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Waiting Times of Quasi-homologous Coronal Mass Ejections from Super Active Regions

Yuming Wang*, Lijuan Liu, Chenglong Shen, Rui Liu, Pinzhong Ye, and S. Wang

CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China

* *To whom correspondence should be addressed. E-mail: ymwang@ustc.edu.cn*

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Abstract. Why and how may some active regions (ARs) frequently produce coronal mass ejections (CMEs)? It is one of the key questions to deepen our understanding of the mechanisms and processes of energy accumulation and sudden release in ARs and to improve our capability of space weather prediction. Although some case studies have been made, the question is still far from fully answered. This issue is now being tried to address statistically through an investigation of waiting times of quasi-homologous CMEs from super ARs in solar cycle 23. It is found that the waiting times of quasi-homologous CMEs have a two-component distribution with a separation at about 18 hours. The first component is a Gaussian-like distribution with a peak at about 7 hours, which indicates a tight physical connection between these quasi-homologous CMEs. The likelihood of occurrences of two or more CMEs faster than 1200 km s^{-1} from the same AR within 18 hours is about 20%. Furthermore, the correlation analysis among CME waiting times, CME speeds and CME occurrence rates reveals that these quantities are independent to each other, suggesting that the perturbation by preceding CMEs rather than free energy input be the direct cause of quasi-homologous CMEs. The peak waiting time of 7 hours probably characterize the time scale of the growth of instabilities triggered by preceding CMEs. This study uncovers more clues from a statistical perspective for us to understand quasi-homologous CMEs as well as CME-rich ARs.

1 Introduction

Magnetic free energy is thought to be the energy source of coronal mass ejections (CMEs). Active regions (ARs) carry a huge amount of free energy and therefore are the most probable place where CMEs come out. Lots of efforts have been devoted to the triggering mechanisms of CMEs. Flux emergence, shear motion and mass loss all could be the initial cause of an isolated CME [e.g., *Forbes and Priest*, 1995; *Amari et al.*, 1966; *Chen and Shibata*, 2000; *Manchester*, 2003]. No matter which one takes effect, the determinative factor of the CME's launch is the force balance between the inner core field and the outer overlying arcades [e.g., *Wang and Zhang*, 2007; *Liu*, 2007; *Schrijver*, 2009]. Free energy stored in the source region will be consumed when a CME launches [e.g., *Sun et al.*, 2012].

The picture of isolated CMEs is somewhat clear. However, it is still a question how CMEs could lift successively in a limited region within a relatively short interval. Usually the energy accumulation is a gradual process in time scale of hours to days [e.g., *LaBonte et al.*, 2007; *Li et al.*, 2010], while a CME is a sudden process releasing accumulated energy in minutes. Why and how could some ARs frequently produce CMEs? Does the occurrences of successive CMEs from the same AR mean that the source AR accumulate free energy quickly? The waiting time distribution of quasi-homologous CMEs contains clues.

Homologous CMEs were defined by *Zhang and Wang* [2002] after the definition of homologous flares [*Woodgate et al.*, 1984]. Strictly speaking, homologous CMEs must originate from the same region, have similar morphology, and be associated with homologous flares and EUV dimmings. Here, we use the term 'quasi-homologous' to refer to successive CMEs originating from the same ARs within a short interval, but may have different morphology and associates.

A previous study on 15 CME-rich ARs during the ascending phase of the last solar cycle from 1998 to 1999 have suggested that quasi-homologous CMEs occurred at a pace of about 8 hours, and there was at most one fast CME within 15 hours [*Chen et al.*, 2011b]. These results are important for space weather prediction, and did imply that the accumulation rate of free energy in an AR may not support such frequently occurrences of quasi-homologous CMEs, and the triggering mechanisms of the first and the following CMEs are probably different. Three scenarios were proposed to interpret the averagely 8-hour waiting time of quasi-homologous CMEs.

Before deepening our understanding of such a phenomenon, we need to check if a similar waiting time distribution of quasi-homologous CMEs could be obtained for the whole solar cycle. In this paper, we extend the period of interest to the whole solar cycle 23 from 1996 to 2006. Instead of searching all ARs and the associated CMEs, which are too many to be identified manually, we investigate super ARs that were reported in literatures. Super ARs are those with larger area, stronger magnetic field and more complex pattern, and thought to be the representative of CME producers. In the following section, we present the selected data and the method. In Sec.3, an analysis of waiting times of quasi-homologous CMEs from these super ARs during the last solar cycle is performed. Finally, conclusions and discussion is given in the last section.

2 Data Preparation

2.1 Super ARs and Associated CMEs

Super ARs were studied by many researchers [*Bai*, 1987, 1988; *Tian et al.*, 2002; *Romano and Zuccarello*, 2007; *Chen et al.*, 2011a]. It was first defined by *Bai* [1987, 1988] as a region producing four and more major flares. In most studies, super ARs were selected based on several parameters, such as the largest area of sunspot group, the soft X-ray flare index, the 10.7 cm radio peak flux, the short-term total solar irradiance decrease, the peak energetic proton flux, the geomagnetic Ap index, etc. No matter which one or more criteria are used, most selected super ARs are CME-productive (that could be seen at the last paragraph of this sub-section).

In our study, we focus on super ARs during solar cycle 23. Instead of identifying super ARs by ourselves, we simple use existent lists of super ARs in literatures. To our knowledge, there are three lists regarding to super ARs in solar cycle 23. The first one is given by *Tian et al.* [2002], who found 16 super ARs from 1997 to 2001 base on their selection criteria. The second one is given by *Romano and Zuccarello* [2007], which contains 26 super ARs from 2000 to 2006. The last one is in paper by *Chen et al.* [2011a], in which 12 super ARs were identified during the last solar cycle. Since *Chen et al.* [2011a] used stricter criteria, the last list is actually a subset of the other two. Totally, we have 37 super ARs from 1996 to 2006.

To identify the CMEs originating from these super ARs, we examine imaging data from Large Angle and Spectrometric Coronagraph (LASCO, *Brueckner et al.* 1995) and Extreme Ultraviolet Imaging Telescope (EIT, *Delaboudinière et al.* 1995) onbard Solar and Heliospheric Observatory (SOHO). The identification process is the same as that applied by *Wang et al.* [2011] and *Chen et al.* [2011b]. The CMEs listed in the CDAW LASCO CME catalog (refer to http://cdaw.gsfc.nasa.gov/CME_list/, *Yashiro et al.* 2004) are our candidates. Through a careful identification, it is found that a total of 285 CMEs are associated with these super ARs. Figure 1 shows the distribution of the CME productivity of super ARs, in which the numebr of super ARs almost linearly decreases with increasing CME number though there is a sharp decrease below the CME productivity of 3.

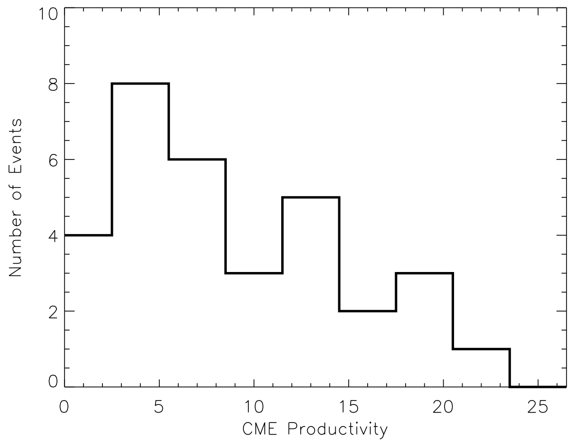

Figure 1: Distribution of CME productivities of super ARs.

It should be mentioned that there are 7 super ARs with too many large data gaps in LASCO and/or EIT observations, and therefore their CME productivity cannot be obtained. Except them, there were 28 super ARs producing 3 or more CMEs (called CME-rich ARs), among which 14 super ARs generated at least 10 CMEs. The other 2 super ARs produced only one or two CMEs though sporadic data gaps existed. This fact suggests that not all of super ARs are CME productive. But it is definite that super ARs are more likely to be CME productive. *Chen et al.* [2011b] identified 108 ARs during 1997–1998 and found that only 14% of these ARs produced 3 or more CMEs. This percentage is much lower than that for super ARs, which is about 93% (28/30). In this study we focus on the 28 CME-rich ARs, which produced 281 CMEs in total. A list of all the CMEs associated with these CME-rich super ARs can be retrieved from http://space.ustc.edu.cn/dreams/quasi-homologous_cmes/.

2.2 Waiting Times

As long as there is no large data gap, we tentatively believe that all CMEs originating from a super AR of interest are recognized based on combined observations from SOHO LASCO and EIT. The waiting time of each CME is obtained according to the times of first appearance of the CME and its preceding one from the same super AR in the field of view of LASCO/C2. However, data gaps exist, and some CMEs may missed. If there was a large data gap between two CMEs from the same super ARs, the waiting time of the second CME cannot be obtained. Here, all data gaps less than 3 hours are ignored, because it is almost impossible for a CME to stealthily escape the field of view of LASCO in 3 hours.

Before analyze the waiting times of these CMEs from the super ARs, it has to be noted that there are probably about 32% of frontside CMEs missed by SOHO [*Ma et al.*, 2010; *Wang et al.*, 2011]. Of course, these missed CMEs might be generally weak and faint. The statistical study by *Chen et al.* [2011b] have suggested that the properties of ARs have effects on the CME productivity, but do little with the kinetic properties of CMEs. Thus, it is possible that some CMEs originating from the super ARs are missed in our study, though such CMEs might be very weak and erupt in a gradual manner. So far. it is hard to evaluate how significant an influence this error will cause, and one may bear it in mind that the following analysis is performed with a bias of normal to strong CMEs.

3 Results

3.1 Waiting Time Distribution

The average value of the waiting times is about 17.8 hours. The waiting time distribution is shown in Figure 2. Similar to that shown in Figure 10 of the paper by *Chen et al.* [2011b], the distribution consists of two components. One component locates less than 18 hours and looks like a Gaussian distribution, and the other beyond 18 hours. For the first component distribution, the peak waiting time is about 7 hours. In *Chen et al.* [2011b], the separation of the two components of the distribution is near 15 hours, and the first component distribution peaked near 8 hours, which are both slightly different than those obtained here. These slight differences might be caused by the solar cycle variation.

An interesting result in *Chen et al.* [2011b] is that any AR cannot produce two or more CMEs faster than 800 km s^{-1} within 15 hours. In other words, the time intervals between fast CMEs are longer than 15 hours. If this result obtained during the last solar minimum also holds for the whole solar cycle, we could expect that any AR cannot produce two or more CMEs faster than a certain speed threshold within 18 hours. However, such a speed threshold cannot be found. The blue line in Figure 2 shows the waiting time distribution for CMEs faster than 1200 km s^{-1}. Note that all the slower CMEs are ignored when we calculate waiting times for CMEs faster a certain speed threshold. Some fast CMEs did occur in the same ARs within 18 hours. For example, there were four CMEs from the super AR 10720 on 2005 January 15 at 06:30 UT, 23:06 UT, on January 17 at 09:30 UT and 09:54 UT, respectively, which were all faster than 2000 km s^{-1}. The first two CMEs were separated by about 16.6 hours, and the other two by about only 24 minutes. These fast CMEs caused ground-level enhancement (GLE) event [e.g., *Grechnev et al.*, 2008].

Although a similar result cannot be obtained, we find that the likelihood for an AR producing two or more fast CMEs within 18 hours is much smaller than normal. For all CMEs, 68% of the waiting times are shorter than 18 hours, while for CMEs faster than 1200 km s^{-1}, the fraction decreases to only about 18%. The dependence of the likelihood on the CME speed threshold is given in Figure 3. Generally, the likelihood monotonically decreases as the speed threshold increases. When the threshold reaches to about 1200 km s^{-1}, the likelihood stops decreasing and stays between 15%–25%, suggesting a limit likelihood of approximate 1/5.

The waiting time distribution for all CMEs from 1999 February to 2001 December was investigated by *Moon et al.* [2003], which is significantly different from the distribution for quasi-homologous CMEs obtained here (see Figure 1 in their paper). This difference reveals that the occurrence of CMEs follows a Poisson process [*Scargle*, 1998; *Wheatland*, 2000], but that of quasi-homologous CMEs does not. In a statistical view, we may conclude that there are tight physical connections between quasi-homologous CMEs, but for CMEs from different source regions, the connection is quite loose.

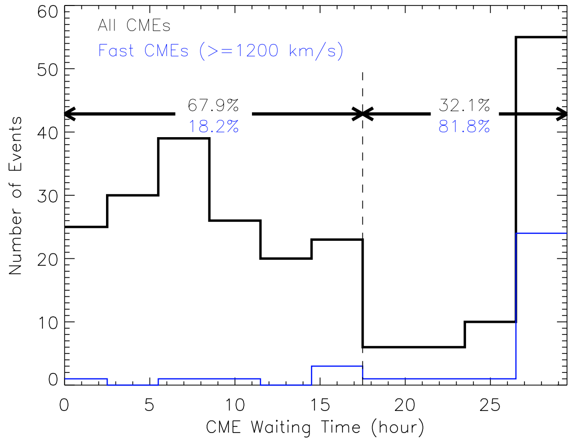

Figure 2: Waiting time distributions for all quasi-homologous CMEs (black line) and for quasi-homologous CMEs faster than 1200 km s^{-1} (blue line).

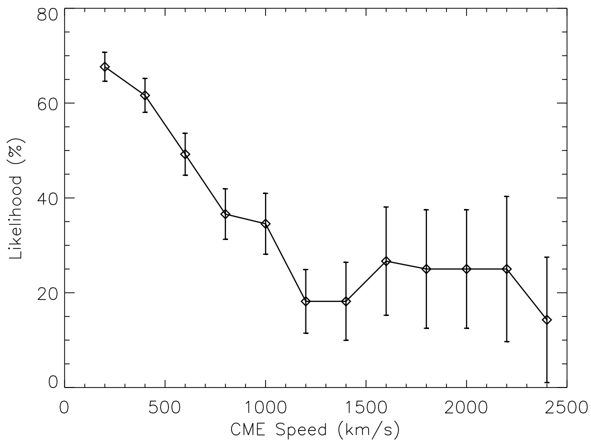

Figure 3: Dependence of likelihood of quasi-homologous CMEs occurring within 18 hours on CME speed.

3.2 Role of Free Energy Input in Causing Quasi-Homologous CMEs

Sufficient free energy is a necessary condition for an AR to produce CMEs. Generally, the accumulation rate of free energy could be approximately represented by the magnetic helicity injection rate, which is another important parameter in evaluating the productivity of ARs. Magnetic helicity measures the twists, kinks and inter-linkages of magnetic field lines, which indicate the complexity and non-potentiality of a magnetic system. The close relationship between the free energy and magnetic helicity could be seen from their formulae [*Kusano et al.*, 2002]. Thus it is not surprising that a higher injection rate of magnetic helicity often implies a higher probability of an eruptive activity, as suggested by many studies [e.g., *Zhang et al.*, 2006; *LaBonte et al.*, 2007].

However, it is still questionable if free energy input is a direct cause of quasi-homologous CMEs. Some studies did show that CMEs do not always occur during a quick injection of magnetic helicity or free energy, even if the stored free energy in an AR was much higher than that required for a CME [e.g., *Démoulin and Pariat*, 2009; *Vemareddy et al.*, 2012]. This issue is addressed here in a statistical perspective from two aspects. First, we investigate the correlation between the CME speeds and waiting times. If free energy input is a direct cause, it is expected that there is some regulation between CMEs' speeds and their waiting times, as a long waiting time may lead to more free energy in an AR. This expectation is established under the assumption that the injection rate of free energy or magnetic helicity varies in a relatively small range for different ARs, This assumption is statistically true based on previous studies. For example, the statistical study by *Park et al.* [2010] suggested that the magnetic helicity fluxes in 378 ARs observed by SOHO/MDI were on the order of about 10^{40} Mx h^{-1}, especially for those ARs with large magnetic flux (see, e.g., Fig.1, 3 and 4 in their paper). The value does not change much even if deriving from higher-resolution data from SDO/HMI, e.g., the helicity injection rate in AR 11158 and 11166 [*Vemareddy et al.*, 2012].

Figure 4a shows the dependence of CME speed on the waiting time. Overall, no clear correlation could be found between them, except that there is seemingly an upper limit in CME speed depending on the CME waiting time. However, although the distribution is statistically true, it does not imply that an AR is difficult to produce a fast CME if it had waited too long. It is a result simply from a combination of two Gaussian-like distributions. The CME waiting time is a Gaussian-like distribution, at least for the first component (as shown in Figure 2). The CME speed is actually also a Gaussian-like distribution. If the two quantities are independent, the 2-D distribution composed by them is like that shown in Figure 4a. As a test, Figure 4b shows the distribution, in which the CME speeds in our sample are randomly associated with the CME waiting times. The two distributions given in Figure 4a and 4b are quite similar. It reflects that the CME speed is independent on the CME waiting time.

Second, we check if the waiting time of a CME depends on the CME occurrence rate in the past 18 hours before its preceding CME. Figure 5a shows the scattering plot between them. Apparently, a low or high CME occurrence rate may lead to a short waiting time of the next CME, and a long waiting time tends to appear when the CME occurrence rate is around 0.1 per hour. However, similar to the previous one, this distribution is also just a manifestation of probability, and contains less physical meaning. If we randomly associate the CME waiting times with the occurrence rates, a possible distribution of the data points is like that shown in Figure 5b, which is statistically same as that in Figure 5a. Thus the CME waiting time is independent on the previous CME occurrence rate. Both results suggest that free energy input is not a direct cause of quasi-homologous CMEs though sufficient free energy is a necessary condition for an AR to produce CMEs.

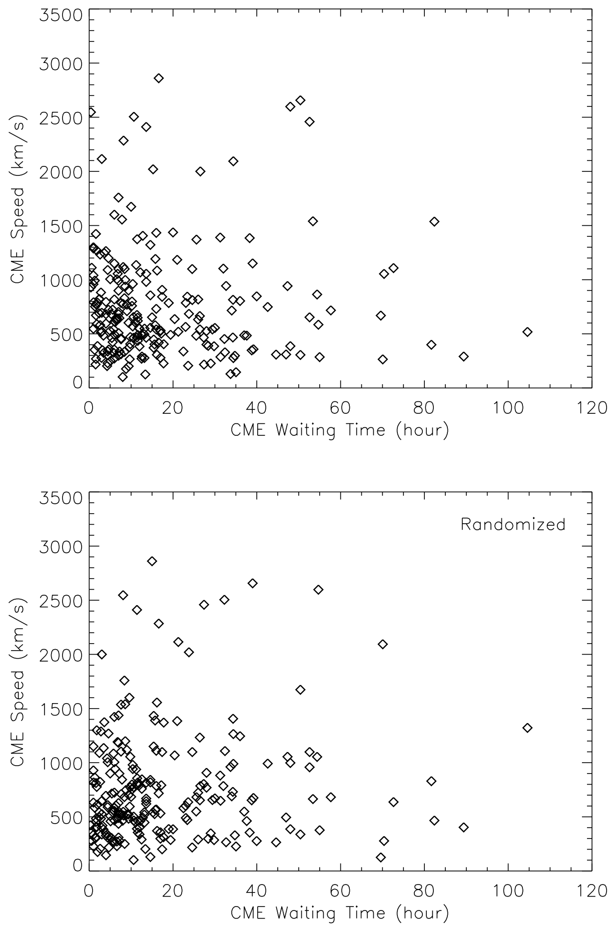

Figure 4: *Upper Panel*: Scattering plot of CME speeds versus CME waiting times. *Lower Panel*: Same as *Upper Panel*, but the association between them is randomized.

4 Summary and discussion

In summary, by investigating 281 quasi-homologous CMEs originating from 28 CME-rich super ARs over the last solar cycle, we find a two-component distribution of their waiting times with the separation of the two components at about 18 hours and the peak waiting time of the first component at about 7 hours. These results suggest a close physical connection between quasi-homologous CMEs which fall in the first component. Furthermore, the likelihood of occurrences of two or more fast CMEs within 18 hours decreases as CME speed increases. A limit likelihood of about 20% is reached when CME speed is larger than 1200 km s^{-1}.

The correlation analysis among CME waiting times, CME speeds and previous CME occurrence rates shows us the statistical evidence that the free energy input is not a direct cause of quasi-homologous CMEs. It is well known that that the free energy stored in ARs may be much higher than that could be consumed by one single CME [e.g., *Sun et al.*, 2012]. Thus the direct cause of quasi-homologous CMEs is not the quick re-fill of free energy after preceding CMEs, but the perturbation by preceding CMEs, which may lower the threshold of eruption or trigger instabilities to cause the next CME.

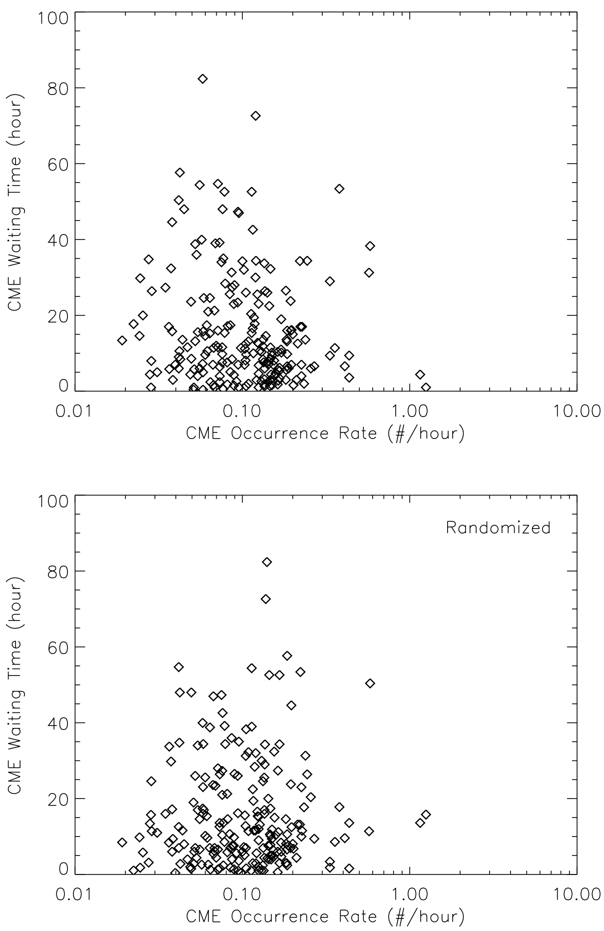

Figure 5: *Upper Panel*: Scattering plot of CME waiting times versus CME occurrence rate in the past 18 hours. *Lower Panel*: Same as *Upper Panel*, but the association between them is randomized.

Pre-eruption flux rope is precisely balanced by outward force from inner core field and inward force from overlying arcades [e.g., *Török and Kliem*, 2005; *Wang and Zhang*, 2007; *Liu*, 2007]. A CME may reduce the constraint of its nearby flux rope system by removing overlying arcades, and cause the balance broken. As shown in the numerical simulation by *Török et al.* [2011], which was designed to study the physical mechanism of a global sympathetic eruptions on 2010 August 1 [*Schrijver and Title*, 2011], the second and third eruptions were actually caused by preceding eruptions. In their eruption processes, the preceding eruption caused the overlying arcades reduced through reconnection, and then instability developed. A similar result was obtained in the simulation by *Bemporad et al.* [2012], in which the second CME was caused by the rearrangement of coronal magnetic field after the first CME.

Connecting the above picture to the peak waiting time of 7 hours, we may speculate that the 7-hour waiting time probably characterizes the average time scale of the growth of instabilities. In our previous work [*Chen et al.*, 2011b], we proposed three scenarios to interpret the peak waiting time. Here we may tentatively narrow down them to the last two, in which quasi-homologous CMEs probably hatched from a long magnetic flux system or different magnetic flux systems in one AR. A simple/small AR should be difficult to frequently produce CMEs. A detailed investigation on this point is worthy to be carried out in future work.

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