Analysis of Deformation and Erosion during CME Evolution

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Abstract: Magnetised coronal mass ejections (CMEs) are quite substantially deformed during their journey form the Sun to the Earth. Moreover, the interaction of their internal magnetic field with the magnetic field of the ambient solar wind can cause deflection and erosion of their mass and magnetic flux. We here analyse axisymmetric (2.5D) MHD simulations of normal and inverse CME, i.e., with the opposite or same polarity as the background solar wind, and attempt to quantify the erosion and the different forces that operate on the CMEs during their evolution. By analysing the forces, it was found that an increase of the background wind density results in a stronger plasma pressure gradient in the sheath that decelerates the magnetic cloud more. This in turn leads to an increase of the magnetic pressure gradient between the centre of the magnetic cloud and the separatrix, causing a further deceleration. Regardless of polarity, the current sheet that forms in our model between the rear of the CME and the closed field lines of the helmet streamer, results in magnetic field lines being stripped from the magnetic cloud. It is also found that slow normal CMEs experience the same amount of erosion, regardless of the background wind density. Moreover, as the initial velocity increases, so does the influence of the wind density on the erosion. We found that increasing the CME speed leads to a higher overall erosion due to stronger magnetic reconnection. For inverse CMEs, field lines are not stripped away but added to the magnetic cloud, leading to about twice as much magnetic flux at 1 AU than normal CMEs with the same initial flux.

Keywords: magnetohydrodynamics (MHD); magnetic reconnection; Sun; coronal mass ejections (CMEs)

1. Introduction

Hosteaux et al. [1] performed CME simulations based on a simple high density-pressure blob model to investigate the evolution of ICMEs under different initial solar wind and different initial CME conditions. We here further analyse these simulations, focusing on the forces causing the observed deformations (which are depending on the CME polarity) and the magnetic erosion caused by the interaction of the internal magnetic field of the CMEs with the also magnetised ambient solar wind. The work of Hosteaux et al. [1] builds on the very much simplified MHD models used by [2–7]. This simple magnetised high density-pressure blob model completely ignores the CME onset and focuses on the evolution of the CME as it propagates through the solar wind. Indeed, in these simulations the CME initiation is not self-consistent and not in equilibrium. Hence, the CME evolution is unrealistic in the very beginning of the simulations, but it becomes realistic afterwards. It has the advantage over self-consistent but CPU demanding CME onset models, that it is much faster and thus enables fine-tuning of the input parameters. As a result, this simple model is very well capable of fitting the observational data at L1 [3,10]. In fact, the L1 data fitting obtained by these authors, exploiting the efficiency of the model and considering many parameter sets, is at least as good as that obtained by the more advanced models that involve a realistic initiation mechanism like, for instance, the Bastille Day event that was modelled by Török et al. [11].
In a space weather prediction context, however, the wall-clock time of the simulation is very important as ensemble simulations, involving many simulations using different parameter combinations, are used to take into account the uncertainty on the simulation parameters that are derived from observational data. As a result, the CPU time demanding CME triggering mechanism itself is often dropped form the simulation and the prediction model starts from a CME model that is superimposed on a steady background wind with a reasonable initial velocity. For instance, Manchester et al. [12], Lugaz et al. [13], Jin et al. [14] used the Gibson-Low flux rope model [15], a radial contraction of a spheromak, and inserted or superposed it on a background solar wind. Gibson and Low [15] provided expressions for the density $\rho$ and pressure $p$, and in order to balance the Lorentz force, regions with convex magnetic field have enhanced density, while regions with concave magnetic field show a density depletion. However, the formulae derived by Gibson & Low do not guarantee a positive density and pressure and numerical tricks are required to prevent negative values of these quantities. Therefore, Jacobs [16] triggered the CME by launching a modified Miller–Turner [17] solution in a (3D) stationary solar wind and imposing an additional density and radial velocity profile inside the flux rope. Yet, such 3D calculations are still CPU demanding and, as mentioned above, 2.5D (axisymmetric) simulations can yield very satisfactorily event data fittings too.

In the present paper we thus stick to the simplified axisymmetric simulations that artificially impose a magnetic flux-rope CME model on a steady background solar wind. More precisely, we further analyse the simulations already discussed by Hosteaux et al. [1]. In that paper, we made distinction between the effects of the background solar wind and those of the CME initiation parameters on the evolution of an ICME during its propagation from the Sun to Earth. There, the focus was on the influence of the surrounding background wind speed and density and the initial velocity and magnetic field polarity of the CME on the CME evolution. The kinematics of the leading CME shock front and the deformation of the magnetic cloud have been examined in detail. The analysis was based on high-resolution numerical experiments with the MPI-AMRVAC code [18] superposing magnetised plasma blob CMEs with different initial conditions on three steady bi-modal wind solutions with different densities, namely 4, 8 and 12 cm$^{-3}$ on the equatorial plane at 1 AU, respectively. The superposed CMEs had a higher pressure and density than the surrounding coronal plasma. Two different magnetic polarities (normal and inverse) were considered and initial velocities of 400 km/s, 800 km/s and 1200 km/s were used. It was found that the arrival time of the CME shock is shorter for lower density winds and higher initial CME velocities, and that inverse CMEs arrive up to 4.5 h sooner than normal CMEs. Moreover, normal CMEs initially accelerate more than inverse CMEs, but are overtaken again by inverse CMEs within ~25 R$_{\odot}$ [1]. CMEs with a higher initial velocity and/or in a higher density wind decelerate more.

Hosteaux et al. [1] found that inverse CMEs have a larger opening angle than normal CMEs, and that it is inversely proportional to the wind densities but proportional to the initial CME velocity. These differences are, among other reasons, due to the differences in the magnetic reconnection process. As a matter of fact, when the CME magnetic polarity is opposite from the background wind (normal CME), the reconnection occurs at the fronts, while for inverse CMEs with the same polarity as the surrounding wind, it occurs at the rear. Moreover, it was concluded that the background wind density has almost no effect on the $B_z$ component (apart from the arrival time) and only the normal CMEs had a strong negative $B_z$, i.e., can potentially cause geomagnetic storms. However, the inverse CMEs would become more geoeffective for an inverted solar dipole.

In the present paper, we continue and deepen the analysis to the simulation runs. In particular, we elaborate on the force analysis. Hosteaux et al. [1] considered the forces on the separatrix only. Here, we are widening the analysis to the entire computational domain, and we quantify the erosion of the CMEs as they propagate through the inner heliosphere disclosing substantial differences between normal and inverse CMEs.
2. Modelling Set-Up

The 2.5D MHD simulations that are analysed in the present paper are the same as those described in Hosteaux et al. [1], i.e., based on a very simple 'blob' CME model with radius 0.29 R⊙ and centred at 2.0 R⊙. This simple model ignores the initiation phase, but is taking into account the internal magnetic structure of the CME. The latter turns out to be key for the evolution (erosion, deformation) of the ICME and, therefore, for its arrival time and geoeffectivity. The simulations being performed on a 2.5D (axisymmetric) grid mean that the MHD equations are solved on a 2D mesh, so that the plasma quantities do not have any \( \phi \) dependence but all three vector components (radial distance \( r \), polar angle \( \theta \), and azimuthal angle \( \phi \) in spherical geometry) of the velocity and magnetic fields are included in the calculations. The blob density is determined such that the 2.5D CME evolves very similar to a 3D spheromak CME [19]. This yields a rather high CME–solar wind pressure ratio, and thus a very rapid CME expansion.

The centre of the CME was chosen to be at 2.0 R⊙ on the equatorial plane with its radius being 0.29 R⊙. The magnetic flux is chosen so that it connects smoothly to the background wind [3]:

\[
\psi = \psi_1 \left( d - \frac{d_{cme}}{2\pi} \sin \frac{2\pi d}{d_{cme}} \right). \tag{1}
\]

In this equation \( d_{cme} \) and \( d \) represent the radius of the blob and the distance to the centre of the blob, respectively. The polarity of the internal CME magnetic field depends on the sign of the constant \( \psi_1 \): \( \psi_1 < 0 \) yields an 'inverse' CME with the same polarity as the background coronal magnetic field, while \( \psi_1 > 0 \) yields a so-called normal CME with the opposite polarity as the background coronal magnetic field ([20]). The maximum magnetic field strength in the blob is initially 20 G. For a more detailed introduction to the model, the reader is referred to Sections 2 and 3 of Hosteaux et al. [1].

We here consider the same simulations as Hosteaux et al. [1] and analyse the forces at work and the CME erosion in much more detail. Three different background solar winds have been combined with three different initial CME velocities (400 km/s, 800 km/s and 1200 km/s) with both normal and inverse polarity. The background solar wind models all assume quiet solar conditions and start from a dipole magnetic field, but have different densities. The numerical domain for these simulations ranges from 1 to 216 R⊙ radially and from 0 to \( \pi \) radians in the latitudinal direction. A block-based solution adaptive mesh refinement scheme is applied using a density gradient threshold and starting from a base grid with \( 300 \times 220 \) logarithmically stretched cells. The mesh refinement is limited to 4 levels, i.e., 3 refinements, each doubling the resolution locally (in both spatial directions).

3. Detailed Analysis of ICME Evolution

The first analysis of the results of the simulations have been presented by Hosteaux et al. [1], where the focus was on the effect of the background wind density and the polarity of the internal CME magnetic field on the evolution of the CME morphology, deformation, speed and arrival times of the magnetic cloud and the CME driven shocks. The main findings have been mentioned in the introduction of the present paper.

3.1. Thorough Force Analysis

3.1.1. Initial Forces

Hosteaux et al. [1] only briefly touched upon the forces that are behind the CME cloud and shock deformations and those causing the acceleration and deceleration of the magnetic clouds. They determined the separatrix, the largest closed magnetic structure in the numerical domain, and defined the magnetic cloud of the simulated CME as the
volume inside it. The force analysis was limited to the forces along the separatrix for one snapshot and for a slow inverse CME only. The MHD momentum equation is given:

\[
\frac{d\mathbf{v}}{dt} = -\nabla P_p - \nabla \frac{|\mathbf{B}|^2}{2\mu_0} + \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0} + \rho \mathbf{g}.
\]  

(2)

The first term of the right-hand side (RHS) of the equation is the plasma pressure gradient, \(-\nabla P_p\). The next two RHS terms comprise the Lorentz force, which has been decomposed in the magnetic pressure gradient \(-\nabla \frac{|\mathbf{B}|^2}{2\mu_0}\) and the magnetic tension \(\frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0}\). The last RHS term corresponds to the gravity of the Sun and is negligible in comparison with the other terms, also due to the very low plasma density and high radial distance. The forces that govern the kinematics of a CME are shown in Figure 1 at the initiation of the CME, for both normal and inverse polarities. The initial plasma and magnetic pressure gradient force (\(\nabla P_p\) and \(\nabla P_B\), respectively) result in an extremely strong expansion. The magnetic tension \(T_B\) tries to constrain the expansion, but it is not nearly strong enough to do so. In the following analysis, these forces have been calculated over the whole computational domain every 30 min. Note that the evolution of the velocity profile was discussed by Hosteaux et al. [1] (Figures 10–11). The initial profiles are chosen to stabilise the simulation, assuring continuity at the CME border. After a very short evolution time the velocity distribution becomes more realistic.

Figure 1. Forces at \(t = 0\) h for a normal CME (upper row) and an inverse CME (lower row), both ejected with an initial velocity of 800 km/s in a medium density background wind. The black lines depict selected magnetic field lines in all figures. The magnetic field lines that are not part of the CME itself represent the coronal helmet streamer, which stretches around the CME for a normal polarity and behind it for an inverse polarity. The colour contours in the figures in the left column shows the logarithm of the number density, and the vector arrows depict the plasma pressure gradient force direction. The middle and right columns do the same, but for the magnetic field strength and the speed for the colour contours, respectively, and the magnetic pressure gradient force and the magnetic tension for the vectors, respectively.
3.1.2. Force Dynamics

The upper panels of Figures 2 and 3 show the magnitude and direction of the forces 5 h and 20 h after ejection, respectively. The shock is represented by a thin region of strong plasma pressure gradient directed away from the CME, and is not visible as a discontinuity in magnetic pressure gradient or magnetic tension. This means that latter forces are not as important at the shock. Plasma from the background wind has been swept up by the CME, resulting in it being piled up in the sheath and causing a high $\nabla P_p$ directed towards the separatrix. Here, the plasma pressure gradient is the dominant force as well. At low latitudes, the plasma pressure gradient vectors are directed towards the separatrix, meaning that the magnetic cloud is compressed from the front. At high latitudes the plasma pressure gradient diverts the plasma around the magnetic cloud. The total force has approximately the same direction as the plasma pressure gradient because the other forces are much smaller in the sheath. The high plasma pressure gradient in the sheath decelerates the plasma at the front of the CME while the CME centre is not affected, resulting in strong compression of plasma between the centre of the magnetic cloud and the separatrix. As a result of this compression, the plasma pressure and the magnetic field strength strongly increase. This results in very strong plasma pressure gradient and magnetic pressure gradient forces between the separatrix and the centre of the CME. The magnetic pressure gradient is the dominant force in this region, resulting in a total force vectors being directed towards the centre of the magnetic cloud. In the rear part of the CME, all forces are directed towards the front, with $\nabla P_B$ being the strongest. As the forces are directed oppositely between the front and the rear (both are directed towards the centre), the separatrix loses its original circular shape and becomes “pancacked”. The bottom panels of Figures 2 and 3 show a cross-section of the forces along the equatorial plane. The shock is represented as a sharp $\nabla P_p$ peak, followed by a negative $\nabla P_p$ force in the sheath (~33 R_⊙ in Figure 2 and ~100 R_⊙ in Figure 3), pushing the plasma in the sheath towards the magnetic cloud. At the separatrix, the plasma pressure gradient and the magnetic pressure gradient are both extremely strong and oppositely directed, and since $\nabla P_B$ is larger the net force is positive. In the region between the centre of the magnetic cloud and the separatrix, the gradient forces are again oppositely directed, but both are flipped compared to at the separatrix. $\nabla P_B$ is again the dominant force, resulting in negative net force. In the tail of the CME another peak can be seen, at ~12.5 R_⊙ and ~60 R_⊙ for Figure 2 and Figure 3, respectively. This is an artefact for the high density/pressure blob model. Superimposing the CME in such an abrupt way results in plasma waves reflecting with the boundary and propagating through the tail of the CME. In a model where the initiation of the eruption is included, these artefacts would not be present. Figure 2 also shows that the plasma pressure is dominant at the CME shock, but in the centre of the cloud the magnetic pressure is dominant.
Figure 2. Upper: Forces that govern the CME dynamics five hours after ejection of a normal medium velocity CME in a middle density background wind. Each plot is split into the upper and lower half of the CME showing a different force, with the colour contours representing the magnitude of the force and the vectors the direction. For clarity, colour bars have been flipped between upper and lower panels. The left figure shows $\nabla P_p$ and $\nabla P_B$ in the upper and lower half, respectively. The right figure shows $T_B$ and the resultant force in the upper and lower half, respectively. Lower: Radial cut in the equatorial plane. The red, blue and green dotted vertical lines represent the positions of the shock, magnetic cloud boundaries and magnetic cloud centre, respectively.
Figure 3. Same as Figure 2 but 20 h after ejection.

3.1.3. Influence of the Initial Wind Density

This paragraph discusses the influence of the initial wind density on the forces that act upon the CME. Figures 4 and 5 show the forces 20 h after initiation for a normal CME ejected with a medium velocity in a low and high density background wind, respectively. We will analyse the forces starting at the shock and going towards the centre of the magnetic cloud. As was also seen in Figures 2 and 3, the shock is visible as a very thin strong \( \nabla P_p \) region over the whole length of the CME (at \( x \approx 110 \, R_{\odot} \) and \( x \approx 95 \, R_{\odot} \) for the low and high density wind, respectively). \( \nabla P_B \) and \( T_B \) are of significantly lower magnitude than \( \nabla P_p \). Farther away from the Sun, to the right of the shock in the figure, \( \nabla P_p \) and \( \nabla P_B \) are directed outwards, while \( T_B \) is of opposite direction, but all of them are several orders of magnitude lower than the magnitude of \( \nabla P_p \) in the shock. In the sheath, between the shock and the separatrix of the magnetic cloud, \( \nabla P_p \) is still the dominant force, and significantly
higher compared to the other side of the shock. Comparing the forces in sheath between the two background winds, the plasma pressure gradient is much higher in the high density wind. As the CME propagates through the background wind, it sweeps up the plasma in front of it. As there is more plasma to sweep up in the high density wind, the density and pressure in the sheath increases more, leading to higher pressure gradients. Thus, a higher density wind results in stronger plasma pressure gradient forces compressing the front of the magnetic cloud. This is especially true at higher latitudes, resulting in the flanks of the CME being more pulled backwards for the CME in the high density wind. Going closer towards the separatrix, the magnetic pressure gradient becomes more important. The separatrix itself is visible as a thin red region in front of the large closed magnetic field line of the magnetic cloud. In this region, the gradient forces are very strong as the separatrix represents a discontinuity between the magnetic cloud and the surrounding wind. Following the separatrix, in the region between the separatrix and the centre of the magnetic cloud, another region of strong gradient forces is present which is directed towards the centre of the magnetic cloud. For both background winds, the magnetic pressure gradient becomes the dominant force due to the extreme compression of magnetic field lines between the centre of the magnetic cloud and the separatrix. Both $\nabla P_p$ and $\nabla P_B$ are higher in this region for the high density wind due to the stronger compression coming from the sheath. The compression of plasma between the centre of the magnetic cloud and the separatrix is thus caused by a deceleration of the front of the cloud while the rest of the magnetic cloud keeps propagating at approximately the same velocity. Figure 6 shows the radial cross section in the equatorial plane of the forces for the same simulations as in Figures 4 and 5 at the same time (20 h after ejection). The same structures as the force in the equatorial plane in Figure 3 for a middle density wind can be distinguished, though they differ greatly in position and magnitude for the different winds. The high density wind has a higher $\nabla P_p$ force in the sheath acting upon the separatrix, resulting in a stronger deceleration and compression of the front part of the magnetic cloud. This stronger compression can be seen as a higher $\nabla P_B$ magnitude between the magnetic cloud centre and the separatrix.

Figure 7 shows the cross-section of the forces in the equatorial plane for a normal and an inverse CME ejected in a middle density background wind with a medium initial velocity 20 h after ejection. As was shown in previous sections, the normal CME lags a bit behind the inverse CME. The $\nabla P_B$ peak at the shock is of approximately the same magnitude. The same can be said about the sheath, where the difference in $\nabla P_B$ is barely noticeable. Both simulations show the separatrix as a positive peak in $\nabla P_B$ and a negative peak in $\nabla P_p$, with the magnitude of $\nabla P_B$ being considerably larger. The first noteworthy difference between the two cases is between the centre of the magnetic cloud and the separatrix. Magnetic reconnection processes at the front strip away field lines for normal CMEs, decreasing the distance between the separatrix and the centre of the magnetic cloud. The shorter distance implies that plasma is more compressed in this region for normal CMEs, leading to stronger gradient forces for normal CMEs. This can be seen in both the $\nabla P_p$ and $\nabla P_B$ cross-sections, between the diamond and the downward triangle. This might be the cause of the stronger dimple at the separatrix for normal CMEs. At the rear of the magnetic cloud, inverse CMEs form a current sheet with the accompanying instabilities. This results in much stronger $\nabla P_B$ and $\nabla P_p$ forces in the tail of an inverse CME.

Note that, even though no physical resistivity is present in the equations that we are solving, numerical resistivity will allow for magnetic reconnection in the simulations. The numerical resolution affects the numerical resistivity, but we try to keep it as low as possible by using adaptive mesh refinement.

3.2. Erosion
3.2.1. Mass Erosion

In spite of the fact that we here consider only axisymmetric (2.5D) simulations, we do an attempt to quantify the erosion of the CMEs. The mass obtained here, however, is at
least an order of magnitude higher than observations or 3D simulations predict. The mass of the CME in 2.5D is large because the CME is actually donut shaped all around the Sun due to the axisymmetric geometry of the simulation. The density of the CME is chosen so that the evolution of the expansion is similar to a 3D CME, as shown in Jacobs et al. [19]. The high density is thus the result of the CME in 2.5D being much larger in the longitudinal direction than a 3D CME.

![Figure 4](image)

**Figure 4.** Forces that act upon a normal CME ejected in a low density background wind with a medium initial velocity 20 h after initiation. Colour Contours represent the magnitude of the force and the vectors represent the direction of the force. Upper left: Plasma pressure gradient. Upper right: Magnetic tension. Lower left: Magnetic pressure gradient. Lower right: Total force.

By integrating the density inside the volume of the separatrix every 30 min, we can determine the temporal evolution of the mass of the magnetic cloud. The evolution of the mass for a normal and an inverse CME is shown in Figure 8. Both CMEs show a significant mass increase in their initial evolution phase, which is consistent with observations [21,22]. Because in these simulations we impose a plasma blob of high density inside the equatorial helmet streamer, part of the magnetic flux of the helmet streamer is added to the initial magnetic flux of the magnetic cloud through magnetic reconnection. This effectively increases the size and mass of the magnetic cloud. Other factors that can lead to an increase in mass are mass pile-up from the solar wind or mass supply by outflow from the low corona. We can also see that, for an inverse CME, the mass of the magnetic cloud is significantly higher than that of a normal CME with the same initial velocity and ejected in the same background wind. This is because of the different magnetic reconnection regions between inverse and normal CME. Magnetic reconnection at the rear enables for more magnetic flux to be added to the magnetic cloud. We can notice this in the detail shown in Figure 9. Both panels of this figure show a snapshot of CMEs ejected in identical
conditions, only their polarity differs. The upper panel shows that the tail of a normal CME has propagated substantially after 13 h, with the rear end of the separatrix at approximately 10 Rs, and a smaller structure has been formed when the helmet streamer relaxed back to its initial state. The lower panel on the other hand, shows that the rear end of the separatrix of an inverse CME appears to still be located very close to its initiation location, at approximately 4 Rs. This is because it is continuously reconnecting with the surrounding magnetic field lines, adding flux to the magnetic cloud and keeping the separatrix at a location close to the solar surface while the front keeps propagating forward. A similar process occurs for a normal CME but at the front of the separatrix.

Figure 5. Forces that act upon a normal CME ejected in a high density background wind with a medium initial velocity 20 h after initiation. Colours contours represent the magnitude of the force and the vectors represent the direction of the force. Upper left: Plasma pressure gradient. Upper right: Magnetic tension. Lower left: Magnetic pressure gradient. Lower right: Total force.
Figure 6. Forces in the equatorial plane at \( t = 20 \) h for a medium velocity normal CME ejected in low and high density background winds. Upper left panel: \( \nabla P \). Upper right panel: \( \nabla P_B \). Lower left panel: \( T_B \). Lower right panel: \( F_{\text{tot}} \). Locations of the shock, magnetic cloud edges and magnetic cloud centre are represented by circles, triangles and diamonds, respectively.

Figure 7. Forces in the equatorial plane at \( t = 20 \) h for a two CMEs ejected with a medium initial velocity in a middle density background wind but with a different polarity. Upper left panel: \( \nabla P \). Upper right panel: \( \nabla P_B \). Lower left panel: \( T_B \). Lower right panel: \( F_{\text{tot}} \). Locations of the shock, magnetic cloud edges and magnetic cloud centre are represented by circles, triangles and diamonds, respectively.
other possible reasons for the mass of inverse CMEs being higher are: larger volume of the magnetic cloud of inverse CMEs, small magnetic/density structures formed in the tail merge with the magnetic cloud and reconnection taking place in the tail opens up the field lines and allow mass outflow from the solar surface to enter the magnetic cloud. After approximately 18 h, the CME has left the helmet streamer and starts interacting with a different magnetic field. Then the mass starts to decrease again due to magnetic reconnection now not adding field lines to the magnetic cloud, but in fact stripping them away. This erodes the cloud and thus lowers its mass. This erosion effect is stronger when the reconnection region is at the front of the CME, making the mass decrease more severe for normal polarities. Due to the axisymmetric nature of our simulations, the mass
displayed in Figure 8 is at least an order of magnitude higher than observations or 3D simulations predict.

3.2.2. Magnetic Flux Erosion

The amount of magnetic field inside the separatrix can be quantified by the poloidal magnetic flux, which in our simulations can be determined by integrating $B_z$ from the centre of the magnetic cloud to the front edge of the separatrix or from the centre to the rear edge. Since the separatrix is a closed magnetic structure, the magnetic flux going through the surface between the centre and the front has the same value than that going through the surface between the rear and the centre but of opposite sign. It is sufficient to take the integral of just $B_z$ in the equatorial plane since this direction is normal to the equatorial plane. The upper panels of Figure 10 show the value of $B_z$ in the equatorial plane for a normal and an inverse CME ejected in a middle density wind with a medium initial velocity. The magnetic field is much more compressed between the front and the centre, seen by the thinner and stronger peak in between the centre and front vertical line compared to the peak between the centre and rear vertical line, but the total amount of magnetic flux is the same. This can also be seen in the lower panels of Figure 10, where the magnetic flux is plotted for a medium velocity CME in a middle density wind with both a normal and inverse polarity. The curves representing the magnetic flux at the front are close to the mirror image of those representing the magnetic flux at the rear, making the sum of both zero at all times. At the right end of the plot (at approximately 50 h) the magnetic fluxes seem to go to zero because the magnetic cloud is leaving the grid. The magnetic flux calculated at this time step is not the total magnetic flux inside the separatrix but the magnetic flux inside the largest closed magnetic field line that is still inside the computational grid, and thus somewhere inside the magnetic cloud but smaller than the separatrix. Figure 11 shows the evolution of the magnetic flux for all simulations. In the left panel it can be seen that normal CMEs lose magnetic flux from the moment the CME is ejected. For slow CMEs, the erosion is very strong in the first ~15 R⊙ of their propagation, after which the magnetic flux becomes approximately stable at about $2 \times 10^8 \text{ Tm}^2$. This strong decrease in magnetic flux in the beginning is a result of the nature of the blob simulation, as it causes the CME to expand in all directions. This leads to magnetic reconnection between the magnetic cloud and the helmet streamer. Thus, initially magnetic field lines are stripped due to a current sheet at the front of the CME, where magnetic reconnection occurs with the solar wind, and a current sheet at the rear where there is magnetic reconnection with the helmet streamer. As the CME propagates away, the latter current sheet dissolves and the erosion effect ceases. As slow CMEs spend more time close to the Sun and their expansion towards it is similar because their initial pressure is the same, the amount of erosion is higher for slow CMEs at the beginning. Different background wind densities seem to have little effect on the erosion for slow normal CMEs. Medium and high velocity normal CMEs differ from slow normal CMEs, in that these CMEs do not always experience such a strong flux decrease in the beginning of their evolution and then remain approximately constant, but rather have a slower but steady loss of magnetic flux throughout the entire simulation. There are cases, like the medium velocity CME in a low density wind, that show both a sharp initial decrease in magnetic flux and a slow steady decrease afterwards, signifying a steady rate of erosion after a period of high magnetic reconnection rate immediately after ejection. Increasing the initial velocity leads to a lower magnetic flux measured at the moment the separatrix leaves the numerical domain. Similarly to slow normal CMEs, slow inverse CMEs experience a loss in magnetic flux from their initiation up until approximately 15 R⊙, after which magnetic flux is added to the magnetic cloud. Medium and high velocity CMEs do not lose magnetic flux immediately after initiation, but stay approximately constant until they start to gain magnetic flux as well after ~25 R⊙. Since inverse CMEs gain magnetic flux for most of their propagation while normal CMEs lose magnetic flux, inverse CMEs have a much higher magnetic flux than their normal counterpart. The magnetic flux evolution
of the inverse CME simulations also have a lower spread. At the end of the simulations, normal CME magnetic fluxes fall between 0.6 and 1.0 Tm², while inverse CMEs are over double these values, namely between 2.0 and 2.4 Tm². Ruffenach et al. [23] performed an investigation of the magnetic erosion of CMEs using multi-spacecraft observations. They estimated the azimuthal magnetic flux erosion resulted in a magnetic flux decrease of 44% and 49% of the total initial as the CME propagated to the ACE and STEREO-A spacecrafts, respectively. In comparison, the normal CMEs in our simulations experience a loss of approximately 30–40%.

Figure 10. Upper panels: $B_z$ along the equatorial plane for a normal (left) and an inverse (right) CME ejected in a middle density wind with a medium initial velocity 25 h after initiation. The first and last vertical line represent the front and rear edge of the separatrix while the central vertical line represents the centre of the magnetic cloud. Bottom panels show the total magnetic flux in the front part (dashed), rear part (dotted), and the sum of both (solid).

Figure 11. Magnetic flux evolution of magnetic cloud for a normal CME (left) and an inverse CME (right). The x-axis represents the location of the centre of the magnetic cloud.

3.3. Effect of Adaptive Mesh Refinement (AMR)

In this section, we will discuss the effect of the AMR-scheme on the overall evolution of the CMEs. Increasing the resolution results in sharper gradients and different reconnection rates since the numerical resistivity is dependent on the grid. To study the effect of increasing the resolution in regions of interest (following the CME using a density gradient threshold), the simulation of the medium velocity CME in the middle density background
wind was repeated for both a normal and an inverse polarity, but without applying the grid-refining algorithm, thus only leaving the base grid of 300 × 220 cells. Figure 12 shows a comparison between the simulation where AMR is applied versus where it is omitted. The density structures are clearly more refined in the higher resolution case. With high resolution, the normal CME displays a small dimpled region at the front and has several small high density formations that are formed by magnetic reconnection. The low resolution case shows a much larger dimple at the front, and no small scale structures. At the time of the snapshot, the high resolution case has almost formed closed magnetic structures at the flanks [1], while for the lower resolution simulation these are much less pronounced. For the inverse case the difference in magnetic structure is not as severe, since there is no magnetic reconnection at the front but at the back so the effect will be more developed in the tail. Figure 13 shows a cross section of the number density in the equatorial plane. While the shock for both the normal and the inverse CME is visible as a sharp jump when AMR is applied, the transition between solar wind and ICME sheath is much smoother for lower resolutions. The density dip at the edge between the ICME sheath and the magnetic cloud is not resolved for the low resolution simulations, and the following peak is much weaker. For inverse CMEs without AMR, the density depression that follows the peak at the front of the separatrix dissipates between the time after ejection of the upper panel (25.5 h) and that of the lower panel (44.5 h). Figure 14 shows $B_z$. While the $B_z$-peaks with and without AMR are located at roughly the same location, the magnitude is much higher for high resolution simulations, especially for normal CMEs. If the interest is in the geoeffectiveness of the CME, $B_z$ is of particular importance.

Figure 12. Top row shows logarithmic number density for normal and inverse CMEs. The first panel shows a normal CME ejected in a middle density background wind with 4 levels of refinement, while the second panel shows the same normal CME but now no AMR was applied. The third and fourth panel show the same, but for an inverse CME. White lines represent selected magnetic field lines. The bottom row shows the grid of the same simulation at the same time step as the figure above it. All plots are made at 12.5 h after ejection.
Figure 13. Logarithmic number density for normal and inverse CMEs for a cross section in the equatorial plane 25.5 h (left) and 44.5 h (right) after ejection. Magenta and blue lines represent normal and inverse CMEs, respectively, while full and dashed lines represent with and without AMR, respectively. The location of the shock is represented by green dots, the edge of the magnetic cloud by green triangles and the centre by green diamonds. The edges of these markers have the same colour as the curve on which they are located.

Figure 14. Same as Figure 13 but showing $B_z$ instead of the density.

Figure 15 shows a comparison of some CME propagation properties. In the upper left panel, it can be seen that the stand-off distance is much lower for the higher resolution normal simulations compared to the low resolution simulation. The high resolution normal CME forms a thin current sheet between the magnetic cloud and the solar wind with small magnetic islands due to tearing instabilities. The low resolution normal CME shows no magnetic islands since the resolution is not fine enough for such instabilities to take place, but it has a much stronger dent inwards at the nose where the equatorial high-density current sheet pushes into the CME as can be seen in the second panel of the top row of Figure 12. This results in the front of the CME being at a lower radial distance than the high resolution CME at the same time step, while the location of the shock is approximately the same, as seen in Figure 13. This leads to a larger stand-off distance for low resolution normal CMEs. The effect is much less pronounced for inverse CMEs because reconnection now occurs in the rear. Due to the nature of the logarithmically stretched grid, the size of the grid cells increases with the distance from the Sun. For this reason, the resolution is much better at the rear of the CME (especially for inverse CMEs due to their elongated tail) than the front (even without AMR). The same reasoning can be applied to the magnetic cloud length (upper right panel of Figure 15), where the length for the inverse CMEs approximately the same while the low resolution normal CME is much shorter than the high resolution case. The rear of the magnetic cloud is similar for both simulations while the front is farther when AMR is applied. Figure 12 shows field lines that are still connected to the solar surface and surround the CMEs with normal polarity. These form much thinner structures in the high resolution case, pinching off the two closed magnetic structures at the top and bottom of the normal CME. This results in a lower opening angle of the separatrix in the low resolution case. The opening angle for the inverse CMEs in approximately the same.
Figure 15. Properties of normal and inverse CMEs ejected in a middle density wind with a medium initial velocity. Magenta and blue lines represent normal and inverse CMEs, respectively, while full and dashed lines represent simulations with and without AMR, respectively.

4. Conclusions

We revisited the high density-pressure blob CME simulations of Hosteaux et al. [1] who investigated the evolution of ICMEs under different initial solar wind and different initial CME conditions. We performed a deeper analysis of these simulations, focusing on the effect of the normal-inverse CME polarity on the forces causing the observed deformations and the mass and magnetic erosion caused by the interaction of the internal magnetic field of the CMEs with the also magnetised ambient solar wind. Hosteaux et al. [1] considered a simple magnetised high density-pressure blob CME model that completely ignores the CME onset, focusing on the evolution of the CME as it propagates through the solar wind. A distinction was made between the effects of the background solar wind and those of the CME initiation parameters on the evolution of an ICME during its propagation from the Sun to Earth.

The analysis in the present paper is thus based on high-resolution numerical experiments with the MPI-AMRVAC code [18] superposing magnetised plasma blob CMEs with different initial conditions on three steady bi-modal wind solutions with different densities, namely 4, 8 and 12 cm$^{-3}$ on the equatorial plane at 1 AU, respectively. The superposed CMEs had a higher pressure and density than the surrounding coronal plasma and we considered two different magnetic polarities (normal and inverse) and three different initial velocities, viz. 400 km/s, 800 km/s and 1200 km/s.

By analysing the forces over the whole grid, it was found that as the background wind density increases, the magnetic cloud is decelerated more by a stronger plasma pressure gradient in the sheath. This lead to more compression of plasma between the centre of the magnetic cloud and the separatrix. More compression results in a stronger magnetic pressure gradient in this region, which is the dominant force in the separatrix and causes further deceleration. At higher latitudes, the plasma pressure gradient in the sheath diverts the plasma around the magnetic cloud. If this force in the sheath increases in strength due to a higher background wind density, the flanks of the magnetic cloud are pushed backwards.
By integrating the magnetic field inside the separatrix, we were able to quantify the erosion of the magnetic clouds. Regardless of polarity, as an effect of our model the CMEs form a current sheet between their rear and the *helmet streamer*, resulting in magnetic field lines being stripped from the magnetic cloud. This effect is stronger for slower CMEs. For normal CMEs, the erosion at this stage is a result of this current sheet and the one at the front between the magnetic cloud and the solar wind. Slow normal CMEs experienced the same amount erosion, regardless of the background wind density. As the initial velocity increases, so does the influence of the wind density. At 1 AU, slower CMEs have a higher magnetic flux. This means that although their travel time is higher, thus they spend more time reconnecting with the solar wind, increasing the CME speed leads to a higher overall erosion due to stronger magnetic reconnection. For inverse CMEs, as the CME moves away from the Sun the current sheet between the magnetic cloud and the *helmet streamer* shifts to being located between the rear of the magnetic cloud and the solar wind. Field lines are now not stripped away but added to the magnetic cloud, leading to the magnetic flux approximately twice that of normal CMEs at 1 AU.

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**References**

1. Hosteaux, S.; Chané, E.; Poedts, S. Effect of the solar wind density on the evolution of normal and inverse coronal mass ejections. *Astron. Astrophys.* 2019, 632, A89. [CrossRef]
2. Chané, E.; Jacobs, C.; van der Holst, B.; Poedts, S.; Kimpe, D. On the effect of the initial magnetic polarity and of the background wind on the evolution of CME shocks. *Astron. Astrophys.* 2005, 432, 331–339. [CrossRef]
3. Chané, E.; van der Holst, B.; Jacobs, C.; Poedts, S.; Kimpe, D. Inverse and normal coronal mass ejections: Evolution up to 1 AU. *Astron. Astrophys.* 2006, 447, 727–733. [CrossRef]
4. Chané, E.; Poedts, S.; van der Holst, B. On the combination of ACE data with numerical simulations to determine the initial characteristics of a CME. *Astron. Astrophys.* 2008, 492, L29–L32. [CrossRef]
5. Jacobs, C.; Poedts, S.; Van der Holst, B.; Chané, E. On the effect of the background wind on the evolution of interplanetary shock waves. *Astron. Astrophys.* 2005, 430, 1099–1107. [CrossRef]
6. Savani, N.P.; Shiota, D.; Kusano, K.; Vourlidas, A.; Lugaz, N. A Study of the Heliocentric Dependence of Shock Standoff Distance and Geometry using 2.5D Magnetohydrodynamic Simulations of Coronal Mass Ejection Driven Shock Waves. *Astrophys. J.* 2012, 759, 103. [CrossRef]
7. van der Holst, B.; Poedts, S.; Chané, E.; Jacobs, C.; Dubey, G.; Kimpe, D. Modelling of Solar Wind, CME Initiation and CME Propagation. *Space Sci. Rev.* 2005, 121, 91–104. [CrossRef]
8. Mikic, Z.; Linker, J.A. Disruption of coronal magnetic field arcades. *Astrophys. J.* 1994, 430, 898–912. [CrossRef]
9. Hosteaux, S.; Chané, E.; Decraemer, B.; Talpauur, D.C.; Poedts, S. Ultrahigh-resolution model of a breakout CME embedded in the solar wind. *Astron. Astrophys.* 2018, 620, A57. [CrossRef]
10. Chané, E.; Poedts, S.; van der Holst, B. CME modeling: The a posteriori approach. In *The Dynamic Sun: Challenges for Theory and Observations, Proceedings of the ESPM-11, Leuven, Belgium, 11–16 September 2005*; ESA SP-60; Danesy, D., Poedts, S., De Groof, A., Andries, J., Eds.; ESA: Leuven, Belgium, 2005; ISBN 92-9092-911-1.
11. Török, T.; Downs, C.; Linker, J.A.; Lionello, R.; Titov, V.S.; Mikić, Z.; Riley, P.; Caplan, R.M.; Wijaya, J. Sun-to-Earth MHD Simulation of the 2000 July 14 “Bastille Day” Eruption. *Astrophys. J.* 2018, 856, 75. [CrossRef] [PubMed]

12. Manchester, W.B.; Gombosi, T.I.; Roussev, I.; Ridley, A.; de Zeeuw, D.L.; Sokolov, I.V.; Powell, K.G.; Tóth, G. Modeling a space weather event from the Sun to the Earth: CME generation and interplanetary propagation. *J. Geophys. Res. Space Phys.* 2004, 109, A02107. [CrossRef]

13. Lugaz, N.; Manchester, W.B.I.; Gombosi, T.I. Numerical Simulation of the Interaction of Two Coronal Mass Ejections from Sun to Earth. *Astrophys. J.* 2005, 634, 651–662. [CrossRef]

14. Jin, M.; Manchester, W.B.; van der Holst, B.; Sokolov, I.; Tóth, G.; Mullinix, R.E.; Taktakishvili, A.; Chulaki, A.; Gombosi, T.I. Data-constrained Coronal Mass Ejections in a Global Magnetohydrodynamics Model. *Astrophys. J.* 2017, 834, 173. [CrossRef]

15. Gibson, S.E.; Low, B.C. A Time-Dependent Three-Dimensional Magnetohydrodynamics Model of the Coronal Mass Ejection. *Astrophys. J.* 1998, 493, 460–473. [CrossRef]

16. Jacobs, C. Magnetohydrodynamic Modelling of the Solar Wind and Coronal Mass Ejections. Ph.D. Thesis, KULeuven, Leuven, Belgium, 2007.

17. Miller, G.; Turner, L. Force free equilibria in toroidal geometry. *Phys. Fluids* 1981, 24, 363–365. [CrossRef]

18. Xia, C.; Teunissen, J.; El Mellah, I.; Chané, E.; Keppens, R. MPI-AMRVAC 2.0 for Solar and Astrophysical Applications. *Astrophys. J.* 2018, 234, 30. [CrossRef]

19. Jacobs, C.; van der Holst, B.; Poedts, S. Comparison between 2.5D and 3D simulations of coronal mass ejections. *Astron. Astrophys.* 2007, 470, 359–365. [CrossRef]

20. Low, B.C.; Zhang, M. The Hydromagnetic Origin of the Two Dynamical Types of Solar Coronal Mass Ejections. *Astrophys. J.* 2002, 564, L53–L56. [CrossRef]

21. Feng, L.; Wang, Y.; Shen, F.; Shen, C.; Inoue, B.; Lu, L.; Gan, W. Why Does the Apparent Mass of a Coronal Mass Ejection Increase? *Astrophys. J.* 2015, 812, 70. [CrossRef]

22. Colaninno, R.C.; Vourlidas, A. First Determination of the True Mass of Coronal Mass Ejections: A Novel Approach to Using the Twostereoviewpoints. *Astrophys. J.* 2009, 698, 852–858. [CrossRef]

23. Ruffenach, A.; Lavraud, B.; Owens, M.J.; Sauvaud, J.A.; Savani, N.P.; Rouillard, A.P.; Démoulin, P.; Foullon, C.; Opitz, A.; Fedorov, A.; et al. Multispacecraft observation of magnetic cloud erosion by magnetic reconnection during propagation. *J. Geophys. Res. Space Phys.* 2012, 117, A09101. [CrossRef]