ERUPTIONS FROM SOLAR EPHEMERAL REGIONS AS AN EXTENSION OF THE SIZE DISTRIBUTION OF CORONAL MASS EJECTIONS

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ABSTRACT
Observations of the quiet solar corona in the 171 Å (~1 MK) passband of the Transition Region and Coronal Explorer (TRACE) often show disruptions of the coronal part of small-scale ephemeral bipolar regions that resemble the phenomena associated with coronal mass ejections (CMEs) on much larger scales: ephemeral regions exhibit flare-like brightenings, rapidly rising filaments carrying absorbing material at chromospheric temperatures, or the temporary dimming of the surrounding corona. I analyze all available TRACE observing sequences between 1998 April 1 and 2009 September 30 with full-resolution 171 Å image sequences spanning a day or more within 500 arcsec of disk center, observing essentially the quiet Sun with good exposures and relatively low background. Ten such data sets are identified between 2000 and 2008, spanning 570 hr of observing with a total of 17,133 exposures. Eighty small-scale coronal eruptions are identified. Their size distribution forms a smooth extension of the distribution of angular widths of CMEs, suggesting that the eruption frequency for bipolar magnetic regions is essentially scale free over at least 2 orders of magnitude, from eruptions near the arcsecond resolution limit of TRACE to the largest CMEs observed in the inner heliosphere. This scale range may be associated with the properties of the nested set of ranges of connectivity in the magnetic field in which increasingly large and energetic events can reach higher and higher into the corona until the heliosphere is reached.

Key words: Sun: activity — Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: surface magnetism

1. INTRODUCTION
Eruptive and explosive events in the solar corona exhibit a tendency for self-similar behavior that expresses itself in power-law distributions of frequency versus, e.g., size, total energy, or peak brightness (e.g., Drake 1971, Crosby et al. 1993, Aschwanden et al. 2000, and references therein). In the case of solar flares, there is a remarkable scaling from small flares observed in the EUV to large flares seen in hard X-rays, with essentially the same power-law index describing quiet-Sun “nanoflares,” active-region transient brightenings, and hard X-ray flares over 8 orders of magnitude in estimated flare energy (Aschwanden & Parnell 2002). A similar power-law behavior, albeit observable over a much smaller range in total energies, has been reported on for the energy distribution of large stellar flares (Audard et al. 2000). A power law is also a good approximation to, for example, the distribution of area or flux in recently emerged active regions (Harvey & Zwaan 1993), extending relatively smoothly into the domain of ephemeral regions (Hagenaar et al. 2003) over almost 5 orders of magnitude in absolute magnetic flux.

In a study of the Solar and Heliospheric Observatory (SOHO)/Large Angle and Spectrometric Coronagraph Experiment (LASCO) coronagraphic observations of the inner heliosphere, Robbrecht et al. (2009) present evidence that the angular width of coronal mass ejections (CMEs) exhibits a scale-free power-law distribution that extends from about 20° up to 120°, i.e., over a range of a factor of about 6 in opening angle. This result is based on the use of an automated feature detection method, CACTus, applied to LASCO observations from September 1997 to January 2007. Earlier visual inspection of the LASCO data had suggested that the CME distribution peaks at an angular width of about 30°, but the CACTus software also identifies many smaller structures. On visual inspection by Robbrecht et al. (2009) these are seen to fall into several categories, including visually identified events that are broken up by the CACTus algorithm, trailing outflows, wave-like phenomena, slowly rising loop-like structures, opening field, and some “false detections.” It is unclear whether most of these features should be classified as true CMEs, but the present study puts these results in a perspective that suggests that perhaps these relatively narrow events identified by CACTus (or at least many of them) may well be part of a scale-free continuous distribution of eruptive events.

The apparently scale-free CME frequency distribution function over a factor of about 6 in angular width as found by the CACTus software begs the question as to what happens on even smaller scales. Here, not only the spatio-temporal resolution of the available telescopes comes into play, but also the very real possibility that small-scale, and generally less-energetic, eruptive events may not be able to escape through the overlying coronal field, and thus never develop into a proper CME while possibly having comparable properties for their associated field eruptions lower down (but see, e.g., Mandrini et al. 2005 for an example of a very small eruption that they argue did make it into the heliosphere and Wang & Sheeley 2002 for a discussion of narrow SOHO/LASCO jets in or near coronal holes).

In order to investigate the statistics of small-scale coronal eruptions that are characteristically, but not uniquely, associated with ephemeral bipolar regions in the solar photosphere, I investigate a sample of 10 data sets obtained by the Transition Region and Coronal Explorer (TRACE) telescope between 2000 and 2008 and compare the results to the CME statistics as derived by Robbrecht et al. (2009).

Ephemeral regions are small bipolar magnetic regions that contain no sunspots or pores. Their unsigned magnetic fluxes range up to about 10^{20} Mx, above which bipolar regions are generally called active regions. At the small end of their flux spectrum, they extend into the intranetwork mixed-polarity field; a rather vaguely defined lower limit to their unsigned magnetic...
flux of order $3 \times 10^{18}$ Mx is sometimes used, but no flux range has been formally defined for ephemeral regions. These regions behave like small active regions on initial emergence, with the two polarities fragmented into a set of smaller flux clusters that quickly separate on emergence, often showing complex meandering motions suggesting a tangled emerging field. Shortly after emergence, they are subjected to the supergranular flow, and the polarities drift into the network lanes, subject to canceling collisions or mergings with other network elements that are already there. They emerge almost uniformly across the solar surface, show little dependence on the solar cycle, and have an essentially random orientation although the larger ones seem to have a slight preference for the dipole-axis orientation proper for the dominant magnetic cycle, and their emergence frequency decreases with increasing flux imbalance within the surrounding photosphere as seen in unipolar regions formed by decaying active regions. The distribution of their emergence frequency as a function of unsigned flux appears to be a smooth extension of the near-power-law distribution found for active regions, as a function of unsigned flux of order 3

### Table 1

Summary of TRACE 171 Å Data Sets and the Observed Small-scale Eruptive Events

| Time interval          | $\Delta t$ (h) | Duty Cycle (%) | $\Delta y_{\text{fov}}$ (armin$^2$) | no. images | no. events |
|------------------------|---------------|----------------|-----------------------------------|------------|------------|
| 2000 Aug 26 00:16 UT to 2000 Aug 28 12:59 UT | 60.8          | 92             | 42                                | 1548       | 7          |
| 2003 Mar 25 00:08 UT to 2003 March 26 23:59 UT | 48.0          | 100            | 55                                | 1236       | 10         |
| 2004 Jul 10 01:01 UT to 2004 Jul 11 23:59 UT | 47.0          | 100            | 16                                | 560        | 2          |
| 2005 Apr 2 00:19 UT to 2005 Apr 4 06:39 UT | 54.0          | 95             | 54                                | 1569       | 13         |
| 2006 Aug 4 09:57 UT to 2006 Aug 7 23:59 UT | 86.0          | 94             | 56                                | 4690       | 22         |
| 2006 Oct 15 05:46 UT to 2006 Oct 20 13:58 UT | 128.0         | 99             | 58                                | 4701       | 8          |
| 2007 Apr 5 00:22 UT to 2007 Apr 6 05:55 UT | 29.6          | 100            | 36                                | 609        | 4          |
| 2007 Jun 19 01:11 UT to 2007 Jun 20 23:59 UT | 46.9          | 89             | 58                                | 672        | 5          |
| 2007 Sep 3 01:45 UT to 2007 Sep 4 23:59 UT | 46.2          | 100            | 36                                | 870        | 5          |
| 2008 Feb 12 00:37 UT to 2008 Feb 12 23:59 UT | 23.4          | 100            | 58                                | 678        | 6          |

The observations of the small-scale coronal eruptions were obtained with TRACE (Handy et al. 1999) in its 171 Å passband, which has a peak sensitivity around 1 MK. From the mission archive from 1998 April 1 to 2009 September 30, I selected all data sets pointing at quiet Sun, within 500 arcsec of disk center, extending over at least one day, with 171 Å images as the primary observing passband and with exposures mostly exceeding 42 s in duration in order to ensure an adequate signal-to-noise ratio. The image sequences were analyzed visually by displaying the series with normalized intensity scalings, corrected for particle hits on the detector (“despikes”), and by tracking the region for solar rotation, while offsetting for instrumental pointing changes. Events were selected that resembled small equivalents of active-region eruptions associated with CMEs, specifically looking for (1) erupting dark fibrils (like erupting filaments), (2) rapid dimmings around a compact ephemeral region (equivalents of large-scale coronal dimmings), or (3) very rapid reconfigurations of a mix of dark and bright coronal structures above ephemeral regions often linking to one or more neighboring regions.

For each of the selected events with one or more of the mentioned characteristics, I measured the largest length scale over which the eruption unfolds rather than the extent of the original source region or any particular one of the three above-mentioned characteristics. I do not differentiate between the three characteristics as many events display them in conjunction. I return to this point in Section 3.

Many other events occur within the complex, dynamic quiet-Sun corona in addition to those selected by the above criteria. Their inclusion in, or exclusion from, the currently discussed sample is admittedly subjective. Excluded were, for example, compact, contained flare-like brightenings, many of which are associated with very narrow, jet-like cusps. On the other hand, events with clearly eruptive signatures that included a jet-like event, for example, were included. This selection is similar to the distinction between larger GOES-class flares and CMEs: many (particularly the largest) flares are associated with CMEs, but in this study I focus on events that have clear signatures of a disruption of the magnetic field of the ephemeral region.

Figure 1 shows select examples of the types of events studied here. Rows a and b show very small, bubble-like eruptions (marked by arrowheads in one of the frames for each case), in which a one-sided dimming suddenly appears; the size of the coronal dimming for case a in the image taken at 21:56 UT corresponds to 10 times the 1 arcsec TRACE resolution, which puts it at the limit of what can be reliably interpreted as an eruption based on the TRACE data. Row c shows a much larger example of such an event, with a clear coronal dimming extending over approximately 100 arcsec. Rows d and e show background level owing to a raised detector temperature in that phase of the year). The remaining 10 data sets, with a total of 17,133 exposures, are listed in Table 1. The effective duty cycle (estimated by identifying intervals with useful observations with interruptions of 30 minutes or less) for each of these data sets exceeds 89%.

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For each of the selected events with one or more of the mentioned characteristics, I measured the largest length scale over which the perturbation of the corona was apparent, thus measuring the extent over which the eruption unfolds rather than the extent of the original source region or any particular one of the three above-mentioned characteristics. I do not differentiate between the three characteristics as many events display them in conjunction. I return to this point in Section 3.

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eruptions in which a two-sided dimming is seen (marked by the arrow heads), as sometimes observed in association with an active-region eruption. Row f shows an event with a dimming as well as a small, dark fibril (indicated in the 15:50 UT frame by the arrowhead). Row g shows an example of a very compact eruption in association with a flare that is so bright that the diffraction pattern caused by the filter support grid shows up, as seen in the second and third panels. Row h shows an eruption in which the ephemeral region field connects to two relatively distant neighboring flux concentrations, extending in fact beyond the shown cutout of the full field of view of the observations.

The examples shown in Figure 1 are characteristic in their appearance, although they were selected from image sets that are well exposed with little damage by background radiation by energetic particles or by a high readout noise associated with relatively high detector temperatures in some phases of the orbits (depending on the season in which the observations are obtained). The diversity of phenomena, the frequent short-term interruptions of good observing conditions by energetic-particle impacts or Earth-atmospheric absorption, and the fact that we are evaluating pattern evolution rather than curves (such as flare brightness curves) severely hamper the ready application of an automated feature finding algorithm, instead requiring a visual identification of the events with the associated subjectivity of such a procedure.

The set of all images, covering 570 hr of observing, yielded 80 events that resembled small-scale active-region eruptions as defined above (see Table 1). Most of these events originate in the bright corona over ephemeral regions, but some occur in the connections between such regions, while two occur within the largely unstructured regions over very quiet Sun. The estimated event duration ranges from 3 minutes to 104 minutes with an average and standard deviation of 33 ± 20 minutes. For each eruption, a characteristic length scale was estimated using the maximum extent of the event in any direction as measured on
the images; these length scales range from 6 Mm to 160 Mm with an average and standard deviation of 28 ± 24 Mm. The average histogram of the event size distribution, normalized to events per day on the Sun under the assumption of a homogeneous surface distribution, is shown in Figure 2, binned into intervals with a width of a factor of 2. The assumption of a uniform distribution across the Sun is shown by diamonds, scaled to show the number of events per day per 1 degree bin width for the apparent angular size in heliocentric degrees, assuming a uniform distribution over the solar surface holds only to first order in the size distribution, is shown in Figure 2, binned into intervals with a width of a factor of 2 in apparent width (indicated by the horizontal bars on the diamonds). The vertical bars indicate the uncertainty in the number based on Gaussian statistics. The solid line is the average of the best fits to the distribution of observed coronal mass ejections (CMEs) from Robbrecht et al. (2009) for 2000–2006; the average power-law index and standard deviation are $-1.78 \pm 0.17$; this best fit is extrapolated to smaller scales by the dashed line; the dotted lines show the envelope of maximum and minimum values from the set of fits from Robbrecht et al. (2009) for the same period. To the left of the vertical dashed-dotted line segment, the equivalent width is less than 10 arcsec, or 10 resolution elements in the TRACE EUV images. The gray bar near the top of the diagram is based on the study by Innes et al. (2009); its scaling to this diagram is discussed in Section 3. The dashed-dotted line fits all three data sets with a power-law index of $-2.3$.

3. DISCUSSION AND CONCLUSIONS

The distribution of size scales for eruptive disturbances in the quiet-Sun corona (Figure 2) shows a pronounced decrease in frequency with increasing size above the interval for the smallest selected events. The apparent turnover at the smallest scales is likely an artifact of the instrumental resolution: events smaller than about 10 resolution elements are difficult to assess, and identifying an erupting small filament or a coronal dimming for such compact features is problematic, so that these small events are likely significantly underestimated in the sample. The interval for the largest eruptions contains only two events, both from the same region, so that the uncertainty on its frequency is substantial.

The statistics for the individual time intervals for the three remaining size intervals do not suffice by themselves to say much about the shape of the distribution function as a function of the phase of the solar cycle. Even with all data combined, the slope of the size distribution is rather poorly constrained based on the TRACE data by themselves. I propose, however, that the empirical evidence suggests the combination of the events identified in the present study with the results on CME widths from the study of LASCO observations by Robbrecht et al. (2009). I argue that in both cases, i.e., for the small eruptive events in quiet Sun and for global CMEs, the field somehow destabilizes, erupts, and is at least temporarily disrupted. In the case of the quiet-Sun eruptions of ephemeral-region field studied here, the ultimate extent of the event is likely restricted to the range of the set of magnetic connections of a bipolar region, unless it is energetic enough to breach that and reach into the next set of the overlying hierarchy. The same argument can be made for eruptions in the coronal field over active regions or over large quiet-Sun filaments, although here the highest domain of connectivity obviously reaches into the heliosphere. An illustrative example is shown in Figure 3(a), which mimics the potential-field extrapolations. (a) PFSS-like field model for test charges on the equivalent of the solar surface (circle segment with unit radius) with an upper boundary (outer circle) at a radial distance of 2.5 units at which the field is forced to become radial. This model field is invariant to rotations of 90°. The dashed lines enclose an extended area with the magnetic connections from the dipole centered at 45° and into the open-field domain (corresponding to the heliosphere). (b) Same as (a) but for a potential field model in which only the lower boundary is used. The dotted lines repeat the field lines for the PFSS-like model from panel (a).
equivalent CME would have an opening angle into the heliosphere close to that shown by the two dashed lines; if, however, the field would contain the eruption and ejecta would be contained to within the range of magnetic concentrations to which the central region is connected, a rather comparable angle would be spanned as projected onto the solar surface—as sizes are expressed in this study (Figure 1 in Schrijver & Title 2003 also serves as an illustration in the literature pertinent to this argument for a plane-parallel approximation valid for scales small relative to the solar radius). Figure 3(b) illustrates how insensitive the inner coronal field is to the upper boundary condition of radial field. This single, highly abstract example of a PFSS field extrapolation does not suffice for a general conclusion, of course, but the correspondence of quiet-Sun eruptions and CME statistics may well point to this argument as the reason for their surprising alignment over a range of scales, as I now discuss.

Figure 2 shows that the average power-law fit to the events reported by Robbrecht et al. (2009) for the overlapping period of 2000–2006 forms a continuous extension of the size distribution from the present study, albeit at a somewhat steeper slope than the average fit to the CME distribution. Note that Figure 2 shows the mean power-law fit from Robbrecht et al. (2009) from an angular width of 20° upward, i.e., for the range in their results in which a power law shows a good fit to the observed frequency distribution, and excluding—as for the TRACE observations—very narrow jet-like events (similarly, narrow jet-like “collimated ejections” seen in LASCO observations (e.g., Wang & Sheeley 2002) with width of up to ∼15° are not included in the range to which power-law fits were made to the CACTus CME data). Although the distribution of ephemeral region eruptions lies somewhat above the average best fit to the CACTus CME distribution, they extend that distribution within the range of fits seen in the period of 2000–2006. The CACTus CME distribution does not differentiate between events originating in association with active regions or with quiet Sun, but the CME distribution is dominated by events associated with active regions: Zhou et al. (2003), consistent with earlier studies referenced therein, for example, find that 79% of front-side halo CMEs are associated with activity within active regions.

The results in Figure 2 suggest that the eruption frequency in large bipolar regions (for CMEs associated with bipolar regions) and in their (quiet Sun) surroundings is a scale-free quantity that extends over a factor of almost 100 (but perhaps more), from the largest CMEs to eruptions near the resolvable limit of order 10 arcsec for the highest-resolution EUV telescope.

Our knowledge about what happens on even smaller length scales is, for obvious reasons, rather limited. In a recent study, Innes et al. (2009) discuss what they call “quiet-Sun mini-CMEs.” They analyze a sequence of 171 Å images obtained by the STEREO-A spacecraft, with 150 s cadence (comparable to the average cadence in the data set discussed here) and 1.6 arcsec pixels (3.1 times larger than the TRACE pixels). They estimate a total number of events of 1400 per day for the entire Sun when assuming a uniform surface distribution. They do not specifically count events equivalent to those reported on here that look like eruptions of small active regions, but look for “emission or absorption trains by eye in series of time–distance 171 Å images” and make “sensible choices for selecting events.” They do not provide a size distribution, or an average size, of their events, but do note that “only events seen over 6′′ (three consecutive pixels) were kept.” Assuming that the steep power law found here continues to the smallest scales that they include, the number of smallest events will dominate the total count. If we assume that these events all reside in an interval with a width of a factor of 2, as used for the TRACE data in Figure 2, extending from 6 to 12 arcsec, then the equivalent position of the results by Innes et al. (2009) is shown by the gray bar in Figure 2. As their count includes flare-like brightenings, rapid coronal configurations, as well as the small eruptions counted in the TRACE data analyzed here, the position of the Innes et al. (2009) results is compatible with the TRACE results, even though the mix of event types in their study does not provide a strong constraint on the extension of the power law to very small scales.

Altogether, the data from SOHO/LASCO, TRACE, and STEREO suggest an essentially scale-free frequency distribution for sizes of magnetically driven eruptions in the Sun that extends from the smallest scales that can be observed by present-day high-resolution instruments up to large-scale CMEs. The gray dashed-dotted line in Figure 2 suggests that this frequency distribution may be approximated to first order by a power-law distribution with an index of about −2.3 (to be compared to the equivalent power-law index for length scales of loops involved in small-scale quiet-Sun flaring of −2.10 ± 0.11 reported by Aschwanden et al. 2000).

The characteristic power-law index of −2.3 and the possible steepening when going from large to smaller scales have an intriguing analogy in the flux distribution of newly emerging bipolar regions from large active regions to small ephemeral regions, as summarized by Hагенаар et al. (2003) in their Figure 11: the apparently smooth transition from ephemeral to active regions can be approximated by a single power-law fit with a slope rather close to −2.3. It will be interesting, in a future study, to explore in detail the reasons behind this commonality, which includes at least assessing relationships between the longevity of regions as a function of their size (e.g., Harvey & Zwaan 1993) and the evolution of their propensity to erupt during their lifetime (possibly related to the phenomenon of active-region nesting, see Brouwer & Zwaan 1990; Harvey & Zwaan 1993), and the relationship between the properties of active regions and the extent of their possible eruptions (e.g., Moore et al. 2007).

Although the TRACE data sets studied here span a large part of the past sunspot cycle, the number of events detected per data set is too small to make significant statements about the possible dependence of the number of events on the phase of the sunspot cycle. Data sets at latitudes other than near disk center are even rarer in the TRACE records. In time, the Atmospheric Imaging Assembly on the future Solar Dynamics Observatory should enable a more comprehensive study of the statistics of erupting bipolar regions from ephemeral to active regions both as a function of latitude and cycle phase.

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