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WAITING TIMES OF QUASI-HOMOLOGOUS CORONAL MASS EJECTIONS FROM SUPER ACTIVE REGIONS

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ABSTRACT

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

Key words: instabilities – Sun: coronal mass ejections (CMEs)

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 emerge. Much effort has 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 & Priest 1995; Amari et al. 1996; Chen & Shibata 2000; Manchester 2003). No matter which one takes effect, the determinative factor of a CME's launch is the force balance between the inner core field and the outer overlying arcades (e.g., Wang & 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, there is still the question of how CMEs can be launched successively in a limited region within a relatively short interval. Usually energy accumulation is a gradual process in a timescale 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 do some ARs frequently produce CMEs? Does the occurrence of successive CMEs from the same AR mean that the source AR accumulates free energy quickly? The waiting time distribution of quasi-homologous CMEs contains clues.

Homologous CMEs were defined by Zhang & 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 associations.

A previous study of 15 CME-rich ARs during the ascending phase of the last solar cycle from 1998 to 1999 suggested that quasi-homologous CMEs occurred at a pace of about 8 hr, and there was at most one fast CME within 15 hr (Chen et al. 2011b). These results are important for space weather prediction and imply that the accumulation rate of free energy in an AR may not support such frequent occurrences of quasi-homologous CMEs, and that the triggering mechanisms of the first and the following CMEs are probably different. Three scenarios were proposed to interpret the average 8 hr 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 can be obtained for the whole solar cycle. In this Letter, we extend the period of interest to the entire solar cycle 23 from 1996 to 2006. Instead of searching all ARs and the associated CMEs, which are too numerous to be identified manually, we investigate super ARs that were reported in the literature. Super ARs are those with a larger area, a stronger magnetic field, and a more complex pattern, and are thought to be representative of CME producers. In the following section, we present the selected data and method. In Section 3, an analysis of the waiting times of quasi-homologous CMEs from these super ARs during the last solar cycle is performed. Finally, the conclusions and discussion are given in the last section.

2. DATA PREPARATION

2.1. Super ARs and Associated CMEs

Super ARs have been studied by many researchers (Bai 1987, 1988; Tian et al. 2002; Romano & Zuccarello 2007; Chen et al. 2011a). Super ARs were first defined by Bai (1987, 1988) as regions 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, and the geomagnetic Ap index, etc. No matter which one or more criteria are used,

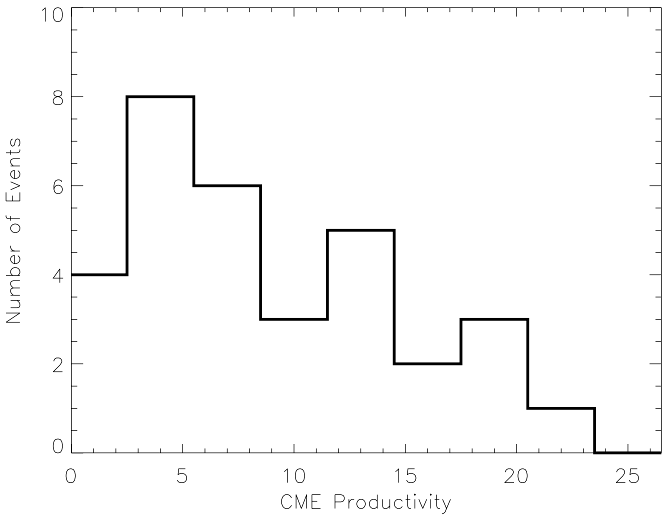

Figure 1. Distribution of CME productivity of super ARs.

most selected super ARs are CME-productive (see the last paragraph of this subsection).

In our study, we focus on super ARs during solar cycle 23. Instead of identifying super ARs by ourselves, we simply use existing lists of super ARs in the literature. To our knowledge, there are three lists regarding super ARs in solar cycle 23. The first one is provided by Tian et al. (2002), who found 16 super ARs from 1997 to 2001 based on their selection criteria. The second one is provided by Romano & Zuccarello (2007), which contains 26 super ARs from 2000 to 2006. The last one can be found in the 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. In total, we have 37 super ARs from 1996 to 2006.

To identify the CMEs originating from these super ARs, we examine imaging data from the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) and Extreme Ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the *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 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 number of super ARs almost linearly decreases with an increasing number of CME, though there is a sharp decrease below the CME productivity level of three.

It should be mentioned that there are seven super ARs with too many large data gaps in LASCO and/or EIT observations, and therefore their CME productivity cannot be obtained. Except for those, 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 two super ARs produced only one or two CMEs though sporadic data gaps existed. This fact suggests that not all super ARs are CMEs productive. However, it is certain that super ARs are more likely to produce CMEs. Chen et al. (2011b) identified 108 ARs during 1997–1998 and found that only 14% of these ARs produced three 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/.

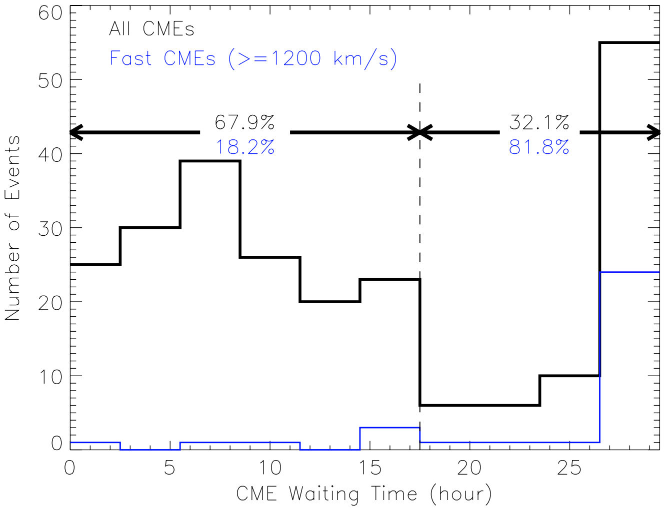

Figure 2. Waiting time distributions for all quasi-homologous CMEs (black line) and for quasi-homologous CMEs faster than 1200 km s^{-1} (blue line).

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 time of the 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 have been missed. If there was a large data gap between two CMEs from the same super AR, the waiting time of the second CME cannot be obtained. Here, all data gaps less than 3 hr are ignored because it is almost impossible for a CME to stealthily escape the field of view of LASCO in 3 hr.

Before we analyze the waiting times of these CMEs from super ARs, it has to be noted that probably about 32% of frontside CMEs are missed by *SOHO* (Ma et al. 2010; Wang et al. 2011). Of course, these missed CMEs might generally be weak and faint. The statistical study by Chen et al. (2011b) has suggested that the properties of ARs have effects on CME productivity, but do not much affect the kinetic properties of CMEs. Thus, it is possible that some CMEs originating from super ARs are missed in our study, though such CMEs might be very weak and erupt in a gradual manner. Thus far, it is hard to evaluate the significance of this error, and one may bear 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 hr. The waiting time distribution is shown in Figure 2. Similar to that shown in Figure 10 of Chen et al. (2011b), the distribution consists of two components. One component shows those less than 18 hr and looks like a Gaussian distribution, and the other shows those beyond 18 hr. For the first component distribution, the peak waiting time is about 7 hr. In Chen et al. (2011b), the separation of the two components of the distribution is near 15 hr, and the first component distribution peaked near 8 hr, both

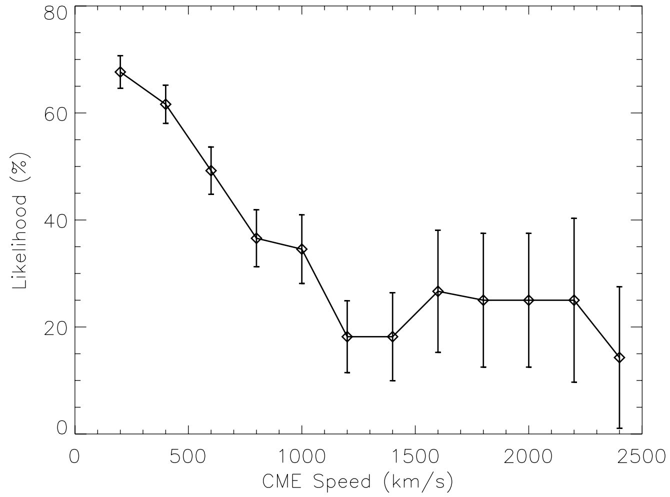

Figure 3. Dependence of the likelihood of quasi-homologous CMEs occurring within 18 hr on CME speed threshold.

of which are slightly different than those obtained here. These slight differences might be caused by 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 hr. In other words, the time intervals between fast CMEs are longer than 15 hr. 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 hr. 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 than a certain speed threshold. Some fast CMEs did occur in the same ARs within 18 hr. For example, there were four CMEs from the super AR 10720 on 2005 January 15 at 06:30 UT and 23:06 UT, and 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 hr, and the other two by about only 24 minutes. These fast CMEs caused a ground-level enhancement event (e.g., Grechnev et al. 2008).

Although a similar result cannot be obtained, we find that the likelihood of an AR producing two or more fast CMEs within 18 hr is much smaller than normal. For all CMEs, 68% of the waiting times are shorter than 18 hr, 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 about 1200 km s^{-1}, the likelihood stops decreasing and stays between 15% and 25%, suggesting a likelihood limit of approximately one-fifth.

The waiting time distribution for all CMEs from 1999 February to 2001 December was investigated by Moon et al. (2003), which was significantly different from the distribution for the 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 the occurence of quasi-homologous CMEs does not. From 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.

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 can 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 interlinkages 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 can 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 whether or not free energy input is a direct cause of quasi-homologous CMEs. Some studies 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 & Pariat 2009; Vemareddy et al. 2012). This issue is addressed here from a statistical perspective in two respects. 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 CME speed and waiting time, 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., Figures 1, 3, and 4 in their paper). The value does not change much even if derived from higher-resolution data from *SDO*/HMI, e.g., the helicity injection rate in AR 11158 and 11166 (Vemareddy et al. 2012).

Figure 4(a) 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 on CME speed depending on the CME waiting time. However, although the distribution is statistically true, it does not imply that it is difficult for an AR to produce a fast CME if it has 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 two-dimensional distribution composed by them is like that shown in Figure 4(a). As a test, Figure 4(b) shows the distribution, in which the CME speeds in our sample are randomly associated with the CME waiting times. The two distributions given in Figures 4(a) and (b) are quite similar. It reflects that the CME speed is independent of the CME waiting time.

Second, we check whether or not the waiting time of a CME depends on the CME occurrence rate in the past 18 hr before its preceding CME. Figure 5(a) shows the scatter plot between them. Apparently, a low- or high-CME occurrence rate may lead to a short waiting time for the next CME, and a long waiting time tends to appear when the CME occurrence rate is around 0.1 hr^{-1}. However, similar to the previous one, this distribution is also just a manifestation of probability, and contains less

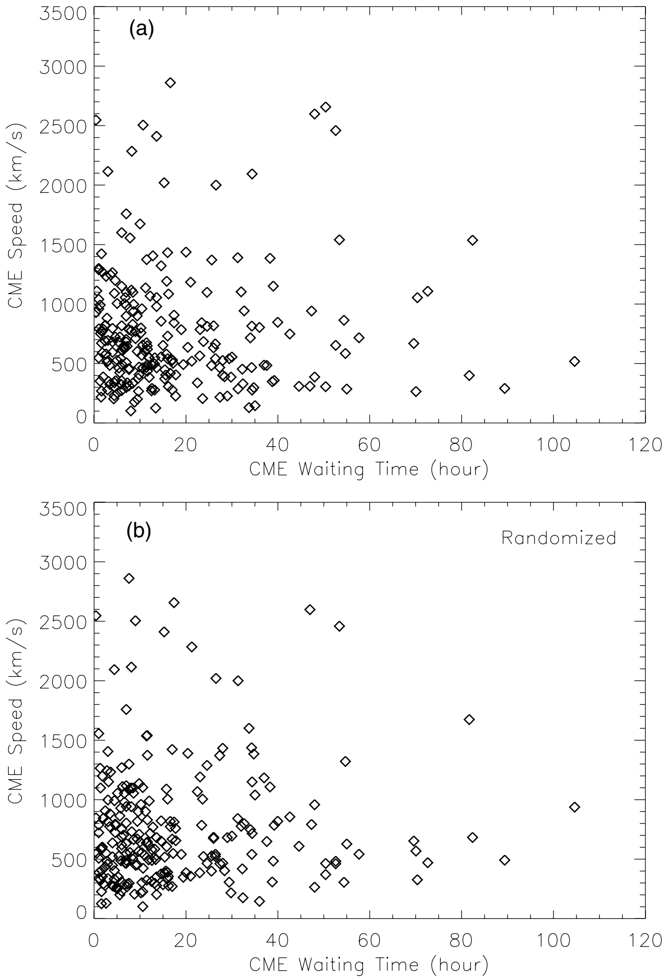

Figure 4. Panel (a): scatter plot of CME speeds vs. CME waiting times. Panel (b): same as panel (a), but the association between them is randomized.

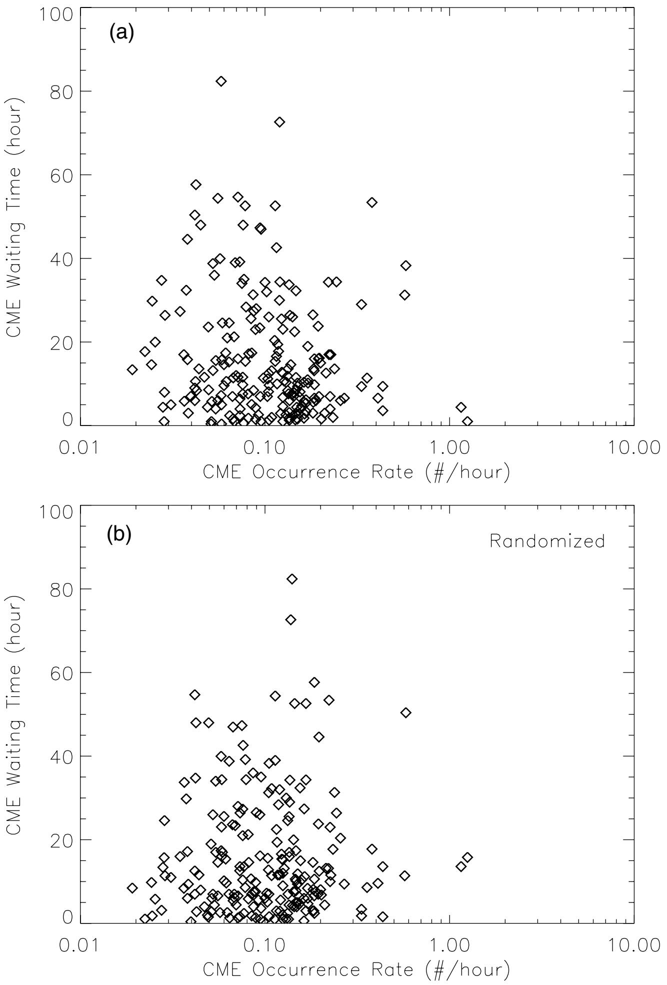

Figure 5. Panel (a): scatter plot of CME waiting times vs. CME occurrence rate in the past 18 hr. Panel (b): same as panel (a), but the association between them is randomized.

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 5(b), which is statistically the same as that in Figure 5(a). Thus, the CME waiting time is independent of 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.

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 hr and the peak waiting time of the first component at about 7 hr. These results suggest a close physical connection between quasi-homologous CMEs, which fall into the first component. Furthermore, the likelihood of the occurrence of two or more fast CMEs within 18 hr decreases as CME speed increases. A likelihood limit 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 statistical evidence that the free energy input is not a direct cause of quasi-homologous CMEs. It is well known that the free energy stored in ARs may be much higher than that which can be consumed by a single CME (e.g., Sun et al. 2012). Thus the direct cause of quasi-homologous CMEs is not the quick refilling of free energy after preceding CMEs, but the perturbation by preceding CMEs, which may lower the threshold of eruption or trigger instabilities, which to cause the next CME. The pre-eruption flux rope is precisely balanced by outward force from the inner core field and inward force from overlying arcades (e.g., Török & Kliem 2005; Wang & Zhang 2007; Liu 2007). A CME may reduce the constraint of its nearby flux rope system by removing overlying arcades, causing the balance to be broken. As shown in the numerical simulation by Török et al. (2011), which was designed to study the physical mechanism of the global sympathetic eruptions on 2010 August 1 (Schrijver & Title 2011), the second and third eruptions were actually caused by preceding eruptions. In their eruption processes, the preceding eruption caused the overlying arcades to be 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 the coronal magnetic field after the first CME.

Connecting the above picture to the peak waiting time of 7 hr, we may speculate that the 7 hr waiting time probably characterizes the average timescale 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 them down 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. It should be difficult for a simple/small AR to frequently produce CMEs. A detailed investigation of this point is worth carrying out in future work.

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