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Ejects and Transient Shocks: Ulysses' In-Ecliptic Observations: 1 to 5 AU

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Abstract

During its travel to Jupiter (1 to 5.4 AU) Ulysses detected 25 ejects signatures attributed to interplanetary counterparts of coronal mass ejections and 32 transient forward shocks. About half of these ejects (13) were associated with shocks. We studied the characteristics and heliocentric evolution of these events. In general, the fronts of the ejects associated with shocks propagated faster than the ambient solar wind. The front of the ejects not associated with shocks propagated at about the same speed as the ambient solar wind. The radial width of the ejects W_r seems to be correlated with the speed of the ejects: large ejects speeds were faster than small ejects speeds. The Mach number of the shocks associated with the ejecta seems also correlated with W_r: stronger shocks (higher Mach numbers) were associated with larger eject a. About forty percent of the ejects associated with shocks were propagating supermagnetosonically in the ambient solar wind. We did not find any clear dependency of the ejects characteristics on heliocentric distance (1 to 5 AU), but their variations were related to temporal and, presumably, geometrical phenomena.

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1. Introduction

We report some characteristics of the ejects and their associated shocks as observed by Ulysses during its travel to Jupiter. In this period, from October 1990 to February 1992, Ulysses detected 32 transient forward shocks and 25 ejects signatures attributed to coronal mass ejections (CMEs). We studied the relationships between the list of in-ecliptic CMES [J. L. Phillips et al., Los Alamos internal report, 1997] and the shock parameters reported by *Balogh et al.* [1994]. The heliographic locations of these events and their temporal (spatial) relation to interaction regions and magnetic sectors was shown graphically in a comprehensive map of solar wind dynamics (plate 1 in *González-Esparza et al. [1996]).* This data set complements previous statistical studies of shocks and ejects within 1 AU [*Borrini et al.*, 1982; *Klein and Burlaga, 1982; Gosling et al., 1987; Marsden et al., 1987; Linsay et al., 1994; Richardson and Cane, 1995]* and allows us, for the first time, to study their evolution from 1 to 5 AU.

The identification of interplanetary counterparts of CMES is still somewhat problematic. Start and stop times of some ejects events vary depending on the signature that we are looking at (see, e.g., *Richardson and Cane [1995]).* The list of in-ecliptic CMEs detected by Ulysses [J. L. Phillips et al., Los Alamos internal report, 1997] is based on hi-directional streaming suprathermal electrons accompanied by some other plasma cloud signatures (e.g., proton temperature depression, high helium abundance, low ion beta, high thermal Mach number, magnetic field **en**hancement and cloudlike field rotations). We did an exhaustive review of these events obtaining independent corroboration for most of them.

2. Ulysses Observations

To study the characteristics of these events we used data of the solar wind plasma experiment (in hourly averages obtained from the NSSDC) which is described by *Bame et al.* [1992]. Figure 1 presents two different spatial aspects of the ejects. At the top of Figure 1 is shown the approximated radial width W_r of 25 ejects versus heliocentric distance. We estimated W_r integrating the points of solar wind bulk speed along the temporal duration of each ejects. We did not find a statistical tendency of ejects signatures to expand with heliocentric distance (l–5.2 AU). At about 2.4 AU there were some very large ejects associated with the 'March 1991' events *[Phillips et al., 1992]* and close to Jupiter ($\sim$ 5 AU) Ulysses detected three relatively small ejects. This result is not surprising as CMES are transient events that could have had a very irregular pattern during the 16 months of these observations (post-maximum cycle 22). The largest ejects had a W_r of about 1.55 AU at 2.5 AU, while small ejects had a W_r of about 0.1 AU at various heliocentric distances.

Not all the ejects were associated with shocks. On the basis of the shock-ejects separation and velocity and pressure profiles, *González-Esparza et al. [1996]* reported that 13 of the 25 ejects (52%) were likely associated with transient forward shocks (these events are pointed out in the list by J. L. Phillips et al.). For these events, the bottom plot of Figure 1 shows the shock-ejects radial separations versus heliocentric distance. We estimated the shock-ejects separations in a similar way as we estimated W_r. We did not find any clear dependency of the shock-ejects separation on heliocentric distance. It is possible to find ejects signatures close to transient forward shocks at distances as great as about 5 AU. The shock–ejects separation varied between 0.1 and 0.8 AU. While looking at these results, note that it is impossible to describe fully the shock-driver geometry due to the limitations of single spacecraft measurements and the temporal and spatial variations of the events. The variations in shock-ejecta separation can be related to these two aspects. This might explain also why the Mach numbers of the transient shocks did not show a clear tendency to decrease with heliocentric distance (see, e.g., Figure 7 in paper 1).

We now study the speeds of the ejects. Figure 2 presents average bulk speeds of 'ejects fronts' and their 'ambient' solar winds versus heliocentric distance. We defined the ambient wind as the first four data points (4 hours) of solar wind plasma just before the ejects (or just before the shock in the cases with shock association). The wind speeds are represented by vertical bars in Figure 2. The ejects fronts were defined as the first four data points (4 hours) of ejects in the data series. Figure 2 shows that: 12 of the 13 ejects associated with shocks (△) had fronts faster than the ambient wind. The only exception is the last ejects △ detected at about 5.17 AU which was propagating through very fast ambient wind (~600 km/s). This ejects was associated with the weakest transient shock detected in the trajectory, which had a Mach number of just about 1 (see, e.g., Figure 7 in paper 1). This event may bean example of a shock-ejecta decelerated in the outer heliosphere. On the other hand, Figure 2 shows that 9 of the 12 ejects without shock (e) had fronts propagating about the same speed as the ambient wind. The solar wind and ejects fronts had a very variable pattern of bulk speeds during the 16 months of these observations. The bulk speeds of the ejects fronts varied between 340 km/s and 805 km/s.

Figure 3 explores two relations with the ejecta radial width W_r (Figure 1). The top panel of Figure 3 shows the bulk speed of the ejects fronts (Figure 2) versus W_r. Large ejects tended to be faster than small ejects. In this case we did not find any clear difference between the two ejects categories, but all the points seem to be indifferently distributed following the same tendency. For those ejects with a shock association, the bottom panel of Figure 3 shows the Mach number of the transient forward shocks versus W_T. *The* Mach numbers are from the shock list by *Balogh et al. [1994]*, Stronger shocks (higher Mach numbers) were associated with larger ejects. The strength of the shocks seems to be correlated with the size of the ejects.

Forward transient shocks are believed to be driven by CMEs. In order to drive a shock, the ejects front needs not just to be faster than the ambient wind, but to propagate supermagnetosonically in the ambient wind. We tested the ejects fronts to verify if they were supermagnetosonic. Figure 4 presents the Mach number of the 25 ejects fronts M_e (vertical lines with symbols) versus heliocentric distance. The M_e were approximated as: the speed difference between the ejects front and the ambient wind (Figure 2) normalized by the MHD fast mode speed in the ambient wind. Figure 4 shows that 5 of the 13 (38%) ejects associated with shocks (△) had fronts propagating supermagnetosonically in the ambient wind, and 7 others had fronts propagating at speeds of 0.5 M_e or higher. The only exception is the last ejects △ that we commented on before in Figure 2. All the ejects not associated with shocks had fronts propagating at speeds lower than 0.36 M_e. As we did not observe any supermagnetosonic ejects beyond 3 AU, this might suggest that ejects eventually decelerate at further heliocentric distances. However, We should keep in mind the shock- ejecta geometry and the temporal variations that we commented on before.

3. Summary and Conclusions

We have studied some aspects of the ejects and their transient forward shocks as detected by Ulysses during its in-ecliptic travel to Jupiter (post-maximum cycle 22). The ejects events were identified by hi-directional streaming suprathermal electrons accompanied by some other plasma cloud signatures. This comprehensive data set allows us to study, for the first time, the statistical characteristics of these events from 1 to 5 AU. Large ejects were faster than small ejects. The ejects associated with shocks and the ejects not associated with shocks had different dynamic characteristics. In general, the fronts of the ejects associated with shocks propagated faster than the ambient solar wind. In fact, about 40% of these fronts were propagating supermagnetosonically in the ambient wind.

The rest of these fronts (which were submagnetosonic) may be examples of ejects drivers that decelerated as they move away from the Sun. From the shocks associated with ejects we found that stronger shocks (higher Mach numbers) were followed by larger eject a and weaker shocks were followed by smaller ejects. We did not find a clear dependency of the shock–ejects characteristics on heliocentric distance, but their variations were more likely related to the temporal and geometrical effects.

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Figure 1. Top: radial width W_r of the 25 ejecta signatures (in AU) versus heliocentric distance. Bottom: for those ejects associated with shocks, shock-ejects radial separation versus heliocentric distance.

Figure 2. Mean bulk speed of ejects fronts (symbols) and their ambient winds (solid bars) versus heliocentric distance. The ejects are divided into two categories: no shock associated (.) and shock associated (A).

Figure 3. Top: mean bulk speed of the ejects fronts (Figure **2)** versus ejects radial width W_r (Figure 1). The eject a arc characterized in the same way as in Figure 2. Bottom: shock Mach number oft he transient forward shocks associated with ejects versus W_r. The Mach numbers are from the list by *Balogh et al. [1595].*

Figure 4. Mach number of ejects fronts M_e versus heliocentric distance. The ejects are characterized in the same way as in Figure 2. If $M_e > 1$ the ejects front was supermagnetosnic. If $1 < M_e < 0$ the ejects front was faster than the ambient wind but no-supermagnetosonic. If $M_e < 0$ the ejecta front was slower than the ambient wind.

Ulysses In-Ecliptic Observations

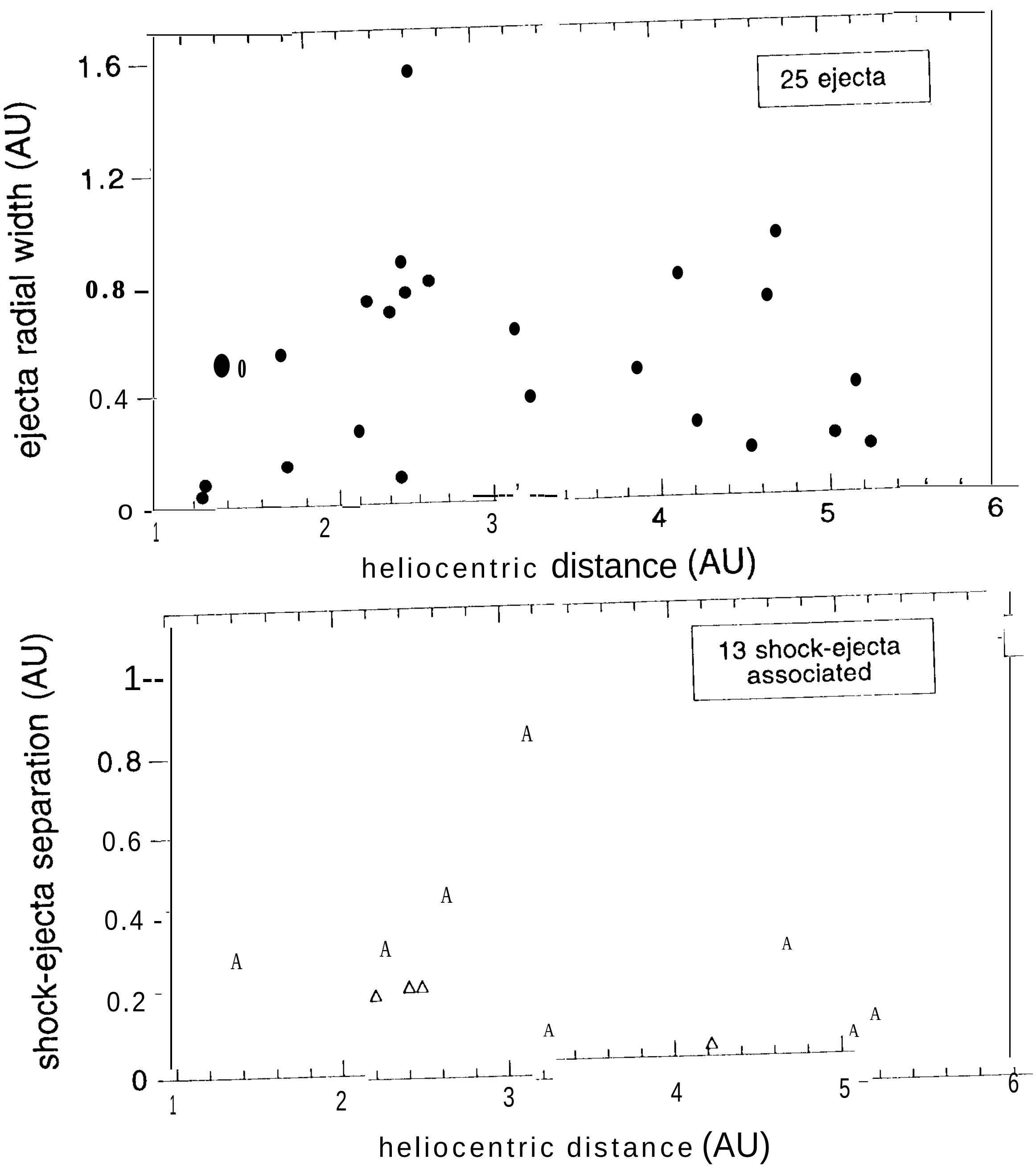

Figure 1