Three-Dimensional Properties of Coronal Mass Ejections from STEREO/SECCHI Observations

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Abstract We identify 565 coronal mass ejections (CMEs) between January 2007 and December 2010 in observations from the twin STEREO/SECCHI/COR2 coronagraphs aboard the STEREO mission. Our list is in full agreement with the corresponding SOHO/LASCO CME Catalog (http://cdaw.gsfc.nasa.gov/CME_list/) for events with angular widths of 45° and up. The monthly event rates behave similarly to sunspot rates showing a three- to four-fold rise between September 2009 and March 2010. We select 51 events with well-defined white-light structure and model them as three-dimensional (3D) flux ropes using a forward-modeling technique developed by Thernisien, Howard and Vourlidas (Astrophys. J. 652, 763–773, 2006). We derive their 3D properties and identify their source regions. We find that the majority of the CME flux ropes (82 %) lie within 30° of the solar equator. Also, 82 % of the events are displaced from their source region, to a lower latitude, by 25° or less. These findings provide strong support for the deflection of CMEs towards the solar equa-

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tor reported in earlier observations, e.g. by Cremades and Bothmer (Astron. Astrophys. 422, 307 – 322, 2004).

**Keywords** Coronal mass ejection

### 1. Introduction

Since the start of science operations in January 2007, the imagers and coronagraphs of the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) suite (Howard et al., 2008), aboard the twin STEREO spacecraft (Kaiser et al., 2008), have provided simultaneous observations of coronal mass ejections (CMEs) from different vantage points in space. Using the white-light synoptic movies provided by the two STEREO/SECCHI/COR2-A and -B coronagraphs, we have compiled a list of 565 coronal mass ejections (CMEs) between January 2007 and December 2010. The CMEs were observed under increasing spacecraft separation angles ranging from about 0° in the early mission phase up to 175° in December 2010. The CME list contains basic information, such as Carrington Coordinates of both spacecraft, CME detection times and position angles, etc. and is available online at the website http://soteria-event.uni-graz.at/. The list was compiled as part of the EU FP7 project SOTERIA (Solar TERrestrial Investigations and Archives).

A comparison of the monthly average CME rate from the SOTERIA COR2 CME list with the CME rate derived from the SOHO/LASCO CME Catalog yields a very good correspondence for CME events with angular widths greater than or equal to 45°. Thus, the SOTERIA COR2 CME list consists of classic large-scale CMEs, such as analyzed, e.g., by Cremades and Bothmer (2004). Figure 1 shows the comparison of the monthly CME rates from SECCHI and LASCO between January 2007 and December 2010, together with the monthly smoothed sunspot number (SSN) provided by the Solar Influences Data Analysis Center (SIDC) of the Royal Observatory of Belgium. Figure 1 shows that the monthly CME rates and monthly smoothed sunspot numbers show generally similar trends but not detailed correlations as has been reported in earlier studies (e.g., St. Cyr et al., 2000). We note that both the CME and sunspot monthly rates rise by a factor of three to four between September 2009 and March 2010 and remain high in the following months. This increase can be interpreted as the start of the rise of solar activity towards the next solar maximum expected around 2012 – 2013. It is interesting to note that the CME rate remains constant (at 10/month for SECCHI and 7/month for LASCO) for several months in 2009 although the corresponding sunspot number hovers around zero. We investigate the low-coronal source regions of these CMEs using the SECCHI Extreme Ultraviolet Imager (EUVI) at 195 and 304 Å. We find that they relate to bipolar photospheric regions of lower magnetic flux and quiescent prominence eruptions, in agreement with the results obtained for the CME source regions studied by Cremades and Bothmer (2004). However, for a number of CMEs, no source region could be identified as in the case of the “stealth CME” reported by Robbrecht, Patsourakos, and Vourlidas (2009). The differences between the CME rates and sunspot

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1 Also available in Tables 1 and 2 in the Electronic Supplementary Material.

2 CDAW Data Center, Solar Physics Laboratory (Code 671) Heliophysics Science Division, NASA / Goddard Space Flight Center, Greenbelt Maryland, USA: 1996 – 2011, SOHO/LASCO CME Catalog, http://cdaw.gsfc.nasa.gov/CME_list/.

3 Solar Influences Data Analysis Center, Royal Observatory of Belgium: 2010, Monthly and monthly smoothed sunspot number, http://sidc.oma.be/sunspot-data/.
numbers after January 2010 can be explained in terms of decaying active regions of less intense magnetic flux remaining unidentified as sunspots but remaining a source of CME origin, again in agreement with what has been proposed by Tripathi, Bothmer, and Cremades (2004).

From the SOTERIA COR2 list of 565 events, we constructed a “Best-of” list of 120 events based on their clear morphology (judged visually) in the COR2 images. So far, we have fitted 51 of these events as flux ropes with a forward-modeling technique developed by Thernisien, Howard, and Vourlidas (2006) and Thernisien, Vourlidas, and Howard (2009). The flux rope structure is represented by a geometrical construction, called the Graduated Cylindrical Shell (GCS) and is based on the idea that the flux rope morphology can account for the CME white-light observation (Chen et al., 1997; Vourlidas et al., 2000; Cremades and Bothmer, 2004).

In the following sections we give a brief introduction to the GCS Model and a brief presentation of the modeling results and comparisons with the CME source region characteristics.

2. The GCS Model

For the investigation of the three-dimensional (3D) structure of the “STEREO/SECCHI/ COR2 Best-of CMEs” the Graduated Cylindrical Shell forward-modeling technique developed by Thernisien, Howard, and Vourlidas (2006) was applied. The geometry and electron density distribution of the GCS flux rope geometry is shown in Figure 2. The GCS geometry consists of two funnel-shaped legs each of length \( h \). The segment \( h \), along the axis through the center of the shell (dash-dotted line), is defined by the center of the Sun, labeled “O”,

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4The complete “Best-of” CME list is shown in Table 3 in the Appendix and in Table 3 in the Electronic Supplementary Material.
Figure 2  The Graduated Cylindrical Shell Model with a face-on view on the left and an edge-on view on the right. The assumed electron density distribution is shown in the upper right and described with a Gaussian-like function (Thernisien, Howard, and Vourlidas, 2006).

Figure 3  Position and orientation of the GCS Model in 3D Space with the parameters $\phi, \theta$ and $\gamma$ for the Carrington longitude and heliographic latitude of the apex and the tilt angle, respectively (Thernisien, Vourlidas, and Howard, 2009).

and by the upper end of the cone. The angle between both axes is $2\alpha$ or $\alpha$ for the half angle, one of the six parameters which define the geometry of the model. The upper part of the model, connecting both legs, is tube shaped. The right image in Figure 2 shows an edge-on view of the model consisting of a circle with the varying radius $a$ for the cross section of the tubelike part and below the tube section the mentioned cone of the legs. As opposed to the length $h$ of the legs $h_{\text{front}}$ describes the distance or height between the center of the Sun “O” and the leading edge of the CME. $h_{\text{front}}$ can be determined using the parameters $h, a, r$ and $\alpha$, which are shown in Figure 2.

In order to describe the position and orientation of the flux rope in 3D space the parameters $\phi, \theta$ and $\gamma$ define the Carrington longitude and heliographic latitude of the apex projection on the solar surface and the tilt angle $\gamma$ of the source region (SR) neutral line (Figure 3). In this figure the GCS model is oriented normal to the solar surface and located with the projection of the apex on the solar surface at the given $(\phi, \theta)$-Coordinates where the center of the neutral line of the SR can be found. The legs of the model are located at the
Table 1 Parameters of the GCS Model and the electron density distribution, adapted from Thernisien, Howard, and Vourlidas (2006).

| Parameter | [units] | Description |
|-----------|---------|-------------|
| $2\alpha$ | [deg]   | Angle between the axis of both legs |
| $h$       | [$r_{\text{sun}}$] | Height of the legs |
| $h_{\text{front}}$ | [$r_{\text{sun}}$] | Distance from center of the Sun to leading edge |
| $\kappa$  | [deg]   | Aspect ratio of $a$ and $r$ |
| $\phi$    | [deg]   | Carrington longitude of the projection of apex on the Sun’s surface |
| $\theta$  | [deg]   | Heliographic latitude of the projection of apex on the Sun’s surface |
| $\gamma$  | [deg]   | Tilt angle of the SR neutral line relative to the solar equator |
| $a$       |         | Cross section radius of the tube section |
| $r$       |         | Distance from center of the Sun to the outer boundary of the shell |

opposite ends of the neutral line (NL), which has a tilt angle $\gamma$ relative to the solar equator. Table 1 provides an overview of the GCS model parameters. Further information regarding the GCS Model can be found in Thernisien, Howard, and Vourlidas (2006) and Thernisien, Vourlidas, and Howard (2009).

3. Examples of GCS Modeling of Events from the “Best-of” List

3.1. CME of 4 August 2009

We apply the GCS model to the CME detected on 4 August 2009 (Figure 4) when the two STEREO spacecraft were separated by 107.5° in heliographic longitude, i.e. they observed the CME from different viewing angles. The two STEREO spacecraft detected the CME at different position angles (PA) of 90° and 270°, respectively, as shown in the COR2-A and COR2-B (left) images in Figure 4. The GCS modeling technique was applied to base-difference COR2 images after they had been processed using the standard routines (secchi_prep). For the fit, we selected the time when the CME was the brightest in the COR2 field of view. On 4 August 2009, the CME was modeled when it was observed at 23:22 UT when its leading edge had reached a distance of about 13 solar radii. The right panels in Figure 4 show the modeling results through overlays of the GCS wireframe flux rope geometry on the CME images. The six parameters which describe the geometry of the GCS model are summarized in Table 2.

The synthetic coronagraphic images generated with a ray-tracing code are shown in Figure 5. The ray-tracing code allows us to render the 3D electron density distribution into a coronagraph image taking into account Thomson scattering. In this case, the CME detected in the COR2 field of view is represented by a flux rope which has its apex located at 222° in Carrington longitude lying in the solar equatorial plane (see Table 2). The radial height

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5Colaninno, R.: 2006–2010, The SECCHI_PREP Homepage, Naval Research Laboratory (NRL/GMU), http://secchi.nrl.navy.mil/wiki/pmwiki.php?n=Main.HomePage.
Figure 4  Left column of images: STEREO/SECCHI/COR2-A (top row) and -B (bottom row) white-light coronagraph observations of the CME detected on 4 August 2009 at 23:22 UT. The separation angle between the two spacecraft was 107° in longitude. Right column of images: wireframe rendering results (overlaid in green) derived through the GCS Model.

Table 2  Model results through GCS forward-modeling of two CMEs observed on 4 August 2009 and 1 February 2010.

| Parameter   | CME 1 (4 August 2009) | CME 2 (1 February 2010) |
|-------------|-----------------------|-------------------------|
| Longitude   | φ [deg]               | 222.5                   | 39.1                   |
| Latitude    | θ [deg]               | −2.8                    | −18.4                  |
| Tilt angle  | γ [deg]               | 0.0                     | 15.1                   |
| Height      | h_f [r_s]             | 13.4                    | 16.8                   |
| Aspect ratio| κ                     | 0.3                     | 0.3                    |
| Half angle  | α [deg]               | 12.0                    | 23.2                   |

of its leading edge is 13 solar radii. Figure 5 further shows the modeled flux rope footpoints and apex locations projected onto the EUVI 195 Å images (right column) for the time of the COR2 modeling. Green crosses signify that the flux rope is located on the visible side of the solar disk whereas white crosses define a backsided flux rope. The white-light structure of
the 4 August 2009 CME reveals features similar to many other cases of the “COR2 Best-of CME” list.

3.2. CME of 1 February 2010

As discussed earlier solar activity as represented by the sunspot number and the monthly rate of CMEs has shown increased levels since about February 2010. In contrast to a CME typical of the solar minimum years, Figure 6 shows a CME detected on 1 February 2010, i.e. in the early rising phase of Cycle 24. At this time STEREO-A and -B were separated by 135.3° in heliographic longitude and observed the CME at PAs of about 180° and 225°, respectively. The GCS modeling results are summarized in Table 2. The flux rope parameters fitting this CME differ from those of the 4 August 2009 event. In this case, the flux rope apex was located 18° south of the solar equator and exhibited a tilt angle of 15°. The
angular width was 46°, i.e. its calculated half angle of 23° was double the size of the August event. During this time period CMEs generally started looking wider and more massive in white-light coronagraph images. Because of the large angular separation of the COR2-A and -B instruments, the CME looks different in the COR2-A and -B images. The GCS synthetic coronagraphic images generated with the ray-tracing code for this event are shown in Figure 7 together with EUVI-A and -B observations taken at 195 Å.

3.3. GCS Modeling Results for “COR 2 Best-of CMEs”

Out of the 120 events of the “STEREO/SECCHI/COR2 Best-of List”6 51 events have been modeled similarly to the sample events described in Sections 3.1 and 3.2. The modeled

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6The complete “Best-of” CME list is shown in Table 3 in the Appendix and in Table 3 in the Electronic Supplementary Material.
events hitherto were from 2010 because they appeared brighter and were easier to model than the fainter cases appearing at solar minimum. Figure 8 shows the calculated latitudes for 51 flux rope apexes resulting from the modeling of the CMEs in 2010. In 2010 the flux rope apexes were located between 30° southern and 40° northern latitude. Figure 9 shows the calculated GCS flux rope tilt angles plotted versus time in 2010. The tilt angle of a modeled flux rope denotes the angle between the line between its footpoints and apex which are projected on the solar surface and the solar equator. The flux rope is oriented parallel to the equator for an angle of 0° and perpendicular for 90°. The CMEs observed north and south of the solar equator show a similar pattern of scatter in the range of up to 30–40°. It is interesting to note that apart from one exception, flux ropes with a tilt angle larger than roughly 40° are lacking. In this context it is important for further studies to inspect the tilt angle of the remaining “Best-of CMEs” observed between 2007 and 2009, because Thernisien, Vourlidas, and Howard (2009) found that e.g. the CMEs on 31 December 2007
and 23 January 2008 exhibit a large tilt angle of 90° and −49°, respectively. A further investigation of this aspect is needed to understand better the inclination characteristics of flux rope CMEs. Figure 10 shows the distribution of the GCS flux rope half angles \( \alpha \) which represents through \( 2\alpha \) the separation angle between both legs of the flux rope. The typical half angle of the flux ropes is estimated to lie between 10° and 25° during 2010 for a CME observed between 10 and 15 solar radii. A half angle of 10° to 25° corresponds to an angular width of the CME lying between 20° and 50° which is comparable to the typical angular width of CMEs observed by SOHO/LASCO (e.g. St. Cyr et al., 2000; Yashiro et al., 2004).

It should be noted that since the fits are done by hand they exhibit the modeler’s subjective understanding of the observed CME. Hence the fit results depend to a certain extent on the experience of the user for the interpretation of the CME white-light observation. In this context Thernisien, Vourlidas, and Howard (2009) used a merit function to determine how well the model is able to reproduce an observed CME’s white-light structure. After performing a sensitivity analysis of the model parameters, the authors found that the deviations in the parameters \( \gamma \) and \( \alpha \) are an order of magnitude larger than the deviations in the longitude and latitude. Hence the values for the tilt angle may exhibit a larger uncertainty than the one of the other parameters.
4. Comparison with source region and discussion

To compare the calculated GCS parameters (Table 4) of the flux ropes with the CME associated source region characteristics, we investigated the source region for each CME using SECCHI and SOHO/MDI data. For each modeled CME event we used the SECCHI/COR1 observations to track the CME back towards the low corona and then used the EUVI 195 Å and 304 Å observations to identify the coronal SR.

After identification of a CME’s source region we compared the calculated apex position provided by the GCS modeling to the SR location. Figure 11 shows a histogram of the differences between the SR longitude and the modeled apex position in bins of 15° Carrington longitude for 39 events. For the 12 remaining CMEs no associated SRs could be determined. We find that for 82% (32 out of 39) of the CME events the discrepancy is not larger than 30°. Larger deviations occur only for a small number of events (7 out of 39) and the larger differences are decreasingly frequent. A similar behavior is found for the difference in solar latitude between identified SR and modeled apex position as shown in Figure 12. Here 82% (32 out of 39) of all CME events exhibit a discrepancy of less than 25° in solar latitude. Considering a 10° difference as insignificant, we can conclude that 41% of all CMEs do not deflect latitudinally while the rest of the same exhibits a very modest 23° average deflection to lower latitudes.

Next we projected the calculated apexes onto SOHO/MDI (Michelson Doppler Imager) Synoptic Charts shown for the CME event observed on 4 June 2010. The center of the observed SR is labeled with a white plus sign and is located within a magnetic bipolar region. For a better visibility the SR is surrounded by a white circle. The radius of the circle is arbitrary with no reference to the spatial extent of the SR. In this case we assume a prominence as the SR, indicated with “P”. The position of the apex is marked with a green asterisk and the footpoints with green squares connected with a line which simultaneously denotes the orientation of the flux rope axis. The length of the footpoint line corresponds to the half angle \( \alpha \), respectively, \( 2\alpha \), the angle between both legs of the flux rope. In this case the apex projection lies only 13° south of the identified CME SR with an offset of only 16° in solar longitude. The MDI map reveals a bipolar photospheric region as a source of the analyzed CME as found in the studies of Tripathi, Bothmer, and Cremades (2004). In

\[ \text{Figure 10 Distribution of the calculated flux rope half angle for 51 GCS-modeled “Best-of CMEs” observed in 2010.} \]
this case also the tilt of the neutral line of the regions of opposite magnetic polarity and the modeled tilt of the flux rope CME, both being of the order 30°, do agree very well.

In contrast to Figure 13, Figure 14 presents an example of a larger discrepancy between the SR latitude and CME latitude for a CME observed on 8 March 2010. In this case the deviation amounts to 37° in solar latitude.

5. Conclusion

In this paper we introduce a CME list based on STEREO/SECCHI/COR2 coronagraph observations. We found that the COR2 CME list is in good agreement with the LASCO CME catalog for events with an angular width greater than or equal to 45°. The COR2 CME list (available online at http://soteria-event.uni-graz.at/) of the EU Seventh Framework Programme project SOTERIA can be considered as a valuable resource of classical large-scale CMEs. We find the monthly CME rates derived by LASCO and SECCHI observations

8Available in Tables 1 and 2 in the Electronic Supplementary Material.
rise by a factor of 3 to 4 between September 2009 and March 2010. This increase can be interpreted as the start of the overall rise of solar activity towards the next solar maximum expected around the year 2012–2013.

From the SOTERIA COR2 CME list we selected 120 events as a “Best-of” list based on their brightness appearance in the COR2 field of view. Fifty-one of the “Best-of CMEs” have been modeled using the GCS forward-modeling technique developed by Thernisien, Howard, and Vourlidas (2006) and Thernisien, Vourlidas, and Howard (2009) to infer the CME’s 3D structure. The modeling results reveal:
• A good fit of the observed CME white-light structure as GCS flux ropes.
• The calculated GCS apex latitude position is between 30° southern and 40° northern hemisphere of the solar equator for CMEs observed in 2010.
• The tilt angle for GCS modeled flux ropes is distributed between roughly ±40°.
• The flux rope half angle extends from 10° up to 25° which corresponds to an angular width of the CME lying between 20° and 50°.

From the comparison of the GCS modeled apex position with the identified associated source region position it is found that in 82% of the CME events the discrepancy extends from 0° up to 30° in Carrington longitude. Larger deviations occurred only for a smaller number of events and the larger differences are also less frequent. A similar behavior is found for the difference in solar latitude between the identified SR and modeled apex positions. Here 82% of all CME events exhibit a discrepancy of less than 25° in solar latitude. These findings imply that the observed CMEs were commonly deflected away from the radial direction over the first few solar radii.

Some issues which were not discussed in detail in this study but are important and very interesting pertain to error bars of the GCS model parameters. So for example, it should be considered that the deviation for the parameters \( \gamma \) and \( \alpha \) are an order of magnitude larger than the deviation for the longitude and latitude. Hence the values for the tilt angle exhibit a larger uncertainty than those for the other parameters (Ternisién, Vourlidas, and Howard, 2009). Further analysis of the calculated GCS flux rope parameters and the investigation of possible CME deflection and CME distortion will be undertaken in the near future.

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Appendix

"Best-of CME" List:

| No  | Date yyyyymmdd | Time(A) hh:mm:ss | PA(A) [deg] | Time (B) hh:mm:ss | PA(B) [deg] | Comments  |
|-----|----------------|-------------------|-------------|-------------------|-------------|-----------|
| 005 | 20070101       | 15:02:40          | 90          | 15:02:46          | 90          | A++, B−   |
| 007 | 20070110       | 11:02:40          | 270         | 12:02:48          | 270         | A+, B−    |
| 020 | 20070312       | 00:02:40          | 90          | 00:03:01          | 90          | B−, A+    |
| 025 | 20070331       | 09:52:30          | 270         | 09:52:58          | 270         | B+        |
| 035 | 20070509       | 04:22:30          | 90          | 04:53:14          | 90          | A+, B−    |
| 038 | 20070515       | 19:22:30          | 45          | 20:23:17          | 45          | A++, B−   |
| 049 | 20070604       | 21:22:30          | 270         | 03:23:24n         | 270         | A+, B−    |
| 050 | 20070607       | 20:22:30          | 225         | 21:23:25          | 225         | A+, B−    |
| 060 | 20070708       | 20:22:30          | 90          | 21:23:32          | 90          | A+, B−    |
| 071 | 20070821       | 08:52:30          | 270         | 10:53:33          | 270         | A+, B−    |
| 078 | 20071008       | 17:22:30          | 270         | 16:53:22          | 270         | A−, B−    |
| 083 | 20071104       | 13:52:20          | 45          | 20:23:02          | 45          | A+, B−    |
| 086 | 20071116       | 10:52:20          | 225         | 12:52:57          | 225         | A+, B−    |
| 092 | 20071231       | 01:22:20          | 135         | 01:52:42          | 135         | A++, B+   |
| 093 | 20080102       | 10:22:20          | 90          | 11:22:41          | 90          | A++, B+   |
| 095 | 20080122       | 23:52:20          | 180         | 23:52:38          | 135         | A+, B+    |
| 096 | 20080129       | 00:22:20          | 270         | 00:22:37          | 270         | A+, B−    |
| 100 | 20080212       | 07:52:20          | 225         | 09:22:36          | 225         | A+, B−    |
| 104 | 20080223       | 20:52:20          | 45          | 17:52:37          | 45          | A+, B−    |
| 105 | 20080227       | 12:52:20          | 270         | 10:22:37          | 270         | A+, B−    |
| 107 | 20080317       | 15:52:20          | 270         | 12:52:40          | 270         | B−, A−    |
| 111 | 20080325       | 19:22:20          | 90          | 19:52:42          | 90          | A+, B−    |
| 113 | 20080405       | 16:22:20          | 270         | 16:52:45          | 270         | A+, B−    |
| 121 | 20080426       | 14:52:20          | 45          | 15:52:53          | 315         | A+, B−    |
| 125 | 20080517       | 10:52:20          | 90          | 12:23:01          | 90          | A+, B−    |
| 130 | 20080601       | 23:22:20          | 90          | –                 | –           | A+        |
| 141 | 20080731       | 06:22:20          | 270         | –                 | –           | A−        |
| 145 | 20080908       | 02:22:20          | 270         | 03:53:22          | 90          | A−, B+    |
| 156 | 20081017       | 09:52:20          | 270         | 10:53:14          | 90          | A−, B+    |
| 158 | 20081026       | 23:52:20          | 270         | 22:23:11          | 270         | A−, B+    |
| 162 | 20081103       | 01:22:20          | 45          | 01:53:09          | 315         | A−, B−    |
| 167 | 20081113       | 16:22:20          | 225         | 15:23:06          | 135         | A+, B−    |
| 172 | 20081212       | 22:22:20          | 270         | 04:23:02n         | 270         | A+, B−    |
| 175 | 20081208       | 17:22:20          | 315         | –                 | –           | A++       |
Table 3 (Continued)

| No | Date       | Time(A)    | PA(A) [deg] | Time (B)    | PA(B) [deg] | Comments |
|----|------------|------------|-------------|-------------|-------------|----------|
|    | yyyy:mm/dd | hh:mm:ss   |             | hh:mm:ss    |             |          |
| 176| 20081212   | 08:22:20   | 90          | 08:22:55    | 270         | A−, B+   |
| 179| 20081227   | 06:52:20   | 45          | 10:52:50    | 315         | A−, B−   |
| 186| 20090114   | 06:22:00   | 90          | 11:22:00    | 270         | A+, B−   |
| 188| 20090117   | –          | –           | 14:22:24    | 90          | B+       |
| 195| 20090210   | 20:52:00   | 270,90      | 01:52:19n   | 225,90      | A+, B−   |
| 198| 20090218   | 09:22:00   | 90          | 15:22:19    | 45 – 315    | A+, B−   |
| 207| 20090316   | 14:22:00   | 90,270      | 12:22:19    | 90,270      | A−, B+   |
| 208| 20090318   | 00:22:00   | 90          | 07:22:19    | 315         | A+, B−   |
| 213| 20090326   | 09:22:00   | 270         | 19:22:20    | 135         | A+, B+   |
| 217| 20090410   | 19:22:00   | 270         | –           | –           | A+       |
| 226| 20090423   | 00:22:00   | 90,315      | 00:22:26    | 90          | A+, B−   |
| 228| 20090502   | 23:22:00   | 270         | 20:22:28    | 90          | A−, B+   |
| 234| 20090521   | –          | –           | 19:22:35    | 135         | B+       |
| 243| 20090613   | 13:52:00   | 90          | 14:52:43    | 270         | A+, B−   |
| 244| 20090615   | 02:52:00n  | 90          | 21:22:43    | 270         | A+, B−   |
| 245| 20090616   | 16:52:00   | 270         | 16:52:44    | 270         | A+, B−   |
| 259| 20090723   | 08:22:00   | 270         | 06:52:49    | 90          | A−, B+   |
| 262| 20090804   | 18:22:00   | 90          | 18:22:49    | 270         | A+, B+   |
| 263| 20090808   | 16:52:00   | 90          | 22:22:49    | 90          | A+, B−   |
| 264| 20090811   | 14:22:49   | 90          | 20:22:00    | 270         | A−, B++  |
| 265| 20090813   | 03:22:00   | 270         | –           | –           | A+       |
| 267| 20090819   | 03:08:15   | 270         | 05:09:04    | 90          | A+, B−   |
| 271| 20090903   | 12:08:15   | 90          | 05:09:04    | 270         | A−, B+   |
| 288| 20091031   | 05:08:15   | 90          | 05:09:04    | 270         | A−, B+   |
| 291| 20091108   | 05:08:15   | 270         | 06:09:04    | 45          | A++, B−   |
| 293| 20091115   | 13:08:15   | 270         | –           | –           | A−       |
| 299| 20091121   | 08:08:15   | 90          | 11:09:04    | 270         | A++, B−   |
| 307| 20091216   | 03:08:15   | 90          | 04:08:58    | 270         | A+, B−   |
| 325m| 20100201  | 23:08:15   | 135 – 270   | 22:09:04    | 225         | A−, B++  |
| 333m| 20100211  | 21:08:15   | 90          | 23:08:41    | 270         | A−, B++  |
| 337m| 20100214  | 08:08:15   | 45          | 05:08:40    | 270         | A−, B+   |
| 347m| 20100225  | 01:08:15   | 135,225     | 02:08:38    | 225,45      | A++, B−   |
| 350m| 20100228  | 18:08:15   | 315         | 19:08:37    | 45          | A++, B+   |
| 351m| 20100301  | 09:08:15   | 135 – 180   | 08:08:37    | 225         | A−, B+   |
| 359m| 20100309  | 08:08:15   | 270         | 12:08:36    | 90          | A+, B−   |
| 365m| 20100314  | 13:08:15   | 225         | 14:08:36    | 90          | A−, B++  |
| 369m| 20100319  | 20:08:15   | 90          | 21:08:35    | 270         | A+, B++  |
| 370m| 20100320  | 09:08:15   | 270         | 11:08:35    | 315 – 135   | A++, B−   |
| 373m| 20100326  | 16:08:15   | 90          | 17:08:35    | 270         | A−, B+   |
| 376m| 20100329  | 12:08:15   | 270         | 14:08:35    | 90          | A+, B−   |
| 377m| 20100330  | 12:08:15   | 135,315     | 14:08:35    | 45,225      | A++, B+   |
| 379m| 20100403  | 11:08:15   | 135         | 12:08:35    | 225         | A++, B++  |
| 383m| 20100408  | 09:08:15   | 90          | 07:08:36    | 270         | A−, B−   |
| 386m| 20100411  | 09:08:15   | 225         | 11:08:36    | 135         | A+, B−   |
| No | Date yyyyymmdd | Time(A) hh:mm:ss | PA(A) [deg] | Time (B) hh:mm:ss | PA(B) [deg] | Comments |
|----|----------------|-------------------|------------|-------------------|------------|----------|
| 387m | 20100412 | 10:08:15 | 225 | 13:08:36 | 135 | A−, B− |
| 389m | 20100413 | 15:08:15 | 45 | 14:08:36 | 315 | A−, B++ |
| 391m | 20100419 | 05:08:15 | 135 | 04:08:36 | 225 | A−, B+ |
| 392m | 20100419 | 23:08:15 | 45 | 00:08:37n | 315 | A−, B++ |
| 404m | 20100506 | 01:08:15 | 180 | 02:08:39 | 225 | A−, B+ |
| 415m | 20100523 | 00:08:15 | 270 | 00:08:43 | 90 | A+, B− |
| 416m | 20100523 | 21:08:15 | 90 | 22:08:43 | 270 | A+, B++ |
| 418m | 20100524 | 17:08:15 | 90 | 17:08:43 | 270 | A−, B+ |
| 426m | 20100604 | 16:08:15 | 270 | 16:08:46 | 90 | A+, B++ |
| 429m | 20100612 | 16:08:15 | 45 | 18:08:49 | 0 | A+, B− |
| 432m | 20100615 | 03:08:15 | 225,45 | 04:08:49 | 135,0 | A+, B+ |
| 434m | 20100616 | 19:08:15 | 90 | 20:08:50 | 270 | A−, B− |
| 435m | 20100619 | 03:08:15 | 315 | 04:08:51 | 45 | A+, B− |
| 437m | 20100620 | 22:08:15 | 90 | 23:08:15 | 270 | A−, B− |
| 444m | 20100703 | 07:08:15 | 270 | 08:08:55 | 90 | A+, B++ |
| 445m | 20100703 | 13:08:15 | 180,90 | 14:08:55 | 225,315 | A+, B+ |
| 448m | 20100705 | 21:08:15 | 315 | 20:08:56 | 45 | A−, B− |
| 449m | 20100706 | 08:08:15 | 90,360 | 09:08:56 | 270 | A−−, B+ |
| 464m | 20100801 | 04:08:15 | 90 | 05:09:04 | 270 | A−, B− |
| 465a | 20100801 | 09:08:15 | 90 | 10:09:04 | 315 | A+, B++ |
| 465b | 20100801 | 08:08:15 | 45 | 10:08:15 | 315 | A−, B− |
| 470m | 20100807 | 20:08:15 | 90,225 | 21:09:05 | 270 | A++, B++, H |
| 471m | 20100808 | 17:08:15 | 225 | 18:09:06 | 135 | A+, B+ |
| 474m | 20100814 | 12:08:15 | 135 | 13:09:07 | 225−270 | A+, B+, H |
| 476m | 20100815 | 14:08:15 | 45 | 16:09:07 | 315 | A+, B− |
| 479m | 20100818 | 06:08:15 | 45 | 07:09:08 | 315 | A+, B+ |
| 500m | 20100911 | 06:08:15 | 45,225 | 07:09:12 | 315,135 | A+, B− |
| 511m | 20101001 | 05:08:15 | 315 | 06:09:14 | 45 | A++, B+ |
| 515m | 20101006 | 10:08:15 | 90 | 14:09:14 | 270 | A+, B+ |
| 516m | 20101007 | 15:08:15 | 0 | 16:09:14 | 0 | A+, B+ |
| 519m | 20101011 | 05:08:15 | 90 | 06:09:14 | 270 | A++, B++ |
| 525m | 20101026 | 15:08:15 | 135,315 | 16:09:14 | 225,0 | A++, B+ |
| 525m | 20101028 | 16:08:15 | 215 | 15:09:13 | 90 | A++, B++ |
| 546m | 20101116 | 14:08:15 | 135 | 15:09:11 | 225 | A+, B− |
| 551m | 20101124 | 09:08:15 | 135 | 10:09:10 | 270 | A−, B+ |
| 552 | 20101126 | 00:08:15 | 225 | 01:09:10 | 135 | A+, B+ |
| 558 | 20101202 | 13:08:15 | 270 | 16:09:09 | 90 | A−, B− |
| 561 | 20101206 | 00:08:15n | 135 | 23:09:08 | 225 | A++, B+ |
| 566 | 20101212 | 08:08:15 | 45,135 | 10:09:06 | 225,315 | A+, B+, pH |
| 568 | 20101214 | 18:08:15 | 45 | 19:09:06 | 315 | A+, B+ |
| 574 | 20101223 | 12:08:15 | 90 | 13:09:04 | 270 | A+, B+ |
| 576 | 20101226 | 09:08:15 | 225 | 10:09:03 | 135 | A++, B++ |

One event was found in the synoptic movies subsequently, it was labeled with 465b and the previously found event 465 with 465a.
Fit results of the modeled “Best-of” events:

| No  | φ [deg] | θ [deg] | γ [deg] | $h_{\text{front}}$ | $r_{\text{sun}}$ | κ [deg] | Time of modeling | \(\text{yyyymmdd-hhmmss}\) |
|-----|--------|--------|--------|----------------|---------------|--------|------------------|---------------------------|
| 325 | 39.132 | −18.446 | 15.091 | 16.786         | 0.277         | 23.198 | 20100201 – 210815 |
| 333 | 219.132| −15.653 | −22.919 | 11.714         | 0.234         | 16.491 | 20100211 – 230815 |
| 337 | 197.888| 11.180  | −27.392 | 12.214         | 0.330         | 17.888 | 20100214 – 050815 |
| 347 | 339.876| −24.037 | −19.566 | 13.071         | 0.336         | 18.167 | 20100225 – 000815 |
| 350 | 144.223| 36.335  | 1.118   | 11.714         | 0.517         | 28.229 | 20100228 – 180815 |
| 351 | 19.008 | −19.008 | 5.031   | 14.714         | 0.397         | 18.167 | 20100301 – 070815 |
| 359 | 48.074 | 12.857  | −13.415 | 13.143         | 0.333         | 18.726 | 20100309 – 110815 |
| 365 | 19.008 | −8.384  | 2.236   | 13.786         | 0.376         | 11.180 | 20100314 – 130815 |
| 369 | 106.211| −11.740 | −6.709  | 13.714         | 0.385         | 18.726 | 20100319 – 200815 |
| 370 | 205.715| 12.857  | −24.037 | 12.214         | 0.597         | 40.528 | 20100320 – 090815 |
| 373 | 21.244 | −1.118  | −39.690 | 15.000         | 0.244         | 9.783  | 20100326 – 170815 |
| 376 | 126.335| 1.678   | 25.715  | 11.857         | 0.388         | 22.640 | 20100329 – 120815 |
| 377 | 253.789| −28.510 | −16.771 | 15.000         | 0.410         | 14.533 | 20100330 – 140815 |
| 379 | 258.260| −26.273 | −1.118  | 13.643         | 0.419         | 16.491 | 20100403 – 120815 |
| 383 | 195.653| 8.383   | 14.928  | 14.928         | 0.367         | 16.211 | 20100404 – 080815 |
| 386 | 326.459| −15.993 | 23.477  | 12.214         | 0.394         | 16.771 | 20100411 – 080815 |
| 387 | 266.087| −25.155 | −29.630 | 13.429         | 0.244         | 9.783  | 20100412 – 110815 |
| 389 | 159.876| 35.217  | −21.803 | 14.786         | 0.499         | 17.888 | 20100413 – 150815 |
| 391 | 91.678 | −21.242 | 12.857  | 13.357         | 0.514         | 15.932 | 20100419 – 040815 |
| 392 | 86.087 | 26.271  | −27.950 | 15.286         | 0.622         | 10.901 | 20100420 – 000815 |
| 404 | 251.554| −24.597 | 90.000  | 15.500         | 0.665         | 11.460 | 20100506 – 020815 |
| 415 | 125.215| −0.560  | −32.422 | 12.072         | 0.336         | 11.739 | 20100523 – 000815 |
| 416 | 320.868| 7.826   | −9.506  | 12.857         | 0.480         | 13.975 | 20100523 – 220815 |
| 418 | 304.099| −3.913  | −31.304 | 11.929         | 0.520         | 20.123 | 20100524 – 170815 |
| 426 | 319.752| 2.236   | 28.510  | 14.429         | 0.333         | 26.553 | 20100604 – 160815 |
| 429 | 336.521| 30.186  | −40.810 | 16.286         | 0.327         | 6.149  | 20100612 – 180815 |
| 432 | 228.074| −30.186 | −7.267  | 14.571         | 0.351         | 24.317 | 20100615 – 020815 |
| 434 | 326.459| 2.795   | −7.828  | 14.000         | 0.262         | 24.595 | 20100616 – 210815 |
| 435 | 98.381 | 20.124  | −23.477 | 13.214         | 0.311         | 18.726 | 20100619 – 040815 |
| 437 | 305.219| 10.622  | 2.236   | 13.714         | 0.213         | 15.652 | 20100621 – 030815 |
| 444 | 346.583| 10.062  | −22.919 | 14.928         | 0.428         | 14.255 | 20100703 – 080815 |
| 445 | 205.715| −26.273 | 1.118   | 18.072         | 0.284         | 15.373 | 20100703 – 140815 |
| 448 | 320.868| 40.806  | −40.250 | 12.643         | 0.434         | 13.975 | 20100705 – 210815 |
| 449 | 134.161| −5.031  | −21.242 | 14.000         | 0.268         | 9.783  | 20100706 – 100815 |
| 464 | 102.856| 7.267   | 36.335  | 12.000         | 0.127         | 11.739 | 20100801 – 060815 |
| 465a| 79.380 | 13.415  | −67.640 | 14.000         | 0.272         | 23.198 | 20100801 – 100815 |
| 465b| 135.281| 32.981  | −15.653 | 4.857          | 0.271         | 16.211 | 20100801 – 100815 |
### Table 4 (Continued)

| No  | $\phi$ [deg] | $\theta$ [deg] | $\gamma$ [deg] | $h_{\text{front}}$ | $\kappa$ | $\alpha$ [deg] | Time of modeling yyyyymmdd-hhmmss |
|-----|--------------|----------------|----------------|-----------------------|-----------|----------------|----------------------------------|
| 470 | 324.223      | $-1.118$       | $-32.422$      | 21.857                | 0.539     | 8.663          | 20100807 – 210815                |
| 471 | 200.124      | $-22.919$      | 2.795          | 12.857                | 0.431     | 23.478         | 20100808 – 180815                |
| 474 | 353.293      | $-5.031$       | 3.535          | 14.357                | 0.816     | 31.025         | 20100814 – 120815                |
| 476 | 310.806      | 32.981         | $-25.155$      | 15.214                | 0.373     | 21.522         | 20100815 – 150815                |
| 479 | 348.818      | $-6.709$       | $-43.043$      | 16.071                | 0.717     | 12.019         | 20100818 – 070815                |
| 500 | 264.967      | 22.360         | 2.795          | 13.214                | 0.579     | 19.565         | 20100911 – 070815                |
| 511 | 176.645      | 42.484         | $-1.118$       | 14.714                | 0.299     | 22.919         | 20101001 – 050815                |
| 515 | 280.620      | 21.802         | $-4.471$       | 9.429                 | 0.345     | 20.404         | 20101006 – 100815                |
| 516 | 8.942        | 45.279         | 23.477         | 13.214                | 0.357     | 37.174         | 20101007 – 150815                |
| 519 | 225.839      | 6.709          | $-41.366$      | 13.571                | 0.523     | 35.496         | 20101011 – 060815                |
| 525 | 69.318       | $-25.715$      | $-40.810$      | 13.357                | 0.545     | 11.739         | 20101026 – 140815                |
| 528 | 205.715      | $-17.888$      | 2.795          | 10.572                | 0.487     | 35.217         | 20101028 – 150815                |
| 546 | 86.087       | $-25.715$      | $-2.795$       | 12.857                | 0.382     | 19.286         | 20101116 – 150815                |
| 551 | 22.360       | $-21.803$      | 22.919         | 13.786                | 0.397     | 22.361         | 20101124 – 090815                |

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