

*Using ghost fronts within STEREO
Heliospheric Imager data to infer the
evolution in longitudinal structure of a
coronal mass ejection*

Article

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1 **Using Ghost fronts within STEREO Heliospheric**
2 **Imager data to infer the evolution in longitudinal**
3 **structure of a Coronal Mass Ejection**

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12 **Key Points:**

- 13 • Multiple fronts observed in STEREO Heliospheric Imager data can be used to in-
14 fer the longitudinal structure of a CME
15 • Simple geometric models do not represent the physical evolution of a CME expand-
16 ing into a structured background solar wind

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17 **Abstract**

18 Images of coronal mass ejections (CMEs) from the Heliospheric Imager (HI) instru-
 19 ments on board the STEREO spacecraft frequently contain rich structure. Here, we present
 20 analysis of the Earth-directed CME launched on 12 December 2008 in which we interpret
 21 the revealed structure as projections of separate discrete sections of the physical bound-
 22 ary of the CME. By comparing the relative position of the outer and inner 'ghost' fronts
 23 seen in the STEREO HI1 cameras with the positions of features determined from three
 24 CME models we show that the two fronts seen in the images correspond to the expected
 25 position of the flank and nose of the CME where the background solar wind is uniform.
 26 In contrast, the flank of the CME observed expanding into a structured background solar
 27 wind results in the elongation between the two fronts being greater than expected.
 28 This is consistent with the CME flank distorting in the presence of a high-speed solar
 29 wind stream. Further work is required to consolidate these results. The presence of a
 30 shock for this event was ruled out by consideration of the low CME speed and by study-
 31 ing in-situ spacecraft data. The CME flank crossing the Thomson sphere was also ruled
 32 out as a cause of the ghost fronts. Ghost fronts could provide information about the lon-
 33 gitudinal shape of the CME independent of geometric models. This technique could sub-
 34 sequently be used to improve space weather forecast models through techniques such as
 35 data assimilation.

36 **1 Introduction**

37 The Heliospheric Imagers (Eyles et al., 2009) on board the twin STEREO space-
 38 craft (Kaiser, 2005) have returned remarkable images of interplanetary CMEs revealing
 39 detailed and often intricate structures within each eruption. During the first four years
 40 of the mission, the spacecraft were in a geometry that enabled the HI instruments to im-
 41 age Earth-directed transients from outside the Sun-Earth line. In principle, this view point
 42 enables the radial speed of CMEs to be estimated directly from the images rather than
 43 inferred from the expansion rate of a CME as viewed along the Sun-Earth line. Tech-
 44 niques developed for estimating the speed, v , and direction of transients relative to the
 45 observer, ϕ (N. R. Sheeley et al., 1999) were extended to the HIs (N. R. Sheeley Jr. &
 46 Rouillard, 2010; Rouillard et al., 2011). These 'fixed phi' techniques use the assumption
 47 that a CME is traveling at a constant speed and use the apparent acceleration within
 48 a sequence of images to infer a constant direction of CME propagation relative to the
 49 observer. This technique, which treats the transient as a single-point, was soon extended
 50 to account for the three-dimensional geometry of a CME. The Harmonic Mean method
 51 (Lugaz, Vourlidas, & Roussev, 2009) treats a CME as an expanding sphere with one limb
 52 anchored to the Sun (known as the Harmonic Mean fitting technique), while the Self-
 53 Similar-Expansion technique (Davies et al., 2012) assumes a spherical CME whose ra-
 54 dius changes as it expands from the Sun in such a way that it has a constant angular
 55 width. The Harmonic Mean and fixed-phi models are examples of the self-similar expan-
 56 sion model with the half width of the CME set to 90° and 0° respectively. In all these
 57 techniques, the apparent elongation angle of the CME from the Sun is estimated by tak-
 58 ing slices through the HI images (most often along the ecliptic) and stacking these to form
 59 a 'J-map' - a plot of image brightness as a function of elongation and time. On a J-map,
 60 a transient appears as a bright feature with a positive gradient. These features are then
 61 (usually manually) scaled and a two parameter fit in speed and direction is carried out.
 62 All these techniques make assumptions about the extent of a three-dimensional struc-
 63 ture from two-dimensional images. Recent work (Barnard et al., 2017) on a subset of Earth-
 64 directed CMEs, for which arrival times at Earth were available from in-situ observations
 65 at the L1 point, took initial values of CME speed, angular extent and propagation di-
 66 rection from coronagraph data and, using these, investigated the efficacy of these geo-
 67 metrical models in predicting the speed and time of a CME's arrival at Earth. Their work
 68 showed that, despite minimizing the uncertainties in all known variables, none of these

69 techniques were able to generate physically realistic and consistent predictions from both
 70 spacecraft within the expected uncertainties. They concluded that the assumptions about
 71 a symmetric CME geometry did not adequately describe the evolution of a CME. This
 72 is unsurprising. An interplanetary CME should not be considered as a coherent struc-
 73 ture since the longitudinal expansion rate of a CME quickly exceeds the Alfvén speed
 74 of the solar wind plasma, preventing information to be transmitted across a CME front
 75 (Owens et al., 2017). A more realistic physically constrained model of CME evolution
 76 (Owens et al., 2006) follows an initially circular flux rope CME as it becomes distorted
 77 in a constant solar wind flow. This Kinematically Distorting Flux Rope (KDFR) model
 78 was subsequently extended to consider CME distortions generated by a CME expand-
 79 ing into a non-uniform solar wind (Owens, 2006).

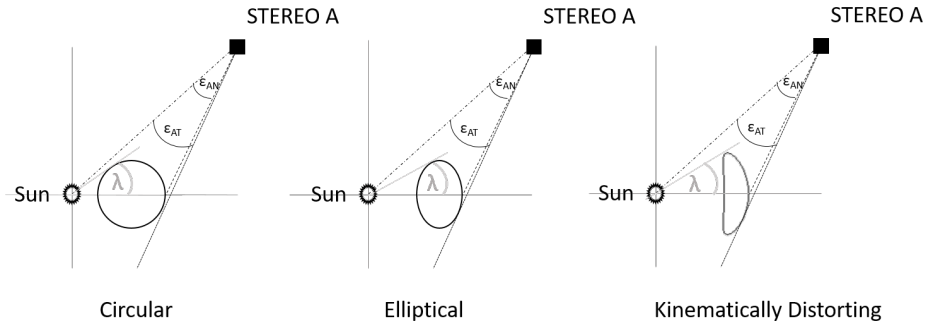
80 **2 Multiple Fronts in HI images**

81 One characteristic that seems to be extremely common among CMEs observed by
 82 the HI-1 cameras is the presence of a secondary ‘ghost’ front that is similar in shape to
 83 the observed outer edge of the event but separated by a few degrees in elongation. The
 84 intensities seen in each pixel of an HI image result from Thomson scattering of sunlight
 85 by electrons integrated along the line of sight. A bright feature within an image can there-
 86 fore be interpreted as a discrete, relatively dense region of solar wind plasma, contribu-
 87 tions from an extended region of plasma distributed along the line of sight, or a com-
 88 bination of the two. In any given line of sight, the weight given to a particular solar wind
 89 structure depends on its density and its distance from the Thomson Sphere. In a spheri-
 90 cally symmetrical solar wind plasma whose density decreases with distance from the Sun,
 91 this will correspond to the point closest to the Sun. For an observer at a distance from
 92 the Sun, this region of enhanced weighting describes a sphere whose diameter lies be-
 93 tween the observer and the Sun - known as the Thomson Sphere. It is conceivable there-
 94 fore that multiple enhanced returns may result from the same extended feature, both
 95 where the plasma density is enhanced at the front of the CME and where that structure
 96 crosses the Thomson sphere. Modelling work by Manchester IV et al. (2008) demonstrated
 97 such behaviour for a CME in synthetic HI-2 images. The Thomson Sphere is better called
 98 the Thomson Plateau, a broad region centered on the Thomson Sphere that is about 50–
 99 60° wide, where the scattered white light has approximately equal intensity (Howard,
 100 2011; Howard & DeForest, 2012). Alternatively, multiple fronts may result from the same
 101 extended feature corresponding to both the dense region of plasma accumulating at the
 102 leading edge, or ‘nose’, of a CME and the extended region of plasma along the flank of
 103 the CME corresponding to the tangent of the structure with respect to the observer (fig-
 104 ure 1). Some authors have interpreted the multiple fronts as a pile up of material cor-
 105 responding to the position of a shock ahead of the material being swept up by the mag-
 106 netic cloud within the CME (Pant et al., 2016). Lugaz et al. (2012) discuss the complex-
 107 ity of confidently associating features in HI images with different components of CME
 108 structure.

112 **3 The CME of 12 December 2008**

113 STEREO was launched into one of the deepest solar minima for a century (see, for
 114 example, the sunspot data at <http://sidc.be/silso/>) and so there were few Earth-
 115 directed events occurring during the early phase of the mission, with the spacecraft sep-
 116 arated from the Earth by an Earth-Sun-Spacecraft angle of 42 degrees. We note that
 117 this is similar to potential new operational space weather missions situated near the L5
 118 point.

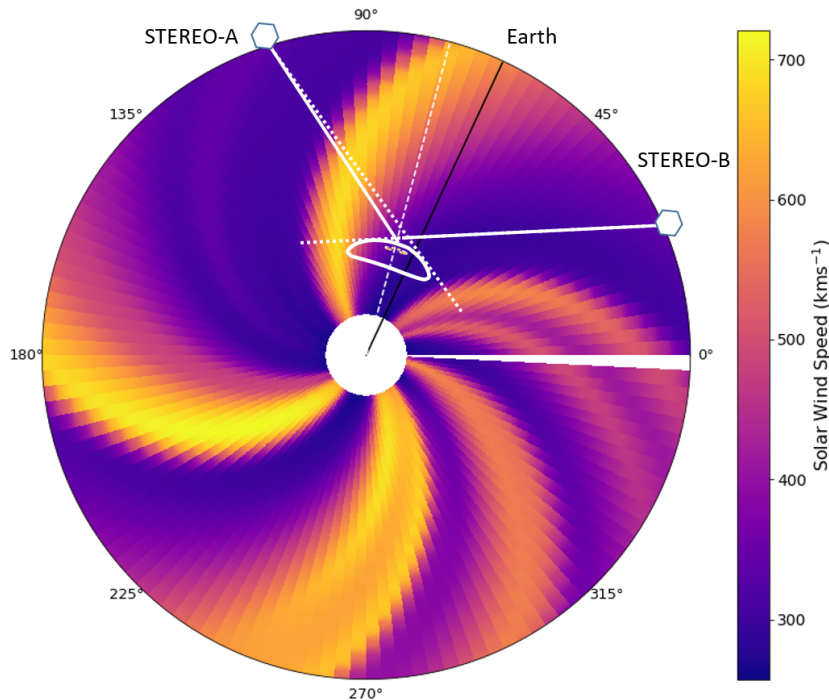
119 In the current paper, we consider the multiple ‘ghost’ fronts observed in HI images
 120 during the CME of 12 December 2008. This was the first Earth-directed CME to be tracked
 121 to Earth with the HI instruments on board both STEREO spacecraft and so has been



109 **Figure 1.** Three cartoons demonstrating the difference in elongation angle for the nose (ϵ_{AN})
 110 and tangent point (ϵ_{AT}) of a circular (left), elliptical (center) and Kinematically Distorted (right)
 111 CME. In each case, the CME is assumed to expand with a constant longitudinal half-width, λ

122 the subject of much analysis (Davis et al., 2009; Liu et al., 2010; Byrne et al., 2010). Davis
 123 et al. (2009) tracked three features observed in images from the HI instruments on both
 124 spacecraft. Adopting the techniques developed by N. R. Sheeley et al. (1999) and N. R. Shee-
 125 ley Jr. and Rouillard (2010), they tracked these features in time/height profiles (J-maps)
 126 independently for each spacecraft and showed that the arrival time of the first feature
 127 at Earth was consistent with a constant propagation speed of $411 \pm 23 \text{ km s}^{-1}$ for HI-
 128 A and $417 \pm 15 \text{ km s}^{-1}$ for HI-B. Subsequently Liu et al. (2010) used J-maps to iden-
 129 tify transient features in both STEREO spacecraft and, assuming that both spacecraft
 130 were observing the same isolated feature, triangulated on this point to determine the loca-
 131 tion and movement of that feature in the equatorial plane. A CME is a three-dimensional
 132 structure and, as the authors themselves state; *However, the imaging observations pro-
 133 vide integrated line-of-sight information through a three-dimensional structure. Projec-
 134 tion and Thomson-scattering effects may affect the tracks in the time-elongation maps
 135 in ways that are difficult to assess quantitatively without detailed modelling of the coro-
 136 nal brightness.* Barnard et al. (2017) discuss the limitations in feature tracking using J-
 137 maps rather than through tracking fronts in the images. A comparison of predicted ar-
 138 rival of the fronts at 1 AU presented by Liu et al. (2010) is consistent with the in-situ
 139 data at L1. However, the extended region of enhanced solar wind density seen ahead of
 140 the CME allows for considerable uncertainty in the predicted arrival time of the first front
 141 and the second front coincides with an enhancement that is barely greater than ambi-
 142 ent solar wind. It should be noted that Davis et al. (2009) achieved similar, if not bet-
 143 ter, agreement with the in-situ data from their analysis by tracking an entirely differ-
 144 ent third front seen in the HI images.

145 One consequence of assuming a line-of-sight integration of scattered light is coming
 146 from a point source (as is done in the analysis of Liu et al. (2010)) is that any asym-
 147 metric expansion of an extended 3-D structure will manifest itself as a change in prop-
 148 agation direction, as was presented their analysis. Here we use an empirical model (de-
 149 scribed by Riley, Linker, and Miki (2001) and available at [http://www.predsci.com/
 150 mhdweb/home.php](http://www.predsci.com/mhdweb/home.php)) to examine the background solar wind for the epoch of this event
 151 (figure 2). This model suggests that while the background solar wind encompassing the
 152 nose and eastward flank of the CME (as observed from HI-A) was indeed uniform and
 153 relatively slow, the westward portion of the CME was expanding into a stream of fast
 154 solar wind and so would be expected to evolve asymmetrically compared with the east-
 155 ern flank.

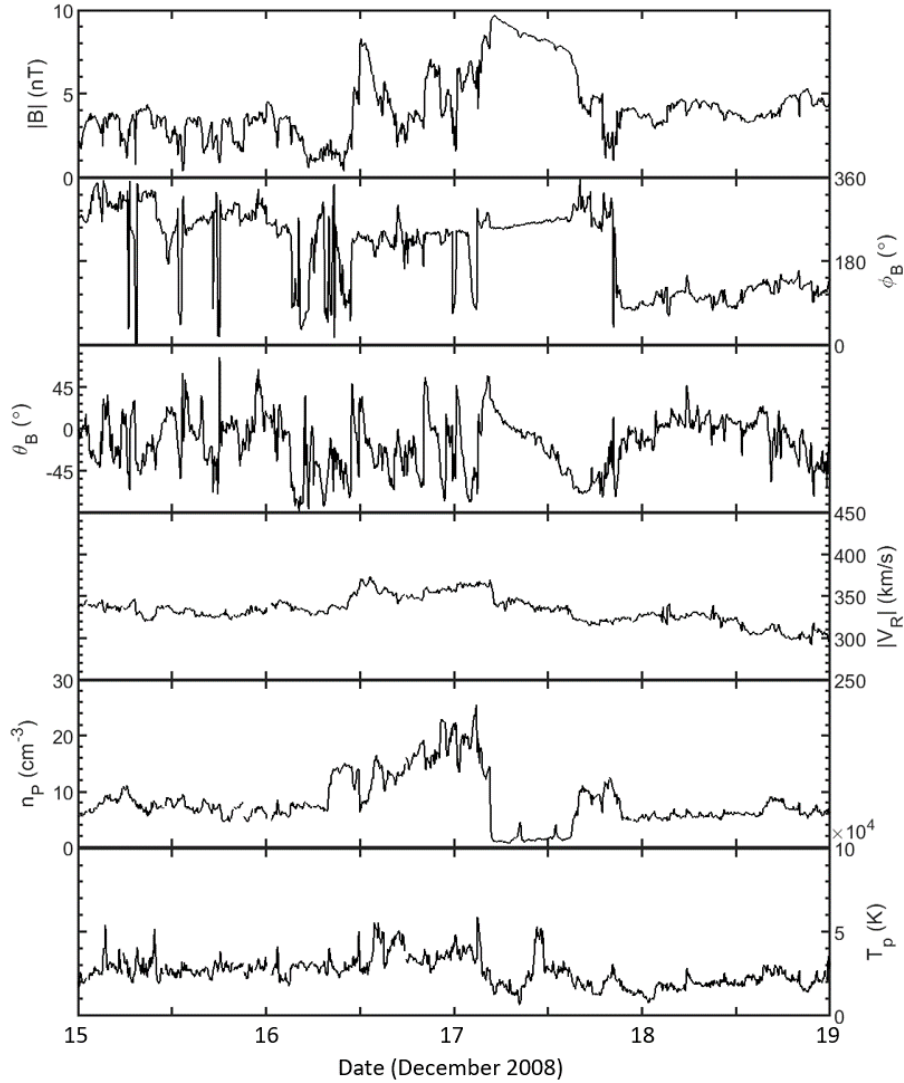


156 **Figure 2.** The CME of 12 December 2008 (here represented in white as a kinematically dis-
 157 torting flux rope) overlaid on the modeled background solar wind field. The nose and eastern
 158 flank of the CME (as observed from STEREO-A) is expanding into a uniform region of slow solar
 159 wind. In contrast, the western flank of the CME (as observed from STEREO-B) is expanding
 160 into a region which includes a fast solar wind stream. Lines of sight from the spacecraft to the
 161 CME nose are represented as a white solid line while lines of sight from the spacecraft to the
 162 CME flanks (tangent to the front) are represented as dotted lines. The CME direction of propa-
 163 gation (as determined from coronagraph observations) is represented by a white dashed line and
 164 the Sun-Earth line is represented by a solid black line.

165 Lugaz et al. (2010) considered a set of four CMEs, including the event of 12 De-
 166 cember 2008, and made estimates of their azimuthal properties by the application of a
 167 pair of models that assumed either a spherical CME connected to the Sun expanding into
 168 the heliosphere with a varying direction of propagation or a spherical CME expanding
 169 along a fixed direction with a variable radius. For the 12 December 2008 CME, they found
 170 the two brightest features to be propagating along longitudes separated by around 10° .
 171 Both these models assume a symmetrically expanding front. Any asymmetry in the ex-
 172 pansion of the actual CME (as would be expected in the case of the 12 December 2008
 173 CME) could explain this apparent difference in propagation direction.

174 All of the analyses described above are valid attempts to model this CME given
 175 the current information available. Assumptions need to be made in order to fill in the
 176 gaps necessary to estimate the size, shape, speed and propagation direction of a CME.
 177 We here present an alternative approach, in which the initial shape and position of the
 178 CME is characterized from coronagraph data. An assumption is then made that its half
 179 width remains constant as it propagates and the two fronts observed in the HI images
 180 from a single spacecraft (figure 4) are interpreted as two sections of the same front. In
 181 this way, no assumption is made about the evolution of the CME shape other than of
 182 it expanding with a constant angular width. Instead, the relative separation of these fronts

183 can be used to infer information about the longitudinal properties of the CME. By com-
 184 parison with established CME propagation models, we show that our results are broadly
 185 consistent with geometric models where the background solar wind is constant but de-
 186 viates from these where the background solar wind is more structured. Nevertheless the
 187 observations are consistent with the expected distortion of the CME front. Since we are
 188 determining the CME half-width from coronagraph data, we here do not consider the
 189 Harmonic Mean technique as this effectively assumes a CME half-width of 90° .



190 **Figure 3.** In-situ solar wind data at L1 as measured by the ACE spacecraft. From top to
 191 bottom panels the parameters are; total magnetic field, magnetic field azimuth angle, magnetic
 192 field inclination angle, radial speed, proton concentration and temperature.

193 While there is some range in predicted values for the speed and direction of this
 194 event, all studies conclude that this event was Earth-directed, with an average radial speed
 195 between the Sun and the Earth of approximately 400km s^{-1} . Such a speed is usually in-
 196 sufficient to generate a shock ahead of the CME, although Owens, Cargill, Pagel, Sis-
 197 coe, and Crooker (2008) and Lugaz et al. (2017) demonstrated that this can sometimes
 198 happen. Slow CMEs can still drive shocks but they do so by either expanding (so while
 199 the average speed is low, the leading edge speed can be relatively high) or by propagat-
 200 ing into very slow upstream wind (300km s^{-1} or less). For the December 2008 ICME,
 201 neither is really applicable (figure 3). The in-situ data, recorded by the ACE spacecraft
 202 (Stone et al., 1998) as the transient swept past the L1 point upstream of the Earth con-
 203 tains little evidence of continued expansion and the upstream solar wind is approximately
 204 340km s^{-1} . There is some compression of the upstream solar wind but there is no ob-
 205 vious shock at 1 AU. While the CME may have been initially traveling faster than this
 206 average speed, it is unlikely, in this instance, that a shock traveling ahead of the CME
 207 magnetic cloud can explain the multiple fronts observed in HI data.

208 4 Analysis of coronagraph data

209 Multiple, independent methods were used to reconstruct the CME in the coron-
 210 agraph field of view. One of the methods is an extension of SWPC-CAT (Millward et
 211 al., 2013), which is a tool that uses a 3D, balloon-like shape to visually match the white-
 212 light image observed by STEREO-A, STEREO-B, and SOHO corresponding to the outer,
 213 dense leading edge of the CME. The fitting tool we used differs from SWPC-CAT, in that
 214 the shape used to approximate the CME can have an elliptical cross-section; in addition,
 215 the curvature of the leading edge can be changed from a flat leading edge (a cone with
 216 no ice cream) to a highly rounded leading edge (a cone with a generous scoop of ice cream).
 217 Another method we used is a purely geometric technique, geometric localization (Pizzo
 218 and Biesecker (2004); de Koning, Pizzo, and Biesecker (2009)). The third method we used
 219 is the method of equal masses (Colaninno & Vourlidas, 2009).

220 The angular extent of the CME was determined using enhanced SWPC-CAT, only.
 221 The East-West half-width was estimated to be $21\pm 3^\circ$ while the North-South half-width
 222 was estimated to be $23\pm 2^\circ$. So, initially, this CME had a nearly circular cross-section.
 223 The initial position of the CME leading edge within the coronagraph data was estimated
 224 to be at a radial distance of 7.9 ± 0.4 solar radii at 10:37 on 12 December 2008.

225 The latitude of propagation was estimated using two of the above methods. Us-
 226 ing enhanced SWPC-CAT with two or three spacecraft, resulted in a latitude of $8\pm 1^\circ$
 227 in Heliocentric Earth Equatorial (HEEQ) coordinates, slightly north of the solar equa-
 228 tor. The estimated latitude did not strongly depend on whether two or three spacecraft
 229 were used, or on the curvature of the leading edge. Using the purely geometric technique,
 230 the latitude of propagation was found to be similar, $10\pm 3^\circ$ HEEQ. The method of equal
 231 masses is not sensitive to the latitude of propagation; therefore, that technique is not ap-
 232 plicable. Combining these results in an ensemble of (two) methods, results in a latitude
 233 of $9\pm 2^\circ$ in HEEQ coordinates. The longitude of propagation was estimated using all
 234 three methods. Using enhanced SWPC-CAT with two or three spacecraft and balloon
 235 shapes with various leading-edge curvature, resulted in a longitude of $10\pm 2^\circ$ HEEQ,
 236 slightly west of the Sun-Earth line. Using geometric localization, the longitude was es-
 237 timated to be $8\pm 1^\circ$ HEEQ. The method of equal masses generated a value of $17\pm 3^\circ$
 238 HEEQ. Combining all analyses in an ensemble of techniques (in which approximately
 239 equal weight is given to each method), results in a longitude of $10\pm 4^\circ$ in HEEQ co-
 240 ordinates.

241 The CME speed within the coronagraph field of view was estimated using two dif-
 242 ferent methods. Using enhanced SWPC-CAT, the speed was dependent on the leading-
 243 edge curvature. The flatter the leading edge, the lower the speed. For a highly flattened

244 leading-edge, the speed was estimated to be $350 \pm 10 \text{ km s}^{-1}$; for a rounder cone, the speed
 245 was estimated to be $410 \pm 20 \text{ km s}^{-1}$. Using geometric localization, the speed was esti-
 246 mated to be $390 \pm 40 \text{ km s}^{-1}$. Combining all results in an ensemble of techniques (in this
 247 case, no attempt was made to give equal weight to each shape and method), results in
 248 a radial speed of $380 \pm 30 \text{ km s}^{-1}$.

249 Analysis of coronagraph data (following the method of Colaninno and Vourlidas
 250 (2009)) determined that the CME had a de-projected mass of 2.610^{12} kg . Epistemic un-
 251 certainty due to a lack of knowledge about the CME's morphology and mass distribu-
 252 tion (see de Koning (2017)) suggests that the CME's true mass may be 30% higher than
 253 the de-projected mass. While Webb and Howard (2012) have carried out a more recent
 254 survey of CME masses, our analysis is more directly comparable with Burkepile, Hund-
 255 hausen, Stanger, St. Cyr, and Seiden (2004) who looked at limb-event CMEs only as ob-
 256 served by the Solar Maximum Mission, in order to eliminate projection effects. They found
 257 an average mass for limb CMEs of $4.5 \pm 0.5 \cdot 10^{12} \text{ kg}$. Thus, this CME is lighter than the
 258 average limb CME, even accounting for uncertainty.

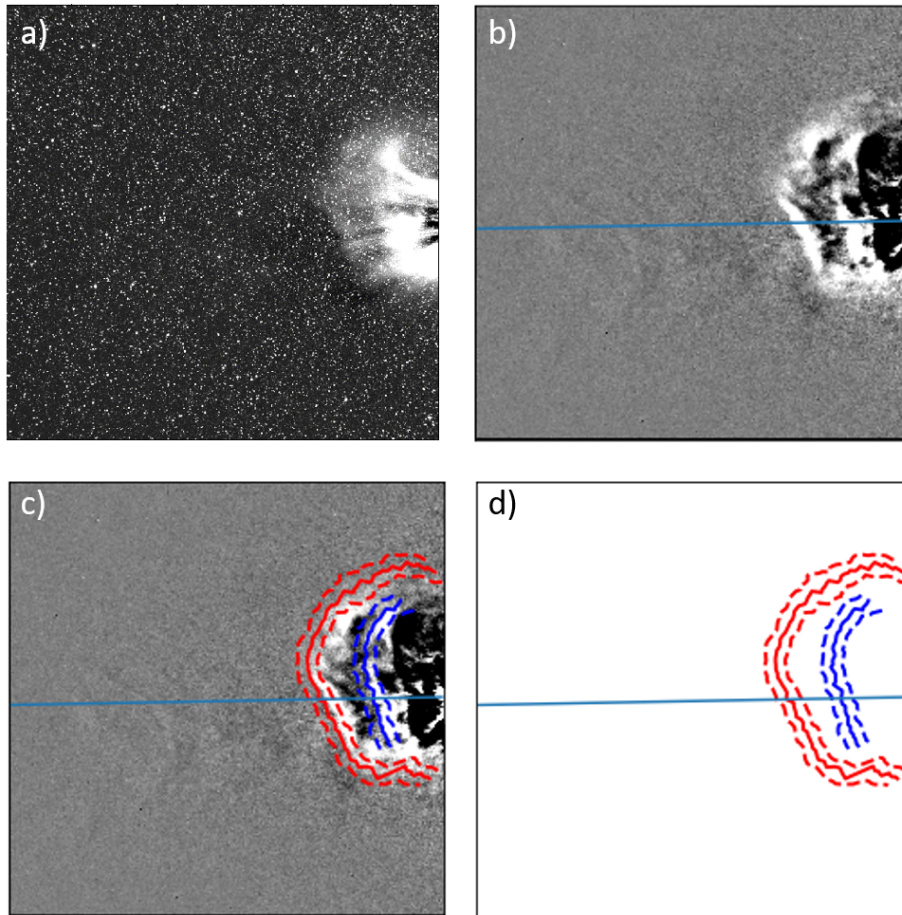
259 Combined with low speed, this was not an energetic CME, which may make it sus-
 260 ceptible to distortion. The kinetic energy for this event was $2.0 \cdot 10^{23} \text{ joule}$ ($2.0 \cdot 10^{30} \text{ erg}$).
 261 However, according to Burkepile et al. (2004), the average kinetic energy for a limb CME
 262 was $2.4 \cdot 10^{24} \text{ joule}$ ($2.4 \cdot 10^{31} \text{ erg}$), which is an order of magnitude higher than this event.
 263 In fact, the CME parameters detailed above best describe the CME in the outer coro-
 264 nagraph field of view, but do poorly in the inner coronagraph field of view, suggesting
 265 that the CME underwent some distortion as it propagated through the STEREO/COR2
 266 field of view.

267 5 Analysis of Heliospheric Imager data

268 For the purposes of this analysis, images from only the inner HI1 cameras were used.
 269 The main reasons for this was that the plasma density within a CME is greater closer
 270 to the Sun and so CMEs appear brighter in HI images since the amount of sunlight scat-
 271 tered through Thomson scattering increases with plasma density. Though the ghost fronts
 272 are visible in images from which the background F-corona signal has been subtracted
 273 (Figure 4 a), running differenced images, in which two consecutive images are aligned
 274 and the difference taken, are used for this analysis since this improves the contrast of the
 275 features of interest. As a result, static features within the images are removed while any
 276 transient features increase the signal in pixels gaining plasma and decrease the signal in
 277 pixels in which plasma has been lost. When imaged in monochrome, a transient mov-
 278 ing away from the Sun therefore shows as a feature with a bright leading edge followed
 279 by a darker trailing edge.

280 A sequence of images from each HI1 instrument was examined independently by
 281 multiple researchers using tools developed by the Zooniverse team, originally for clas-
 282 sifying galaxies (Lintott et al., 2008). The leading edge of each of the two most promi-
 283 nent fronts were identified multiple times in each image by marking them with a series
 284 of points. These points were then passed through a kernel density analysis similar to that
 285 used in previous analyses (Barnard et al., 2017), the output of which gives the location
 286 of each front, along with uncertainties (see figure 4d). The data are then further reduced
 287 by considering only the front at the elevation angle corresponding to the ecliptic. In this
 288 way, the propagation of the two CME fronts can be plotted as a function of elongation
 289 angle, ϵ , against time for each spacecraft.

296 At this stage it becomes possible to estimate the radial speed of the CME in the
 297 HI data. We initially focus on data from HI-A since the nose and flank of the CME ob-
 298 served from this spacecraft fit are expected to be expanding into a uniform solar wind.
 299 For the given geometry, the second front - the ghost front, most likely corresponds to the

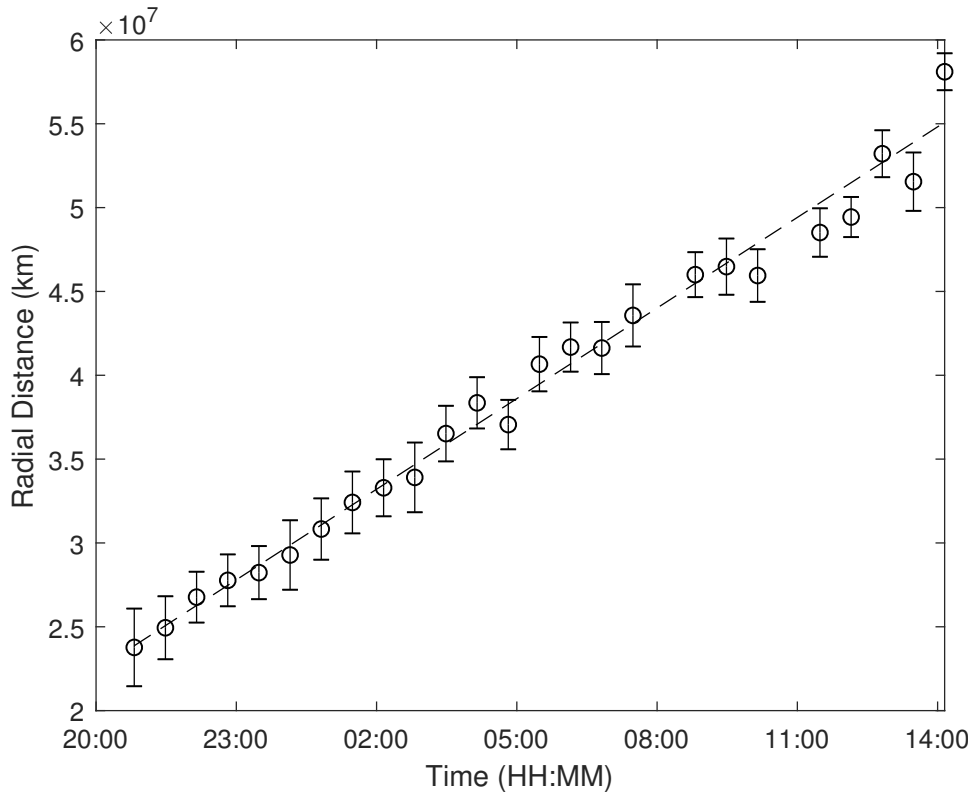


290 **Figure 4.** An example HI-A image from 22:49 UT on 12 December 2008 showing a) back-
 291 ground subtracted image b) running difference image, c) the same image with the two fronts
 292 identified from the kernel density analysis and (d) the fitted fronts alone. We argue that, for
 293 this event, the outer and inner fronts correspond to the tangent and nose respectively, of a single
 294 CME front. The dotted lines represent the standard error in elongation derived from multiple
 295 identifications of each front. The ecliptic is marked with a blue line

300 leading edge, or nose, of the CME and so this was used to estimate the radial speed. By
 301 using the direction of propagation determined from the coronagraph data (10° west of
 302 the Sun-Earth line), the elongations within the HI data can be converted to radial dis-
 303 tances. Plotting these as a function of time generated a straight line (Figure 5), indicat-
 304 ing that the speed of the CME was constant throughout the HI field of view. A weighted
 305 fit to this line gives a speed estimate of $500 \pm 15 \text{ km s}^{-1}$. It should be noted that this
 306 process is analogous to the 'fixed phi' fitting routine for a point source introduced by N. R. Shee-
 307 ley et al. (1999) and N. R. Sheeley Jr. and Rouillard (2010) although in the current anal-
 308 ysis the angle of propagation is determined from the coronagraph data and the subse-
 309 quent radial speed only calculated after inspection of the resulting distances showed they
 310 followed a linear relationship with time. While the radial CME speed measured in HI
 311 is greater than the speed estimated from the coronagraph data, it is not inconceivable
 312 that the CME underwent further acceleration before reaching radial distances visible within
 313 the HI1 field of view. As a sanity check, the CME speed was also estimated from the time

314 taken to propagate from the initial observation within the COR field of view to the first
 315 point within the HI field of view that was used in the analysis (34.2 ± 3.3 solar radii at
 316 20:49 on 12 December 2008, assuming a propagation direction of 10° west of the Sun-
 317 Earth line). This was found to be $497 \pm 63 \text{ km s}^{-1}$, consistent with the radial speed es-
 318 timated from the HI data alone.

319 It should be noted that the two fronts identified by Liu et al. (2010), from their scal-
 320 ing of features in the J-map presented in their figure 3, approximate to the outer (tan-
 321 gent) front of our analysis and some other feature that seems to sit at lower elongations
 322 than the second front we have identified as the ghost front (see their figure 2). The speed
 323 profiles of the features presented in their figure 4 show that they estimated the speed of
 324 their outer front to reach speeds in excess of 600 km s^{-1} , while their inner front reached
 325 speeds of around 400 km s^{-1} . Despite the difference in methods (direction of propaga-
 326 tion was a free parameter in their analysis while ours was fixed from the coronagraph
 327 observations) it is not unreasonable that the speed we find for our nose front lies between
 328 these extremes. Ours is also an average speed derived from HI-1 data only whereas the
 329 speeds derived by Liu et al. (2010) correspond to individual times manually scaled from
 330 J-maps.



331 **Figure 5.** Radial distance versus time for the front corresponding to the leading edge of the
 332 CME. Times start on 12 December 2008. Time is in UT. Coronagraph data were used to esti-
 333 mate the direction of propagation (10 degrees west of the Sun Earth line).

334 In order to model how the nose, tangent point and Thomson sphere crossings would
 335 appear in HI images, elongation angles were calculated for the nose (ε_{AN}), tangent (ε_{AT})
 336 and Thomson sphere crossings (ε_{ATS}) in three CME models; Self-Similar Expansion of
 337 a circular CME front (SSE-C)(Davies et al., 2012), self-similar expansion of an ellipti-
 338 cal CME front (SSE-E)(Rollett et al., 2016) and a Kinematically Distorting Flux Rope

(KDFR)(Owens et al., 2006). These models took their initial conditions (half-width, $\lambda=21$, and direction of CME propagation with respect to the observer, $\phi = 32.3^\circ$) from the analysis of coronagraph data.

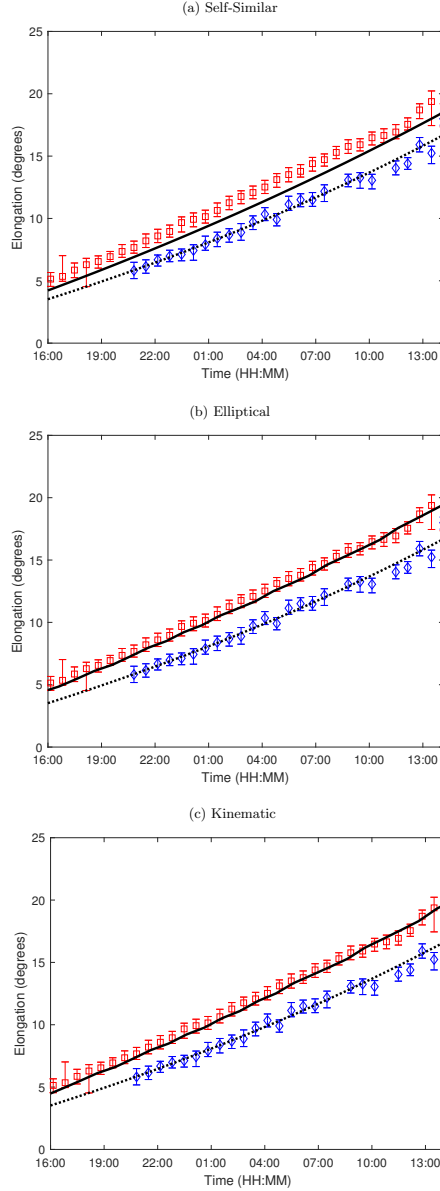
The elliptical CME was arbitrarily assumed to have a ratio of 3 : 2 between the major and minor axes. While the elongation angle of the tangent to a circle and ellipse can be derived analytically, for the KDFR model a numerical solution was adopted. For this approach, the nose of the CME was identified, and its elongation (ε_{AN}) calculated geometrically. This angle was then incremented until the resulting spacecraft-CME line did not intercept any points defining the outer boundary of the CME. By adopting this approach, the elongation of the tangent point can be determined to within the increment used (in this case 0.1 degrees). For the KDFR model, a nominal expansion ratio, $A = 0.15$, was used, as assumed by Owens et al. (2006). The intersections between the CME and the Thomson sphere were also identified, and the elongation of these points (ε_{ATS}) then calculated geometrically. Since the modeled radial speed of the CME sets the gradient of the elongation versus time plot, an initial value of 500km s^{-1} was used, as determined from the fit to the HI data. The observer is assumed to be at the location of STEREO-A for the purposes of the initial analysis, since the CME flank expanding into slow, unstructured solar wind will be visible from this viewpoint where the CME expansion is expected to result in the least distortion of the CME front. For this date, the longitudinal separation (STEREO A-Sun-Earth angle) was 42.3° with the spacecraft at a distance of $0.967AU$. An estimate of the quality of the fit is obtained by calculating R for each front, where R is the root mean square difference between the model and data (in degrees). The KDFR model used assumed that the CME was expanding into a solar wind flowing at a constant speed which, for the flank viewed by STEREO-A, is consistent with the solar wind model for this epoch (figure 2).

6 Results

The results for the three models for HI-A observations are presented in figure 6. In all three models, the outer boundary of the CME does not intercept the Thomson sphere until the CME has propagated sufficiently far into the heliosphere that the resulting elongations (ε_{ATS}) are in excess of 20 degrees. Such intersections cannot account for the multiple fronts seen at much lower elongations in HI-1 images (though they may be apparent at larger elongations in the outer HI2 cameras) and so are discounted as a cause for the ghost fronts. When considering the elongations of the nose (ε_{AN}) and the tangent point (ε_{AT}) in the SSE-C model (that assumes a circular front) (figure 6a), it can be seen that the two modeled fronts are consistently closer in elongation than the two fronts scaled from the HI data. The residual between model and data for the leading edge of this fit, $R_{LE} = 0.092^\circ$ while the residual between model and data for the tangent front, $R_T = 0.168^\circ$. The same two fronts in the SSE-E model (which assumes an elliptical front, figure 6b) diverge in elongation and matched the offset predicted by the model well ($R_{LE} = 0.092^\circ$, $R_T = 0.079^\circ$). While the ratio assumed between the major and minor axes of this elliptical CME is arbitrary, it appears, in this case, to closely model the observations. The results for the KDFR model are presented in figure 6c. Unlike the previous two examples, in this physically constrained model, the CME front evolves in shape as it moves outwards and this too closely models the observations ($R_{LE} = 0.092^\circ$, $R_T = 0.079^\circ$).

Having established that the two observed fronts are consistent with enhanced returns from the nose and tangent of a CME propagating into a region of uniform solar wind, and that the SSE-E and KDFR models best represented the shape of the CME in this case, the KDFR model was rerun, allowing the fit parameters to vary within the uncertainties of the observations used to constrain the model.

Since the estimate of radial speed relies on an assumed direction of CME propagation, this calculation was repeated for the range of possible values indicated by the coro-



383 **Figure 6.** Elongation versus time for modeled elongations of the nose (ε_{AN} , dashed black line)
 384 and tangent (ε_{AT} , black solid line) compared with the elongations of the two fronts scaled from
 385 STEREO HII-A data. Times start on 12 December 2008. The results in panel a) assume a cir-
 386 cular self-similar expansion model CME, the results in panel b) assume an elliptically expanding
 387 CME, while panel c) assumes the front evolves like a Kinematically Distorting Flux Rope. In all
 388 cases, the models assume the CME is moving at a radial speed of 500km s^{-1} . It should be noted
 389 that in all the above models, the evolution of the CME nose (dotted line) is the same.

397 nagraph data. The best fit was achieved for a CME propagating 9° west of the Sun-Earth
 398 line, giving an estimated speed of $496 \pm 15\text{km s}^{-1}$. Having ascertained the optimum propa-
 399 gation direction by minimising the residual in fit to the inner front, the optimum half-
 400 width of the CME was determined by optimising the fit of the leading front (correspond-

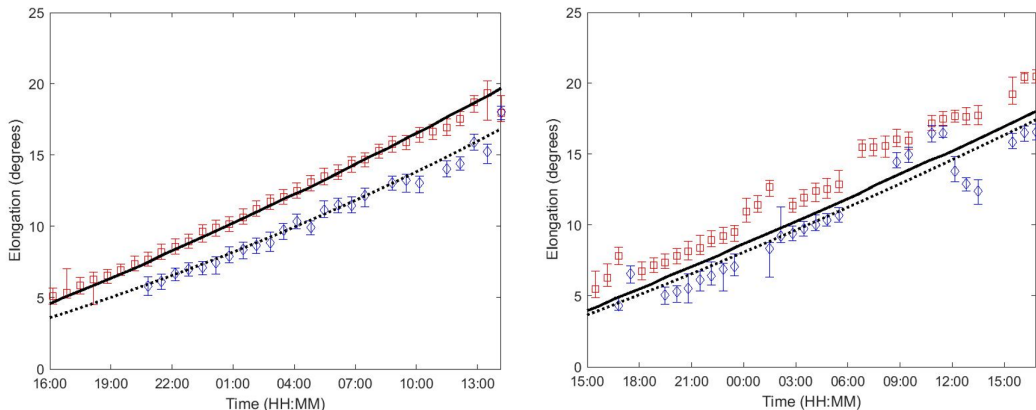
ing to the flank of the CME). This produced a minimum root mean square residual of 0.072° for $\lambda = 23^\circ$ (figure 7, left). These values lie within the uncertainties of the coronagraph data from which the initial estimates were made.

That the modeled elongations matched the observations while assuming a CME transit speed of $496 \pm 15 \text{ km s}^{-1}$ between the COR and HI-1 fields of view is further corroboration that the transit speed of the CME was likely higher than that estimated from the coronagraph data alone.

Having established that the ghost fronts conformed to the expected separation and evolution in elongation between the nose and the tangent to a single CME front for conditions in which the CME is propagating into a constant background solar wind, the same analysis was conducted for the HI images taken from STEREO-B assuming the same half-width and propagation direction. As can be seen from figure 2 the direction of travel of the CME is such that from this viewpoint the elongation of the nose (ε_{BN}) and the elongation of the tangent (ε_{BT}) are expected to be more closely aligned than for the view from STEREO-A. The results are presented in figure 7 (right). The fit to CME nose (dotted line, blue data points) in HI-B data is significantly poorer, with an estimated radial speed of $403 \pm 28 \text{ km s}^{-1}$ and a root mean square residual of 0.246° . This is likely due to the difference between the two instruments with HI-B having a wider point-spread function than HI-A and undergoing greater pointing offsets which reduce the efficiency of background removal in differenced images (Eyles et al., 2009; Tappin, 2017). This makes identifying faint features in HI-B more challenging. Despite these challenges it is apparent that the match to the flank of the CME is poor for the assumed propagation direction and half-width. While the speed fitted to the HI-B data is lower than the estimate obtained from the HI-A data, the two speeds match within two standard errors. Further analysis of the HI-B data revealed that if it were considered independently of the HI-A data, the best fit to the inner front in these images was obtained for a propagation direction of 6° west of the sun-Earth line, corresponding to a radial speed of $409 \pm 28 \text{ km s}^{-1}$ although the root mean square residual of 0.244° is not significantly different from the minima obtained when using the parameters determined from the HI-A data. Such a difference could also be interpreted as the plasma build-up at the nose of the CME being extended across a few degrees of solar longitude. It is apparent that the western flank of the CME observed from HI-B is not consistent with a symmetrically expanding front. No realistic value of the CME half-width, λ , can reproduce the observed difference in elongation between these fronts as observed from HI-B while assuming a non-distorted front. Given that the background solar wind is not uniform to the west of the sun-Earth line, we suggest that this flank of the CME would evolve differently from the eastern flank observed by HI-A. This is discussed further in the next section.

7 Discussion and conclusions

The analysis of this event has demonstrated that the ghost fronts seen in HI-A data, for which the CME is expanding into a region of uniform background solar wind, are consistent in elongation with the locations of the CME nose and tangent point. In the geometry of the current example, the second, or ‘ghost’ front in the HI images appears to correspond to the nose of the CME where a pile-up of plasma ahead of the CME leads to enhanced signal due to Thomson scattering in that region. The speed of the CME outer boundary relative to the ambient solar wind is expected to peak at the leading edge, therefore ambient solar wind compression is expected to peak there too (Siscoe & Odstrcil, 2008; Owens et al., 2008). The outer front seen in the HI images is consistent with the line-of-sight along the tangent of the outer boundary of the CME. While the concentration of solar wind plasma along the extended boundary is likely to be lower than at the CME leading edge, nevertheless there is a sufficient increase in plasma density along this boundary for enhanced signal from Thomson scattering to occur when integrated along the line-of-sight.

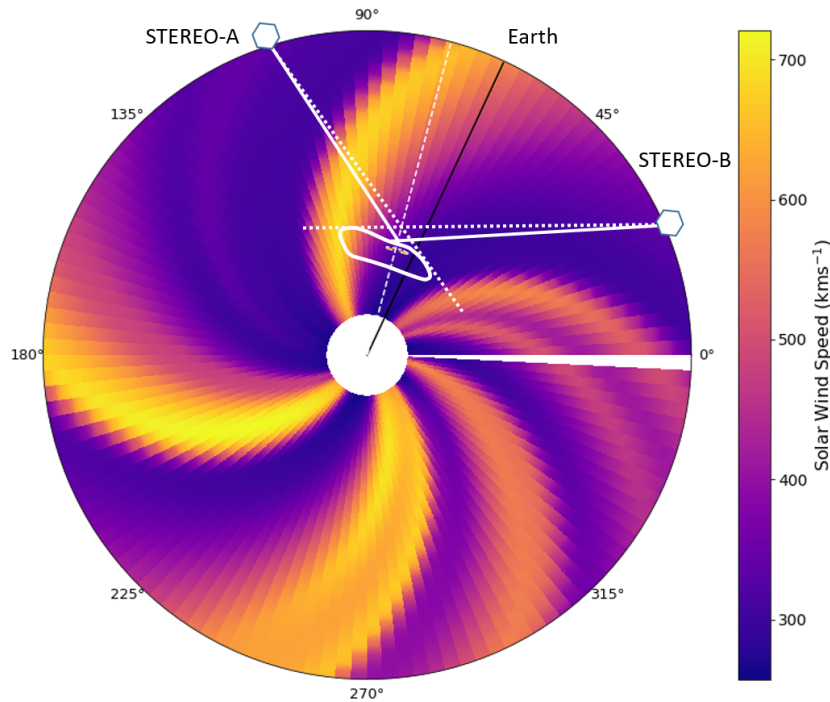


438 **Figure 7.** Elongation versus time plot of the same form as figure 6 for HI-A (left) and HI-
 439 B(right) both assuming half width, $\lambda = 23^\circ$ and a direction of 9° west of the sun-Earth line.
 440 These values generated the optimum fit to HI-A data. The assumed propagation direction results
 441 in a fitted speed for the nose of the CME of $496 \pm 15 \text{ km s}^{-1}$ in HI-A data and $403 \pm 28 \text{ km s}^{-1}$
 442 in HI-B data. These are consistent within 2 standard errors. Times start on 12 December 2008.

458 When compared with a range of CME propagation models, for this CME, the best
 459 fit to the data came by considering the shape of the CME as an ellipse with a 3:2 ratio
 460 between major and minor axes or a kinematically distorting flux rope. The circular self-
 461 similar expanding CME front, while broadly reproducing the observations, did not match
 462 the data as well as the other two models. It appears therefore that the separation in elongation
 463 between the two fronts provides information about the longitudinal shape of the
 464 CME front. Both the elliptical and KDFR models require an additional free parameter
 465 to be set, (the ratio of major to minor axes and the expansion factor respectively) but
 466 since all additional parameters can be estimated from the coronagraph and HI data, this
 467 can be iterated to optimize the fit to the observations. The KDFR model has the ad-
 468 vantage that it more accurately reproduces the expected distortion of a CME as it propa-
 469 gates in the solar wind and can be extended to account for solar wind structure (Owens,
 470 2006).

471 The cartoon in figure 2 shows that for a CME with the properties estimated from
 472 the coronagraph data, expanding symmetrically into the heliosphere would result in the
 473 nose and flank of the CME appearing at similar elongations as viewed from STEREO-
 474 B. However, it can be seen that this flank was expanding into a region in which the back-
 475 ground solar wind was not uniform. We suggest that presence of a fast solar wind stream
 476 at the western flank of the CME has resulted in this portion of the front moving faster,
 477 distorting the shape of the CME as indicated by the cartoon shown in figure 8, gener-
 478 ating the observed separation in elongation between the nose and flank of the CME, which
 479 is larger than expected for a CME expanding into a uniform solar wind.

484 Current forecasts (Pizzo et al., 2011) characterize a CME in coronagraph data and
 485 propagate this using a solar wind model such as Enlil (Odstrcil et al., 2004). It is en-
 486 visaged that data from the HI cameras could ultimately be used in operational space weather
 487 forecasting to refine such a model, either by creating an ensemble of artificial J-maps (as
 488 has been demonstrated by Lugaz, Vourlidis, Roussev, and Morgan (2009) and Xiong et
 489 al. (2013)) from the model to compare with the data, or through data assimilation of other
 490 information gleaned from the HI images.



480 **Figure 8.** Cartoon illustrating how the presence of a fast solar wind stream on the western
 481 flank of the CME could have distorted the CME front, leading to a larger apparent separation
 482 in elongation that expected between the CME nose (solid white line) and the flank (dotted white
 483 line) as viewed from the position of the STEREO-B spacecraft.

491 Information about the longitudinal structure obtained through such analysis of the
 492 ghost fronts could potentially be helpful in constraining solar wind forecast models through
 493 data assimilation methods to ensure that the shape of the CME front remained consist-
 494 ent with the observations. This is particularly important when tracking an Earth-impacting
 495 CME whose direction of propagation is slightly off the Sun-Earth line. In such circum-
 496 stances, information about the longitudinal shape of a CME will improve estimates of
 497 the arrival time and radial speed of the portion of the CME front at Earth.

498 The separation in elongation of the two fronts is a function of CME width, shape,
 499 speed and direction. The elongation at which the two fronts eventually converge occurs
 500 when the observer line of sight to the front is perpendicular to the CME propaga-
 501 tion direction. For this event, where the CME is propagating around 10° west of the Sun-Earth
 502 line, this occurs at elongation angles of 58° and 38° for STEREO-A and STEREO-B re-
 503 spectively. Such elongations lie well outside the HI-1 field of view in this instance. For
 504 an Earth-directed CME observed from the L5 Lagrange point this convergence would
 505 occur at an elongation angle of 30° , corresponding to a distance of 0.5 AU.

506 This study demonstrates that ghost fronts seen in the HI data are consistent with
 507 enhanced returns from the nose and tangent of a CME expanding into a uniform solar
 508 wind and suggests that solar wind structure can cause deviations from this simple model.
 509 It is, nonetheless, a single case study and many more events will need to be analysed in
 510 this way before the technique is proven. There is no evidence for a shock in in-situ data
 511 for this event and so a shock cannot explain the multiple fronts seen in the HI data. Fur-
 512 ther work, studying CMEs with a range of speeds and geometries, is needed to deter-
 513 mine whether the existence of a shock would complicate the interpretation of multiple

514 fronts seen in HI data. It may also prove valuable to look for ghost fronts in coronagraph
 515 data to see whether these too are consistent with enhanced scattering from multiple re-
 516 gions of the same CME front.

517 To date there have been multiple analyses of the 12 December 2008 CME using a
 518 variety of techniques and assumptions to estimate the evolution of this event. Determin-
 519 ing which interpretation best represents the CME is a complex question that depends
 520 on the criteria by which their individual merits are judged and on the constraints im-
 521 posed by the available data. Additional analysis considering multiple events will now be
 522 carried out to investigate the efficacy of using ghost fronts to infer information on the
 523 evolution of CMEs in the inner heliosphere. The KDFR model can be further extended
 524 to consider a non-uniform background solar wind (Owens, 2006; Isavnin, 2016) and it
 525 will be the subject of further work to see if accounting for the presence of solar wind struc-
 526 ture in a time-varying model can reproduce the results presented here.

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546 Data from the STEREO mission used in this study can be accessed from the UKSSDC
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