{mean} \propto r_H^{-1.26}$. This in close agreement with previous studies e.g. Ebert et al. (2009)[6] and Richardson et al. (2014)[7] which both used events observed by Ulysses between 1 and 5 AU and found $B_{mean} \propto r_H^{-1.29}$ and $B_{mean} \propto r_H^{-1.21}$, respectively.
- ICME 2, discussed in Section 2, looks to be an outlier to the overall trend.

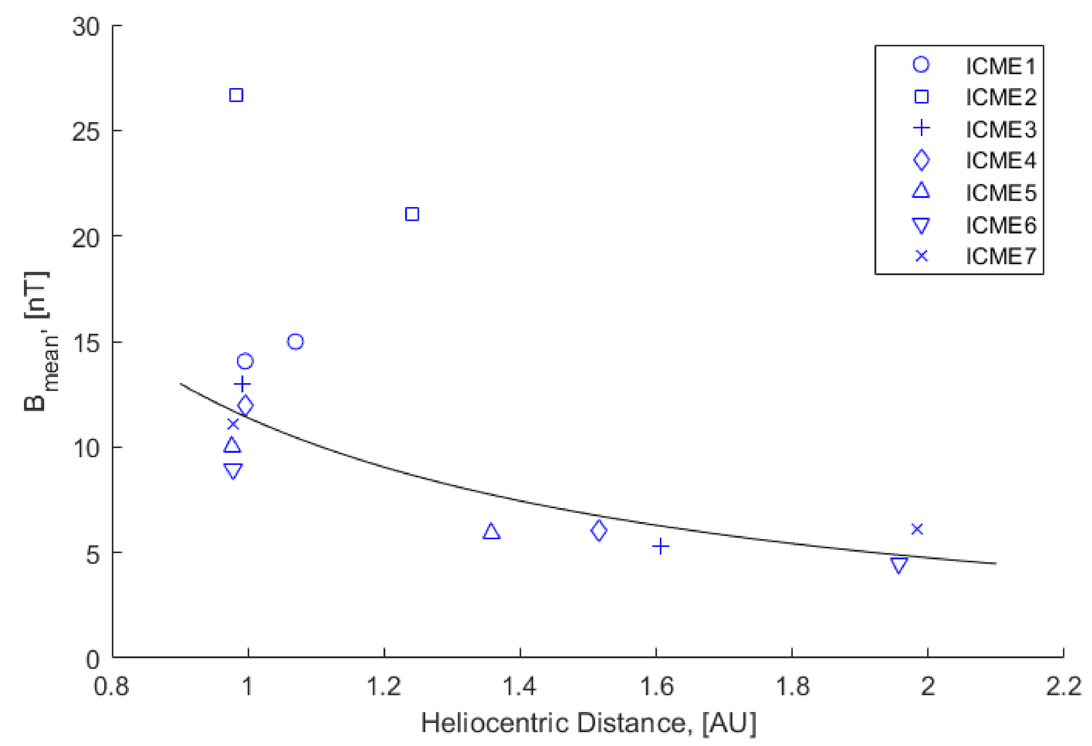

Figure 2: The relationship between the mean magnetic field strength for the 7 events observed by both Wind and Juno. Each event is given a different marker so corresponding datapoints at Wind and Juno can be identified.

4. Summary

- The Juno cruise dataset provides a new opportunity to extend our understanding of the evolution of ICMEs in combination with other spacecraft in the inner heliosphere.
- We find that the mean magnetic field strengths observed fit well with the previous relationships.
- Comparing observations for spacecraft close to radial alignment, we also find that even small longitudinal separations of a few degrees between spacecraft can still result in significantly different observations and event properties.

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