AUTOMATED LASCO CME CATALOG FOR SOLAR CYCLE 23: ARE CMEs SCALE INVARIANT?

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ABSTRACT

In this paper, we present the first automatically constructed LASCO coronal mass ejection (CME) catalog, a result of the application of the Computer Aided CME Tracking software (CACTus) on the LASCO archive during the interval 1997 September-2007 January. We have studied the CME characteristics and have compared them with similar results obtained by manual detection (CDAW CME catalog). On average, CACTus detects less than two events per day during solar minimum, up to eight events during maximum, nearly half of them being narrow ($< 20^{\circ}$). Assuming a correction factor, we find that the CACTus CME rate is surprisingly consistent with CME rates found during the past 30 years. The CACTus statistics show that small-scale outflow is ubiquitously observed in the outer corona. The majority of CACTus-only events are narrow transients related to previous CME activity or to intensity variations in the slow solar wind, reflecting its turbulent nature. A significant fraction (about 15%) of CACTus-only events were identified as independent events, thus not related to other CME activity. The CACTus CME width distribution is essentially scale invariant in angular span over a range of scales from 20° to 120° while previous catalogs present a broad maximum around 30° . The possibility that the size of coronal mass outflows follow a power-law distribution could indicate that no typical CME size exists, i.e., that the narrow transients are not different from the larger well defined CMEs.

Key words: Sun: activity - Sun: coronal mass ejections (CMEs) - solar wind

1. INTRODUCTION

In this paper, we discuss an attempt to quantify the detection of coronal mass ejections (CMEs). CMEs are episodic expulsions of mass and magnetic field from the solar corona into the interplanetary medium. A classical CME carries away some 10^{15} g of coronal mass and can liberate energies of 10^{23} – 10^{25} J (Howard et al. 1985; Vourlidas et al. 2002). In broad band white-light coronagraphic images, CMEs are seen as bright features moving radially outward. Building a CME catalog basically means listing all occurrences of events, defined as CMEs. CMEs can be very bright and often show evidence of magnetic structure (e.g., twisted flux rope), but sometimes, no discernible structure is present or the intensity enhancement is only very weak compared to the background corona (e.g., due to projection effects), which makes it very hard to detect and characterize them. The application of the automated CME detection software on the LASCO archive (see next section for a description of the Software) shows a picture of coronal activity that corresponds well to the variety of CME types presented in Howard et al. (1985).

After three decades of coronagraphic observations, the statistical properties of CMEs are relatively well known. CME angular span, speeds, latitudes, and masses have been measured and statistically analyzed (e.g., Yashiro et al. 2004; Cremades & St. Cyr 2007, and references therein). In contrast to this huge amount of observations and studies of CMEs, there remain a number of unresolved issues and their physics is not well understood, especially their initiation mechanism. Ever since the start of CME observation, several events had an "unclear" status and up to date a large fraction of the observations does not fit in the "flux rope CME" picture. Do they appear differently because of effects of projection and Thomson scattering? Cremades & Bothmer (2004) have shown how big the impact of projection effects can be. Currently, STEREO/SECCHI (Howard et al.

2008) observations show unambiguous evidence that coronagraphic observations only show a two-dimensional reflection of the whole three-dimensional corona. For example, a bright well defined CME was observed in the A spacecraft on 2008 February 13. With the B spacecraft, 45° separated from A, only a faint partial halo was detected (see Figure 1). Undoubtedly, STEREO will greatly advance our insight in these effects. Also instrumental sensitivity influences what we see. The "double spike" events, as classified by Howard et al. (1985), were believed to be part of one event (and hence listed together) consisting of two legs connected by a faint arch. The arch was too faint to be observed by Solwind, but was observed by SMM (MacQueen et al. 1980). So, what we call "background outflow" might actually be an erupting magnetic structure, containing, e.g., a mini-flux rope (mini referring to angular sizes smaller than 20°). Could the "single spikes" simply be double spikes of which only one leg is visible?

Small-scale variations are more numerous than large "structured" events. Are they the signatures of magnetic instabilities seen as episodic expulsions of mass? High-resolution STEREO/ EUVI images show small dimmings across the solar disk, covering the quiet sun. Undoubtedly, part of this activity is seen higher in the corona. Just as the quiet sun is not really quiet, the slow solar wind is not merely a quiet steady flow, but a flow with turbulent nature. Where does the turbulence end and the "foreground" activity start? At solar active times, a wealth of outward moving brightness features is observed mostly as narrow transients, complementary to the well distinct CMEs. Is it possible to draw an imaginary line between "real CMEs" and "small discrete outflow" on physical grounds, or does there exist a continuum from large bright CMEs to small unimportant events? For example, are jets along streamers simply the larger "blobs" observed by Sheeley et al. (1997) or are they at the lower range of CMEs? The problem of the inclusion of "narrow" events in catalogs is not new and dates from pre-LASCO obser-



Figure 1. STEREO/COR2 image pair in running difference (left: B, right: A, separation angle: 45°) illustrating the influence of projection effects on the appearance of a CME. The CME was observed on 2008 February 13 as a near-limb CME by the A spacecraft and a faint partial halo in the B spacecraft.

vations. In an examination of Solwind coronagraphic images, Howard et al. (1985) had "no trouble agreeing that large bright CMEs were significant events. The question became whether to include all faint or very narrow CMEs in our analysis."

The first study to provide a statistical view of the properties of CMEs observed by LASCO during 1996–1998 is given by St. Cyr et al. (2000). In this study, it is explicitly mentioned that "(1) the polar microjets reported by Moses et al. (1997) and (2) the small inhomogeneities that may trace out the low latitude acceleration of the slow solar wind (Sheeley et al. 1997) are both excluded." The authors confirm that these marginal events satisfy the observable definition of CMEs, but they are excluded from the statistical study.

In the next section, we describe the composition of the Computer Aided CME Tracking software (CACTus) catalog and the available data. Thereafter, we focus on the CME rate during cycle 23 (Section 3) and discuss the statistics of the CME parameters (Section 4). Particular attention is given to the small ejections and outflow in the discussion section (Section 5).

2. COMPOSITION OF THE CATALOG

Based on the CACTus, we have constructed an objective CME catalog based on LASCO data (Brueckner et al. 1995) spanning the period 1999 September-2007 January. We refer to it as the "CACTus CME catalog" and it can be found online at http://sidc.be/cactus. The CACTus software package was first reported in Berghmans (2002) and is extensively described in Robbrecht & Berghmans (2004). The CACTus detects CMEs in height-time maps constructed from LASCO C2/C3 images. CMEs are seen as inclined lines in height-time maps and are detected using the Hough transform. The method has two inherent limitations: (1) only radial motion can be detected and (2) no acceleration can be measured since CACTus detects straight lines in the height-time maps. At present, the CACTus measures the following parameters: first time of appearance in C2, CME width, principal direction (defined as the middle direction of the CME) and a linear speed profile along the angular span of the CME. To limit computation time and false detections, we have set three criteria for the selection of CMEs. Only detections with plane-of-sky-speeds between 100 and 2100 km s⁻¹ (slow CMEs require most computation time since they need many images to travel through the C2/C3 FOV

(field of view); the errors on the speed measurements become large for faster CMEs), with an integrated $\Delta I/I$ ridge intensity (in the height-time space) above a fixed threshold and with an angular span $\geq 10^{\circ}$ are retained.

Prior to preprocessing, the images are tested for their reliability. This step is performed in order to limit the amount of false detections due to corrupt images. They arise, for example, from dust particles or small debris flying in front of the telescope just at the time an image was taken, from highly deviating exposure times, and from errors in data acquisition, transmission, and reconstruction. During the first months of the mission, only the equatorial region for the FOV was transmitted. This style of image compression was gradually decreased and abandoned in 1997 September. Moreover, the nominal cadence of both C2 and C3 was only one image per hour (compared to respectively three and two per hour). For these reasons, the current data set used for our long-term analysis runs from 1997 September until 2007 January. Nominal observations have been interrupted as a consequence of exceptional satellite problems.⁴ A three months data gap occurred in 1998 from 24 June to 22 October due to an unexpected loss of contact with the spacecraft. Subsequent failure of all three gyroscopes caused an interruption from 1998 December 21 to 1999 February 6. A third data gap occurred in 2003 June, when SOHO's main antenna became stuck. This problem was overcome and nominal observations resumed on July 10. Additionally, regular gaps of a few days through the whole mission's lifetime occur during the SOHO "keyhole periods."

3. CME RATE DURING CYCLE 23

Figure 2 shows the daily CACTus CME rate for cycle 23 in red, with the International Sunspot Number (e.g., Vanlommel et al. 2004) superimposed in gray as solar cycle reference. We have also plotted the daily CDAW CME rates in blue (Yashiro et al. 2004). It is available online and is widely used by the solar community as a reference LASCO CME catalog. The *average* daily values for CACTus and CDAW are given in Table 1. The CME rates that we report in this paper have been corrected for instrument duty cycle. We applied a different correction to the CACTus CME rates and the CDAW rates, because CACTus does

⁴ http://sohowww.nascom.nasa.gov/about/Recovery/docs/ index.html



Figure 2. Daily SOHO LASCO CME rates for cycle 23 (thin curves: smoothed per month, thick curves: smoothed over 13 months) from 1997 to 2006, extracted from the CACTus (red) and the CDAW (blue) CME catalog. As a reference, we have overplotted the daily and monthly smoothed sunspot number (SSN) (gray) produced by the SIDC-Royal Observatory of Belgium. The CME rates have been corrected for duty cycle (see the text for details).

 Table 1

 Average Daily CME Rates Derived From LASCO (cycle 23) Duty Cycle Corrected

Data	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
CACTus	3.0	4.2	7.2	8.1	7.8	7.8	6.3	4.9	3.7	2.4
CDAW	1.1	3.1	3.4	4.6	4.3	4.7	3.3	3.2	3.5	3.1

not accept all images. For CACTus, we deduced the number of effective observation days from the actual images we used as input, by subtracting all data gaps that were larger than 12 h. We did this based on the C2 data alone, as C2 data gaps overlap greatly with C3 data gaps. For correcting the CDAW CME rate, we used a file containing the C2 door closing times and subtracted all closing times from the total month time. For each catalog, we then scaled the number of CMEs counted during that month to the calculated number of observation days. We have applied a smoothing function on the monthly CME and sunspot rates by computing a boxcar (running) average over a smoothing window of 13 months. Our findings are:

- 1. Solar cycle effects. The smoothed CACTus CME rate (Figure 2, thick red curve) confirms the pre-SOHO observation that the CME rate follows the solar cycle (Webb & Howard 1994), here represented by the SSN. Also, the Gnevychev gap (GG Gnevyshev 1967), the dip in the maximum phase of solar activity, is well retrieved in the CACTus curve. Only the general trend is correlated, on short timescales the CME rate and SSN are not well correlated. The daily CACTus CME rate averaged per year increases roughly with a factor 4 from minimum to maximum. This factor is more or less stable for the different sizes of CMEs. On average there are ~ 2 CACTus events per day during solar minimum and ~ 8 events during solar maximum. Figure 3 shows that nearly half of the CACTus detections are narrow events (< 20°).
- 2. *CACTus rate is higher than CDAW rate.* As can be seen in Figure 2 the CACTus CME rate is much higher than the

CDAW rate (blue curve) for most of cycle 23. CACTus detects all bright outward radial motion independent of morphology or the presence of other activity. An observer will generally not list outflow activity in the aftermath of a large bright CME. In the discussion section, we will focus on the detection and quantization of coronal activity in general. The large discrepancy between the two CME curves is most pronounced during solar maximum years, but it is also present during other years. The flat CDAW curve in the decaying phase of the cycle (2004–2007) is very surprising in Figure 2. Since CACTus measures a systematic decrease from maximum to minimum and also the SSN decreases continuously, we do not interpret the CDAW flat rate as solely due to physical effects. Instead, different criteria used by different personnel could be the cause of differently populating the CME catalog (see Kane 2008, for a discussion). This however is unfortunate for CME statistics and shows the need for automated measurement of CME activity in the corona, in which the introduced biases are consistent for the whole observation.

3. CME cycle lags sunspot cycle. The CME activity of cycle 23 shows a significant peak delay with respect to the sunspot cycle (see Figure 2). Focusing on the monthly averaged curves, we find a lag time varying from six months (max peaks) to one year (Gnevychev gap). The CME rate during cycle 23 thus tracks the solar activity cycle in amplitude but phase shifted. Since this effect was not clearly present in the activity rates of cycle 21-22 (Webb & Howard 1994), this is possibly a peculiarity to cycle 23. The phenomenon of time delay has been observed in several other activity indicators. The chromospheric and coronal emission lines show delays of one to four months with respect to the sunspot index (Donnelly et al. 1983; Bachmann & White 1994) and time lags of 10 to 15 months are found for flare rates (Özgüç & Ataç 2001; Temmer et al. 2003). The mechanism leading to these and similar delays is not understood. An obvious remark to make here is that sunspots only reflect part of the source regions of CMEs. Several studies found that



Figure 3. Percentage of narrow CMEs (width smaller than 20°) compared to the total number of CMEs as listed by the CACTus (red) and CDAW (blue) catalog. As a reference to the solar cycle, we have plotted in gray the monthly and monthly smoothed SSN produced by the SIDC-Royal Observatory of Belgium.



Figure 4. Left: daily CME rate vs. SSN both averaged per year. The asterisks refer to rates for the cycle 23 derived from CACTus (see Table 1). Its absolute scale is shown on the right y-axis. The daily CME rates derived by Webb & Howard (1994) are plotted with diamonds. Its absolute scale is shown on the left y-axis. A scaling factor of ~ 4.7 applies between the CACTus and the Webb & Howard rates. Right: smoothed daily CACTus CME rate vs. smoothed SSN. The triangles denote the start of every year.

the majority of CMEs for which on-disk signatures could be observed are related to filament/prominence eruptions (e.g., Munro et al. 1979; Webb & Hundhausen 1987). Nevertheless, when treating the SSN as proxy for the (long term) solar cycle (i.e., not as a count of individual source regions), the observed time delays give an idea of the time needed to build up the necessary conditions for coronal activity.

4. *CME rate is consistent with past cycles.* Figure 4 (left) shows the daily CME rate versus SSN both averaged per year. The asterisks refer to rates for the current cycle (cycle 23) derived from CACTus, its absolute scale is shown on the right *y*-axis. The daily CME rates derived by Webb & Howard (1994) are plotted with diamonds, its absolute scale is shown on the left *y*-axis. The Webb & Howard rates are corrected for duty cycle and instrumental visibility and are based on data from *Skylab*, *Helios* (zodiacal light

photometer data), Solwind, and SMM. In total, they cover the period between 1973–1989. The absolute rates for the cycle 23 are much higher than those reported for previous cycles. This is due to the better instrument sensitivity, the enormous dynamic range of LASCO, the much larger FOV, and the more uniform coverage of data over a long period of time. Additionally, the CACTus detection system has higher detection sensitivity than manual detection, i.e., it picks up all radial outflow that exceeds the thresholds set for brightness and angle. By applying a simple scaling factor of ~ 4.7 to the previous CME rates, we could fit them to the CACTus scale or vice versa. Given the fact that these data points are derived from different instruments, using different techniques (manual versus automatic) over several solar cycles, these points match extremely well. Once again, this confirms that long-term CME activity is a function of the solar activity, here represented by the SSN.



Figure 5. Graph illustrating the CACTus–CDAW correspondence for two selected samples. It is based on two months during solar minimum (1998) and two months during solar maximum (2000). The gray boxes only cover the CDAW CMEs. Only 60% during solar minimum and 80% during solar maximum of these particular events could be connected to a CACTus–CME detection (green). Besides these, CACTus has detected many other events, which are not present in the CDAW catalog.

It can be seen that the current cycle was less strong than the previous cycles, the SSN only reaches ~ 120 , whereas for the two previous cycles a maximum of ~ 160 was retrieved. Likewise, the ratio of CME rates between solar maximum and minimum is ~ 4 for the current cycle, which is smaller than it was for the previous cycle where the ratio was on average larger than 5. From this comparison, we estimate that the CME activity was lower during cycle 23 compared to the previous cycle, despite the fact that the *absolute* CME rates were higher.

5. *CME rate rises faster than it decays.* In Figure 4 (right), we plot the smoothed CACTus daily CME rate versus the smoothed SSN. From this plot, it can be inferred that just like the SSN the CME rate steeply rises and decays slowly after solar maximum. This means that for the same number of sunspots, more CMEs are produced during the decaying phase. This does not necessarily mean that these sunspots are more active; it could also mean that more CMEs erupt from nonsunspot regions. This will be discussed in a subsequent paper (E. Robbrecht et al. 2008, in preparation).

4. STATISTICS OF CME PARAMETERS

In this section, we discuss the statistics of the CACTus CME parameters and compare them with the CDAW statistics. We also try to estimate the effect of measurement method on the different CME parameters (starting time, principal angle, angular width, speed) by comparing the measurements for a sample of common events (i.e., present in both catalogs). This sample was chosen large enough (336 events), such that the results are statistically significant and expandable toward the whole catalog. CME occurrence depends on the solar cycle; therefore, we have selected two different subsamples, one representing solar minimum (1998 February and May) and the other solar maximum (2000 April and August). For each day in each month we have plotted the detections on an angletime map and have visually inspected the LASCO movies in order to decide which entries are describing the same event. This leads to 114 common events for the minimum sample and 222 common events for the maximum. Figure 5 gives an overview of the CACTus-CDAW correspondence for the two



Figure 6. Histogram of CDAW–CACTus time differences of first detection for the 1998 sample (top) and the 2000 sample (bottom). The bin size was set to 10 minutes. The histogram is heavily biased by the time spacing between the LASCO C2 images. The nominal time spacing peaks around 23 minutes in 2000 and around 30 minutes in 1998.

selected periods. During solar maximum, 80% of the CDAW CMEs had a corresponding CACTus detection, but only 60% during solar minimum. We attribute this lower value to the lower average intensity of the running difference images during solar minimum and a lower image cadence (30 minutes in 1998 versus 23 minutes in 2000). All parameters derived from coronagraphic data are subject to severe projection effects that result in systematic inaccuracies. A study by Burkepile et al. (2004) on a set of 111 limb CMEs identified in SMM data gives estimations for "true" values of the CME parameters.

4.1. Detection of First Appearance

Figure 6 shows a histogram of time differences (CDAW–CACTus) of first detection. The bin size was set to 10 minutes. The histogram is heavily biased by the time spacing between the LASCO C2-images (~ 23 minutes in 2000 and ~ 30 minutes in 1998). From the histogram, we deduce that during solar max, 77% of the first detections differed maximal one image and during solar minimum the corresponding number is 64%. This is a good result given the fact that CACTus approximates the CME trajectory linearly. Both physical and technical reasons account for a difference in detection of the first appearance (both earlier and later), we list some of them below.

- 1. CMEs can drive waves or shocks ahead of them (e.g., Vourlidas et al. 2003). They can be observed as a bright (but faint) area prior to the bulk CME eruption.
- 2. Jackson & Hildner (1978) have observed "forerunners," which are described as regions where the corona is slightly more dense than its pretransient state. In LASCO data, we could also observe several cases where a slow rise in intensity is seen before the actual CME is observed. Depending on its intensity, it will be detected as "first appearance of the CME" by the observer/detection scheme.



Figure 7. First appearance of a CME is not always well defined. Here, we show a sequence of C2 and one C3 background subtracted images. A CME is seen erupting from the east limb, the CACTus speed measured was around 150 km s⁻¹. It is impossible to distinguish the background intensity prior to the event (streamer) and the erupting CME.

- 3. Another underlying mechanism causing a not sharp transition in intensity from background to CME is the preexistence of bright material or the very slow rise of a bright structure, prior to the eruption. This is typically the case, for the so-called 'streamer blowouts' in which the streamer material is blown away as part of the CME (see Figure 7).
- 4. From Figure 6 we can deduce that CACTus has a preference to detect CMEs more often early than late with respect to CDAW. This is a consequence of erroneously linking two sequential detections into one event. This is a typical example where the human interpretation *does* prove to be useful. CACTus detects motion in each (radial) direction independently. Using information on morphology and speed, an observer will notice that the activity occurring simultaneously comprises of two events. However, even for the observer, it is sometimes impossible to decide whether activity distributed around the occulter is actually linked to one another or not.

4.2. Apparent Width of CMEs

The angular width of a CME is a measure of the volume in the corona that is "blown out." The *apparent* width derived from coronagraphic data indicate the angular size of this volume projected onto the plane of the sky. This angular size, measured as the angular span around the occulter, remains quasi constant in the C2/C3 FOV, while the CME is propagating outward. This suggests that CMEs expand radially in a self-similar manner (Low 1982, 1984) above 2 R_{\odot} . A popular way to envision a CME geometrically is a circular cone (Zhao et al. 2002), having its vertex in the source region on the solar disk and the cone oriented in the direction of CME propagation. In the case of a limb CME, the cone angle corresponds to the angular span measured in projection onto the plane of the sky. The angular width (and latitude) derived from projected images is only an apparent quantity that depends on the CME orientation with respect to the observer. A CME launched in a direction close to the Sun-Earth direction appears as a "halo" or partial halo around the occulter. In this case, the angular width derived from the coronagraphic observation does not have a geometrical meaning. The "cone model" is a simplified picture; measurements of spatial parameters like CME width and latitude are thus only proxies for CME "volume" and radial direction respectively.

4.2.1. Error Estimate

In order to quantify how much the CME width distribution depends on the measurement method, we compare the CME widths for the sample of *common* events. CACTus measures the largest width of the CME throughout its outward motion, and it is thus not a function of time. In Figure 8 (left), we have plotted the CME width histograms of the two samples in bins of 2°, which is the CACTus accuracy. The CACTus width distribution is peaked around 20° – 25° . The CDAW on the other hand shows a much flatter distribution and measures systematically wider CMEs. At the right a contour plot of the CACTus versus CDAW CME widths is shown in the range $[0, 200]^{\circ}$. The general direction of the bright contours match well with the y = x line. This confirms, at least for events smaller than 120° , that the CME width indeed is a good parameter for estimating the angular size and, hence, the volume of a CME. However, the large scatter of points indicates that the width is only vaguely defined and, thus, space for interpretation is left. For example, should CME wave or shock signatures be included when measuring the angular extent of the CME or not? This is not merely a definition issue, the question is rather if an observer is capable to make the distinction between a wave or shock pileup and a "real" CME only based on coronagraphic white-light data. A comparative study on "structured CMEs" by Cremades & Bothmer (2004) shows that different measurement criteria can lead to substantial differences in CME width measurements (they found differences up to 200° with values from the CDAW catalog). On average, they measured smaller CMEs and less halos than CDAW, because they did not include deflections of pre-existing structures or shock signatures. Our sample study showed that the CME width is particularly not well defined for CMEs exceeding 120°, especially halo CMEs. This is consistent with the result obtained by Burkepile et al. (2004), who found a maximum width of 110° for SMM limb CMEs. Out of the nine CACTus halo CMEs (from the sample) only two of them were also labeled "halo" by CDAW. Inversely, CDAW lists four halo CMEs which are not labeled halo by CACTus. As a consequence, care has to be taken when interpreting this parameter, especially for large CMEs.

4.2.2. CME Widths During Cycle 23

The CME width histograms of the two catalogs are shown in log–log scale in Figure 9. They overlap quite well for



Figure 8. Comparison of the CME widths for the two test samples. Left: in each graph a histogram of the CME widths is plotted with a bin size of 2° . The upper panel is based on a sample of 114 CMEs selected in the year 1998 (solar minimum) and the lower panel is based on a sample of 222 CMEs selected in the year 2000 (solar maximum). As compared to larger statistics described in this paper, these histograms appear quite "noisy." This is due to the limited sample size. Right: a contour plot illustrating the correspondence between CDAW and CACTus width measurements. The line y = x is plotted in black.



Figure 9. Apparent CME width distributions, displayed per year in log-log scale. The CACTus distribution corresponds to the red curve; the CDAW distribution is represented by the light blue curve. The distributions are not corrected for observing time.

CMEs larger than 40°, but show a remarkable difference toward the small side of the "angular spectrum." The CDAW CME widths are log-normally distributed, broadly peaked around 30° (e.g., Yurchyshyn et al. 2005), while the CACTus CME widths could as well suggest a power-law behavior, meaning that the CME widths θ would be distributed according $N(\theta) =$ $N_0\theta^{\alpha}$ with power $\alpha \approx -1.66$, where $N(\theta)$ is the number of events with angular extent θ , and N_0 is a constant.

The question of which distribution provides the best fit to the data (log normal, power law) cannot be decided solely on the results presented here. The minimal CACTus-CME width was set to 10° , meaning that smaller events were discarded. We, therefore, do not capture the peak in number of events at small angles—which must exist somewhere—or the rise at even smaller scales. However, the point we wish to stress here is that over a range of scales from 20° to 120° , the CACTus distribution is essentially scale invariant while previous catalogs present a broad maximum around 30° . On the other hand, the scale invariance for events larger than 40° is consistent for both data sets, shown by the overlap of both curves. In view of descriptive statistics, it is not so important which distribution describes best the data, but seen in perspective of understanding the initiation mechanism and evolution of CMEs, the type of distribution can give hints on the scaling laws that apply to the initiation mechanism. The power law of Figure 9 could indicate that eruptions and restructuring of the coronal magnetic field is a scale-invariant process: there is no typical size of a CME. For CMEs, this would be a new result, but for other types of coronal magnetic field restructuring it is well known. For flares, for example, Crosby et al. (1993) have shown that a power law of ~ -1.6 characterizes the flare energy over 3 orders of magnitude. The fact that exactly the same power law applies for



Figure 10. Left: Sample comparison of the apparent latitude distribution. The CACTus latitudes correspond to the filled graph, while the CDAW latitude distribution is shown in dashed line. Right: Histogram of the difference in principal angle CACTus CDAW is plotted; we used a bin size of 5° .

CME widths is intriguing. Probably this is merely a coincidence, possibly this hints at common physics of the flare and CME process.

4.3. Apparent Latitude of CMEs

The CME *projected* latitude is defined as the middle angle of the CME when seen in the white-light images. Due to the projection onto the plane of the sky, projected latitudes are always an upper limit of the true direction of propagation.

4.3.1. Error Estimate

In an attempt to deconvolve the latitudinal distributions from measurement effects, we study the latitudinal differences between the two catalogs, based on our two samples of common events. Figure 10 (right) shows the histogram of absolute differences in the latitudinal measurement. Interpreting these latitudinal differences in terms of measurement uncertainty. we can deduce that measurement errors of (at most) 10° and 20° apply respectively to 70% and 90% of the events for both samples. In the left figure, we compare the latitudinal distributions for the two samples (CACTus results correspond to the filled curve). The only peculiar difference is the peak at -10° latitude in the 1998 histogram (upper left). We verified the origin of this peak, but did not find a specific reason why CACTus would favor this latitude. All events in this peak, except one, differed less than 20° from the CDAW value. Hence, we conclude that the CACTus-CDAW differences in apparent latitude of $\sim 10^{\circ}$ have no significant effect on the latitudinal distributions. Apparent latitudes seem thus to have small errors introduced by measurement method. We note that latitudes are subject to large projection effects, so care has to be taken when interpreting the results below in terms of true latitudes. Additionally, CMEs often undergo nonradial motion in the lower corona before they reach the C2 FOV, which makes it difficult to derive CME source regions from latitudes derived from LASCO C2/C3 observations.

4.3.2. CME Latitudes During Cycle 23

Figure 11 (top) shows the latitudinal distribution for CACTus (red) and CDAW CMEs (blue) separated for each calendar year of LASCO observations. The C2 and C3 coronagraphs are both externally occulted. This means a circular occulting disk is placed in front of the entrance aperture. Hence, no direct sunlight falls into the instrument, reducing the stray light significantly. But, as a consequence, the region around the pylon holding the occulter has a smaller signal to noise ratio. This creates a bias in the latitudinal histograms in the region around the pylon. To remove this artificial bias from our statistics, we have corrected the latitudinal distributions in the direction of the pylon (which is either southeast or northwest). Assuming that eastern and western statistics are similar, due to the Sun's rotation, we applied a correction function to the data as illustrated in Figure 12. Let θ be an angle running from 0° to 90° and $N(\theta)$ the number of CMEs with principal angle θ , then $N(90^{\circ} + \theta) \equiv N(270^{\circ} - \theta)$. We have applied this correction to the CACTus and CDAW data sets over the whole period.

Contrary to what was found for the CMEs angular span, the type of the latitudinal distribution does evolve with the solar cycle. During solar minimum years (1997, 1998, and 2005), the CMEs principal directions are distributed quasi normally around the equator in the range $[-20, 20]^\circ$. During solar active years, CMEs erupt almost uniformly at all latitudes, even at higher apparent latitudes (70°) in both hemispheres. These findings are consistent with earlier observations from past cycles (Hundhausen 1993; Howard et al. 1986) and observations of current cycle (Gopalswamy 2004). It is important to note that the apparent latitudes are valid for the coronagraphic FOVs after undergoing deflections. As reported by Cremades & Bothmer (2004), deflections toward the equator are maximal during solar minimum years due to the presence of the polar coronal holes. The latitudinal CME distribution is thus not only governed by the latitude of the source regions, but also by the presence of coronal holes nearby.



Figure 11. Top: Yearly histograms of apparent latitudes of CMEs. The latitudes run from 0 at the equator to ± 90 at the north/south pole. The CACTus distribution corresponds to the red curve, while the CDAW distribution is represented by the light blue curve. Bottom: Difference of latitude histograms, the thick line is the smoothed curve. Positive values correspond to more CACTus CMEs.

According to the previous paragraph, there is a good correspondence between the global latitudinal properties of CMEs derived from CACTus and CDAW. However, there is a systematic difference. While analyzing the differences in CME width distribution between CACTus and CDAW, we discovered that the systematic higher CME rate, produced by CACTus, is mainly due to small events. Figure 11 (bottom half) shows us where these extra events are coming from. In the ascending phase (1998-2002), the small scale seems to be randomly distributed. In the descending phase (2003–2005), however, extra events are strongly restricted to two broad bands around $\pm 50^{\circ}$ latitude, bordered by the polar coronal holes at the pole side and by active regions at the equator side. No extra events (or even a small deficiency) are observed in the CACTus output in the active region band ($<30^\circ$). The fact that they are not just randomly distributed, but clearly structured, indicates they are reflecting an underlying large-scale process. This process must be time dependent, or in other words, solar cycle dependent. Further research is required to study this new subpopulation of CME-alikes and their precise source regions on the disk or higher up in the corona.

4.4. Apparent Speed of CMEs

Finally, we give an overview of the speed measurements and distributions shown in Figure 13. The CACTus CME speeds



Figure 12. Illustration of the correction we applied to the latitudinal distributions. The angles indicated are the principal angles, according to convention running counter clockwise from solar north. The plot applies when *SOHO* is in its normal position. The pylon holding the occulter is then positioned in the southeast. The histogram in the lower left quadrant is replaced with that from the lower right quadrant.

remain log-normally distributed, just like the CDAW speeds (e.g., Yurchyshyn et al. 2005). However, the CACTus CME speed distribution shows a much higher peak, which lies in the range of 200–400 km s⁻¹.



Figure 13. Yearly histograms of apparent radial speeds of CMEs. The speeds are derived from linear measurements and do not take into account acceleration or deceleration. We remind that we can only measure the speed component parallel to the plane of the sky. The CACTus distribution corresponds to the red curve and the CDAW distribution is represented by the blue curve.



Figure 14. Left: CME speed distributions compared for both samples. The CACTus speeds correspond to the filled graph and the CDAW speeds to the dashed line. Right: CDAW–CACTus speed differences.

4.4.1. Error Estimate

The CACTus and CDAW speeds differ by definition: CACTus measures a linear speed profile as a function of the angle around the occulter and lists the median value, while the CDAW observer only tracks the fastest moving feature of the leading edge. In this study, we compare the CACTus speeds with the linear speeds listed CDAW. In Figure 14, we compare the speed measurement for the two samples of common events. At the left, the two histograms are shown and at the right, the difference CDAW–CACTus is plotted. For both periods, the difference curve is slightly skewed toward positive difference values inferring a higher CDAW speed is favored. During solar minimum, a maximal uncertainty of 175 km s⁻¹ applies for more than 80% of the events; during solar maximum, the uncertainty is larger. There are a number of reasons which could contribute to the difference in speed given by CACTus and CDAW:

- The majority of large-speed differences occur for narrow CMEs. Possibly, this is because errors on individual measurements are averaged out better for more data points. The CACTus listed speed is the median of all measured speeds in the CME, the more data points, the more reliable this value is.
- 2. CMEs have internal speed variability, for example, as a consequence of interaction with different background solar wind structures. As example, we show two limb-CMEs in running difference and their speed measurement in Figure 15 (top). The CACTus speed profiles are quite uniform at the leading edge. The profiles are both distorted toward the edges of the CMEs. The magnetic and density structure of the ambient corona plays a not unimportant role in the outward evolution of CMEs (e.g., Jacobs et al. 2005) and vice versa. To illustrate this interaction, we have also plotted background subtracted images for these two



Figure 15. Illustration of two limb CME detections in running difference (top) and in background subtracted images (bottom). The speed profile measured by CACTus is shown in black and the CDAW speed is indicated by the black triangle in each top left frame. The velocity scale is indicated in black concentric circles in km s⁻¹. Bottom: For the left event, pre- and post-CME images are shown to illustrate the streamer displacement. At the right, we show a pre-CME image and an image containing the CME.

events. For the first event (left), pre- and post-CME images are shown. It can be seen that the brightest streamer is deflected down due to the interaction with the CME. For the second event (right), we show a pre-CME image and an image containing the CME. The helmet streamer at the north was pushed aside during the event, but adapted its original position after the CME had left. The disturbance is traveling outward through the streamer, and the radial component of its speed is captured by CACTus.

3. For some CMEs, there is a large uncertainty on the speed measurement, simply because the "front" of the outward moving feature is not clearly outlined. Even for the rather well-observed front of the first CME (erupting to the northeast) from Figure 15, CACTus and CDAW speeds deviate still 100 km s⁻¹.

5. DISCUSSION ON NARROW TRANSIENTS

A discussion on narrow events necessarily leads to a discussion on the definition of CMEs. Many questions arise: Is there a continuum from large CMEs down to narrow ejections representing the continuous coronal wind outflow? Can we introduce the term micro- or nano-CMEs, cfr. nano-flares (Parker 1988)? Are narrow ejections a subset of "normal" CMEs? Or do they form a separate class of events for which the pre-eruptive state is different from the "classical" CME scenario? What can these events, which sometimes occur prior to a larger CME, teach us on the CME initiation mechanism? If CMEs in general contribute to the reorganization of the large-scale magnetic field, does this also apply to these narrow events? If yes, they might act as "lilliputters" gradually untying the magnetic field lines which finally leads to unstable configurations. Too many questions to answer here, and probably several scenarios apply.

A combination of several criteria implies that some of these events are easily recognized as CMEs and others are not. Observable parameters for CME detection in white-light are: brightness, angular extent, well-defined shape and leading edge, suggestion of magnetic structure, time difference with major events occurring in the same direction. For example, jets have an unclear shape and do not often show an organized structure. This implies that if the jet is bright and wide, it is included in a catalog, but when it is faint or very narrow (like polar jets), they are usually not included. It seems thus that at least a number of the above criteria has to be fulfilled in order to count them as CMEs. On a close inspection of 171 "CACTus only" events (from the sample in 1998 and 2000), we find that the majority occur during times of other activity. Here, below is a list that tries to describe the different types of small events that we encountered.

- 1. Events split in space or time from another event, it is often not clear if there is an actual physical connection between the events or if they are just causally related (32, 18.7%).
- 2. Trailing outflow from the CME footpoints (28, 16.3%).
- 3. General activity, may be during or after a large CME (26, 15.2%).
- 4. Stand-alone events, including jets and recurrent events, sometimes ahead of a large CME (25, 14.6%).
- 5. Wavelike disturbances traveling through dense regions (e.g., streamers) (19, 11.1%).
- 6. False detections (13, 7.6%).
- 7. Unclear faint detections (12, 7.0%).
- 8. Slowly rising looplike structures, typically during the evolution of a streamer blowout (10, 5.8%).
- 9. Opening field lines that are crossing have a higher intensity and result in an apparent "blob" moving outward (5, 2.9%).

The above list shows that narrow/small events do not form one separate category, but have a variety in physical appearance. About 60% of the CACTus-only events are related to a larger eruption or reflect the high degree of activity in the corona (bursty outflow during solar active times). A small fraction (15%) are independent events that do not show any direct link to a large CME, e.g., jets (Wang & Sheeley 2002). Also, halo CMEs are often not recognized as such by CACTus, because the interconnection between outflow in different directions may be too faint to be detected, and this results in several smaller detections. The majority of narrow events occur thus as a sign of high coronal activity, i.e., in conjunction with well established CMEs.

The statistics based on the CACTus observations lead to the idea that a CME is not an "atomic" process, but a sequence of mass expulsions of which the dominant one is generally recognized as a (flux rope) CME. The bursty small-scale outflow, observed prior to, simultaneously with, or in the aftermath of the dominant eruption, is interpreted as being the result of multiple reconnections. This hints toward the existence of multiple thin current sheets over the total volume of the eruption, rather than a single monolithic current sheet. Ample observational and numerical evidence proves their existence and dynamics observed as bursty outflow (e.g., Ko et al. 2003; Webb et al. 2003; Riley et al. 2007; Ciaravella et al. 2002; Bemporad et al. 2006, and references therein). The post-eruptive blobs seem to be similar to the blobs observed by Sheeley et al. (1997) in streamer stalks.

A cascade of events down to smaller scales is the typical characteristic of self-organized systems and avalanche models. The observed power law in the CACTus CME width distribution suggests that coronal mass outflow is scale invariant, at least in the range of scales from 20° to 120° . The application of scale invariance to processes in the solar corona is extensively studied for solar flares (Lu & Hamilton 1991; Crosby et al. 1993), and is also investigated for the acceleration of high energetic particles (Vlahos et al. 2004; Cargill et al. 2006). Since all three processes are the result of rapid release of magnetic energy, it would not be surprising that scale invariance also applies to the CME eruption process. Specific studies on the mechanisms governing CME eruptions of various sizes are required to further this interpretation.

6. CONCLUSION

In this paper, we compare our statistics and measurements of CME parameters against the CDAW LASCO CME catalog (Gopalswamy et al. 2003; Yashiro et al. 2004) as reference catalog. In this catalog, small events like jets (not polar jets) are generally listed when they are distinct and bright enough. For the majority of large well-defined events, there is a relatively good agreement, but there are also periods where the two catalogs do not agree at all. This is because at some times, coronal activity is omnipresent, faint, and unstructured; for example, while the corona is restructuring hours to days after a large CME has erupted.

The CACTus CME rate follows the solar cycle, and changes roughly with a factor 4 between minimum and maximum. After applying a correction factor, we find that the CACTus CME rate is surprisingly consistent with CME rates found during the past 30 years. The CME rate shows a delay of 6 to 12 months with respect to the sunspot index. The CACTus CME rate decreases in the descending phase, whereas the CDAW CME rate remains quasi constant between 2004 and 2007, probably due to changes in observation criteria adopted by the operator. CME width and speed distributions do not show a great variation over the solar cycle, whereas the latitude histograms evolve from Gaussian during solar minimum to multimodal during solar maximum years, showing that coronal mass is erupting at all *projected* latitudes.

A comparison of a sample of common events shows that on average the CDAW CME width is wider than the CACTus CME width. A confusion in this parameter exists, since it is difficult to disentangle plasma from wave and shock signatures. Streamer deflections are generally not included in a CME width measurement, but bright waves or shocks sometimes are included by the operator, whereas CACTus only applies

a brightness criterion. There is a particularly bad overlap in halo CMEs, because they usually have several parts of lower intensity. The latitude measurements are quite compatible between CDAW and CACTus with 70% of the events having a difference below 10° in latitude. More than 80% of the CACTus-CDAW speeds differences are in the ± 175 km s⁻¹ range.

Our statistics show that small-scale outflow is ubiquitously observed in white-light data. Overall, CACTus detects many more events than CDAW, because it tracks all outward moving features. A sample study of CACTus-only events shows that the majority (about 60%) are small events related to previous CMEs or to high coronal activity (bursty outflow). Also individual events were detected (about 15%), and thus, small events are not a mere by-product of large well-established CMEs. The CACTus and CDAW CME width distributions diverge significantly for widths smaller than 40°. The CACTus distribution is essentially scale invariant over a range of scales from 20° to 120° . This supports the hypothesis that the corona, indeed, is a selforganized system, an idea that has been developed in relation to the scale invariance of flares and the acceleration of particles.

E.R. thanks Russ Howard for insightful discussions and Spiros Patsourakos for useful comments. This work is supported by PRODEX contract C90204 (Solar Drivers of Space Weather), managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office.

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