Characteristics of interplanetary CMEs observed by Ulysses

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The characteristics of discontinuities associated with interplanetary coronal mass ejections and their distribution in the heliosphere have been studied in detail. For this, jumps in solar wind plasma parameters like wind velocity, IMF and proton density across the shocks and discontinuities have been evaluated and used to characterize them. The distribution of the plasma parameters across the discontinuities with respect to heliolatitude and with radial distance from the Sun have been analyzed using the Ulysses data taken during its three orbits around the Sun.

Keywords: ICME discontinuities, Solar wind, Interplanetary magnetic field, Interplanetary coronal mass ejections

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1 Introduction

The properties of the solar wind highly depend on the heliospheric latitude from which it emanates. Spacecraft observations in the ecliptic plane have provided only limited excursions in heliographic latitude (± 7.25\degree). Ulysses is provided the first ever map of the heliosphere from the equator to the poles. Three orbital passes of Ulysses provided views of the solar wind at times near the minimum, ascending phase, maximum and descending phases of the 11-year solar activity cycle. The main objective of Ulysses mission was to determine the global, three-dimensional properties of the heliospheric magnetic field and the solar wind. Coronal mass ejections are explosive event in the solar corona that spread out solar mass in to interplanetary medium. Coronal mass ejections (CME) were first discovered in the seventies. However, the interplanetary CME (ICME) had been observed prior to this, but was thought to consist of flare ejecta, a misconception that prevailed for some time after CMEs were first observed\textsuperscript{1}. The detailed connection between ICMEs and CMEs; and the role of solar flares in this connection are still not well understood. CMEs interact with the solar wind and the interplanetary magnetic field (IMF) and as a consequence, slow CMEs are accelerated towards the speed of the solar wind and fast CMEs are decelerated towards the speed of the solar wind. Fast CMEs eventually results in a shock. This happens when the speed of the CME in the frame moving with the solar wind is faster than the local fast magnetosonic speed. The frequency of CMEs varies with the sunspot cycle. At solar minimum, about one CME a week was observed. Near solar maximum, an average of 2 to 3 CMEs per day were observed. Using Ulysses data, it was possible to study the high-latitude ICMEs and other transients, rarely seen at the solar minimum, and to investigate giant solar flares and solar energetic-particle events in three dimensions. The high latitude ICME may originate from simple single large solar source, and propagate out smoothly without any hindrance producing shocks with greater strength in magnitude and magnetic field\textsuperscript{2}. Measurements from Ulysses experiments have helped to answer some important questions regarding the latitude dependent solar wind speed change, outward pressure of the wind, cosmic ray modulation, magnetic field distribution, etc. Solar wind observation by Ulysses during its three orbits around the Sun revealed the fundamental changes between the two phases of the solar cycle.

The shocks in the interplanetary medium are, in general, associated with the corotating interaction regions (CIR) and ICMEs. Due to the solar rotation, a slow stream is overtaken by the high speed stream resulting in a shock pair with a forward shock at its leading edge and a reverse shock at the trailing edge. A combined study of the helios solar wind data and solar wind coronagraph observations revealed the nature of interplanetary shocks associated with
ICME$^{3,5}$. Riley et al.$^{6}$ have analyzed the radial trends of ICME events from 1.4 to 5.4 AU. In this study, the discontinuities in solar wind observed by Ulysses during its three orbits around the Sun during 1992 - 2006 have been examined. The distribution of jumps in solar wind plasma parameters, like wind velocity, IMF, and proton density in the heliolatitude range $\pm 80^\circ$ and radial distance range 1-5 AU have been studied.

2 Ulysses observation of ICME transients

Data from the Ulysses Mission experiments, viz.: (i) solar wind observation over poles (SWOOPS) and (ii) vector helio flux meter (VHM) have been used. Solar wind and magnetic field observations have been used for identification of ICME. The four minute data of solar wind plasma parameters have been used to identify the ICME discontinuities by evaluating the simultaneous jump in each plasma parameter. The simultaneous increase of solar wind speed, proton density, interplanetary magnetic field B, and variance of the coordinates $\Theta$ and $\Phi$ of IMF B have been used to the identify ICME$^{7}$. As the spacecraft moves around the Sun, its heliolatitude and radial distance keep on changing so that the solar events are recorded at different heliolatitudes, radial distances and timings. These observations provide an excellent opportunity to investigate the characteristics of ICME plasma discontinuity, the three dimensional distribution of the discontinuities, and evolution of their characteristics.

Figure 1 depicts the observation of an ICME event by Ulysses on 8 May 2001. Identification of ICME plasma is possible by looking for the presence of discontinuities in the plasma, as sudden and steep variation of plasma parameters. The turbulence within the ICME differs from the magnetic cloud of the solar wind that emerges from the corona. Figure 1 describes the solar wind velocity, proton density, temperature and radial IMF variations associated with two ICMEs on either side of a magnetic cloud.

The radial interplanetary magnetic field component initially oscillates with both the magnetic polarities and then settling down to one polarity, which may be due to the opening of the strong closed field. The opening of the closed field lines occur due to the
The destabilization of the coronal magnetic structure by eruption associated with the active region.

3 Features of solar wind plasma at the ICME

The Ulysses’ first orbit during 1992 - 1998, nearly coincided with the descending phase of the solar cycle 22, second orbit during 1998 - 2004 coincided with the ascending and maximum phases of the solar cycle 23 and the third orbit started during 2004 coincided with the descending phase of the solar cycle 23. So, Ulysses provides an opportunity to study the heliospheric distribution of solar wind plasma parameters during the entire period of the solar activity cycle 23.

CMEs typically travel faster than the background solar wind and when the CME attains a sufficiently high velocity, the leading edge of the CME may form a shock front where sudden discontinuous jumps in solar wind velocity, density, temperature and magnetic field strength are observed. Across each discontinuity associated with ICME, the difference in the solar wind velocity, interplanetary magnetic field, plasma temperature and solar wind proton density have been evaluated and defined as jump parameters. The discontinuities associated with each ICME observed by Ulysses during 1991-2006 have been identified and a list of 169 such discontinuities has been prepared. This data provide useful information about the solar wind plasma jump parameters across ICME during the three phases of Sun. Along with the plasma jump parameters, for each ICME event, the radial distance of the observation point and the associated heliolatitude have also been noted. Figure 2 presents the heliolatitude and radial distance distribution of ICME associated discontinuities along with the corresponding solar wind velocity and the solar wind jump speed.

![Graph](image-url)

**Fig. 2 — Solar wind velocity and solar wind jump associated with ICME**
velocity jump across the ICME discontinuity. It has been noticed that the discontinuities are distributed in the entire range of heliolatitudes around the maximum of solar cycle 23 during the second orbit of Ulysses.

In general, the solar wind velocity associated with the ICME follows the typical solar activity phase dependent variation with a maximum around the declining phase. Whereas, the solar wind jump across the ICME discontinuity follows the solar cycle evolution with peak values around the solar activity maximum. The heliolatitudinal variation of the velocity of ICME and the solar wind jump is clear from Fig. 2. Both the parameters show sharp variation around the heliospheric equator during the activity minimum and less prominent variation during the maximum of solar activity. Since the parameters associated with ICME depend strongly on the phase of the solar activity and heliospheric latitude, it is very difficult to separate out the dependence on the radial distance. The solar wind velocity peaks during both the descending phase of solar activity during the first and third orbit of Ulysses in addition to the solar maximum enhancement. The solar wind velocity jump enhancement is less prominent during both the descending phases compared to the solar maximum.

Figure 3 depicts the distribution of jumps in solar wind velocity, the proton density, plasma temperature and IMF magnitude across the ICME discontinuities along with the heliolatitude of observation point and its radial distance in AU during the Ulysses orbits 1 - 3. The x-axis denotes the chronological number of each discontinuity. The vertical dotted lines separate the regions of the three orbits of Ulysses. During the first orbit of Ulysses, most of the transient events are confined to the lower heliolatitudes and the variations in the magnitude solar wind jumps are smaller compared to that during the second orbit. During its second orbit, the transients observed correspond to the period of solar activity maximum. The nature of the distribution of events during this period is completely

Fig. 3 — Solar wind plasma parameters across the ICME discontinuities during three orbits of Ulysses
different from that during the minimum phase. During this period, the transient events are found in all heliolatitudes and the magnitude of the jump in solar wind velocity is larger. Ulysses observed transient events in the entire range of heliolatitudes with larger number of events in the northern heliolatitudes compared to the southern heliolatitudes. During the third orbit of Ulysses, the Sun was in the descending phase of its activity.

The variation of the heliolatitude in Fig. 3 describes the latitudinal distribution of ICME events in the heliosphere observed by Ulysses in three phases of solar activity. Similarly, the plot of the variation of radial distance in the figure denotes the variation of the distribution of ICME events with radial distance as observed by Ulysses. During the ascending and descending phases of solar activity, the ICME events are confined to lower heliolatitudes except for a very short duration. During the second orbit, Ulysses observed ICME events in the entire range of heliolatitudes. The magnitude of the velocity jump was larger during the active phase compared to other two phases. During the maximum phase of the solar cycle, the solar active regions with disordered magnetic fields destabilize loop structure to produce more numbers of shocks. The shocks in the higher latitudes have higher magnetic field intensity than in the equatorial region. The proton density across the ICME discontinuity is comparatively negligible during the ascending and descending phases compared to the maximum phase. Similar is the case with the IMF magnitude. The proton jumps also appear to show a weakening trend with increasing distance. During the maximum phase of solar activity, proton jumps show clear radial dependence probably due to the same strength of proton jumps that arise from the different active regions. Figure 3 shows the distribution of proton particle jumps during the minimum and maximum phase. In the minimum phase, the coronal transients are confined to lower latitudes and so the proton jumps are also confined to lower latitudes just like other parameters. During the solar maximum phase, higher latitudes have greater density proton jumps compared to lower latitude jumps. The possible reason for this is the angular size involved with the higher latitude CMEs. In a larger ICME, there could be substantial proton diffusion in the area to produce high density proton jumps. It has been observed that the IMF jumps, due to discontinuities, crowd together near the equatorial region. The IMF jumps vary from minimum value to maximum of about 10 nT, the variations are due to the observation made from different heliolatitudes and radial distances. In maximum phase, when the magnetic field dominates along the higher latitudes, the IMF jumps show substantial increase in magnetic energy than the jumps observed around equator. The ICME jumps associated with active regions have, on average, more than 20 times higher acceleration than those associated with quiet regions.

4 Discussion
CMEs evolve from regions of closed magnetic configuration. During the minimum phase, the magnetic closed structure exists only around the solar equator. It has been observed that the IMF jumps, due to discontinuities, crowd together near equatorial region. The IMF jumps vary in the range of about 10 nT from minimum to maximum value, the variations are due to the observation made from different heliolatitudes and radial distances. Ulysses recorded massive over expanding CMEs in higher latitudes. In the maximum phase of solar activity, when the magnetic field dominates along the higher latitudes, the IMF jumps show substantial increase in magnetic energy than the jumps observed around equator. The CME jumps associated with active regions have, on average, more than 20 times higher acceleration than those associated with quiet regions. A considerable amount of evidence suggests that CMEs or flares induce protons into the interplanetary medium. Magnetic flux injection in the corona is essential for the onset of CME. As such, the corona is not dense enough to hold the magnetic plasma of CME. Most of the CMEs eject out in to the interplanetary space with huge loop like magnetic field structure with field direction rotating while moving forward. Typically, the magnetic field is found to vary from north to south or variation within one polarity is observed in many CMEs. Bothmer & Schwenn found changes in interplanetary magnetic clouds with polarities in concordance with solar polarity of the hemisphere from which it evolves.

The radial dependence of ejection parameters of CMEs jump depend mainly on the strength, solar cycle and the spatial dependence. Since high latitude CMEs has significant latitudinal structure at any given instant of time the high latitude portion of CMEs extends far out in radial distance. Hence, the ejecta features of high latitude CMEs can be faster than low
latitude ones. The relative speed between the ejecta and ambient solar wind can have a substantial impact on the rate of expansion. Also, the expansion within the plasma maintains the plasma speed as the radial distance increases. The solar wind velocity peaks around the declining phase of solar activity cycle \(^1\), whereas the solar wind jumps are most prominent around the maximum of solar activity. During minimum phase, the velocity jumps are fewer as compared to the maximum phase of the solar cycle. The solar wind jump speed is almost invariant under radial distance. Interplanetary magnetic field radial component is considered to respond to the impulsive solar transients. Since the radial component of the IMF is expected to show appreciable variation even for small solar transients. The radial component of interplanetary magnetic field varies with one polarity or with both polarities depending on the origin of solar shocks. The magnitude of variations of interplanetary magnetic field B component has been plotted in Fig. 3. The IMF jump parameter shows a slow decreasing trend with increasing radial distance from the Sun. The decrease is maximum around 5 AU for two reasons, viz. due to the distance from the Sun; and weak strength and narrowness of the events in the region of the ecliptic plane in comparison to higher latitudes.

5 Conclusions

Ulysses observations of interplanetary plasma made during 1992-2006 have been used to identify the ICMEs and the jumps in plasma parameters across the ICME discontinuity. The velocity of the ICME and the solar wind jump parameters show a strong dependence on the solar activity cycle and on the heliographic latitude. The heliolatitudinal dependence of the velocity of ICME is very sharp around the solar minimum and less prominent around the maximum of solar activity. The jump in solar wind plasma parameters across the ICME discontinuity is most prominent around the solar maximum.

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References