EFFECT OF CORONAL HOLES ON GRADUAL SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

Gradual solar energetic particle (SEP) evnets are thought to be produced by shocks, which are usually driven by fast coronal mass ejections (CMEs). Shock strength and magnetic field configuration are of the most importance in shock acceleration. Conceptually, the two factors are both unfavorable for the production of SEPs in/near a coronal hole (CH). To answer the questions whether and how a CH affects a CME in producing SEP events, a statistical study is performed. By investigating 89 frontside fast halo CMEs, it is found that the occurrence probability of SEP events is relatively low when CMEs are near or far away from CHs, and especially, big nearby CHs are evidently against the production of SEP events. Based on this statistical facts, how a nearby CH affects its CME neighbor in production of SEPs is discussed. Three possible interpretations are proposed.

Key words: acceleration of particles; coronal mass ejections; coronal holes.

1. INTRODUCTION

Solar energetic particle (SEP) events are one of the most important aspects in space weather. Following a widely used criterion, we define a major SEP event when the flux of protons with energy ≥ 10 MeV exceed 10 pfu (1 pfu = 1 $cm^{-2}s^{-1}sr^{-1}$) at 1 AU. Generally, SEP events have two classes: impulsive and gradual (Ref. 1, 2). Current opinion believes that mixed SEP events also exist (Ref. e.g., 3). Statistically, gradual SEP events are larger and longer than impulsive events. Shock acceleration is the main mechanism in forming gradual SEP events (Ref. 2). For a CME, in order to produce a larger SEP event, the driven shock should be stronger and the magnetic field should be more capable of trapping particles for acceleration again and again. However, in coronal holes (CHs) where fast solar wind stream commonly originates (Ref. 4), the flow and MHD fast-mode wave speeds are high, and the magnetic fields are opened and relatively straight, where particles may escape easily. Thus, we expect that CMEs originate from the vicinities of big CHs can not produce at least major SEP events, and this paper designed to test this hypothesis.

2. DETERMINATION OF CORONAL HOLES

CHs are earliest defined as low density and low temperature regions in X-ray images. After the launch of the SOHO spacecraft, the corona are also well observed in four EUV bandpasses at Fe IX/X (171Å), Fe XII (195Å), Fe XV (284Å) and He II (304Å), respectively (Ref. 5). Here, we use EIT 284Å to identify CHs based on the following reasons. (1) EIT has more complete observations of corona in our investigating interval (from 1997 to 2003) than others. (2) In the four bands of EIT, 284Å observes the corona at the highest height, and provides the most useful coronal information for SEP acceleration. This is because, near the solar surface ($\lesssim 2R_\odot$), CHs may expand rapidly and superradially with height increasing (Ref. 6, 7), and the most efficient height of shock accelerating SEPs is likely $\sim 3R_\odot$ (Ref. 8). (3) EIT 284Å images are almost as informative about CHs as the soft X-ray emission (Ref. 9, 10), which are widely used to study CHs.

The brightness of EUV emission recorded by EIT 284Å contains the information of coronal density and temperature. The dark regions usually indicate the CHs. In a EIT 284Å image, the recorded brightness, b, varies in a range. At any value of b, we can plot closed curves and calculate the areas, A, enclosed by them. Lots of EIT 284Å images show that the brightness increases rapidly at CH boundaries from CH to outside. Hence, the derivation, $f = \Delta b/\Delta A = f_{max}$, is applied to determine the CH boundaries. By applying this brightness gradient method, most CHs can be well identified. Filament-dark regions and

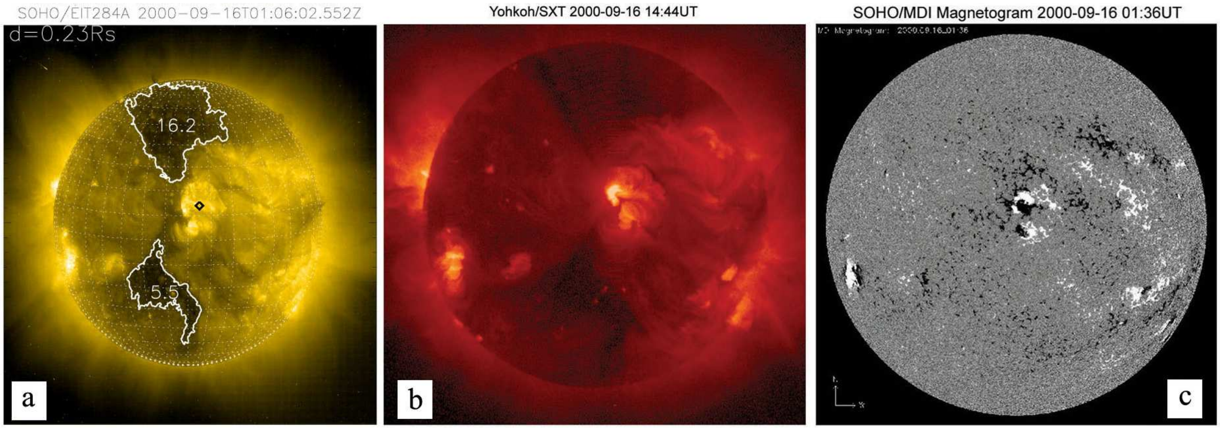

Figure 1. An example showing the determination of EIT 284Å CHs. (a) EIT 284Å image overplotted with determined CH boundaries. (b) Yohkoh/SXT image. (c) SOHO/MDI magnetogram.

small CHs ($A < 5$ gr, where a gr is the area of a $10° \times 10°$ grid as indicated by the mesh covered on the solar surface in Fig. 1a) are discarded.

For example, on September 16, 2000, two big CHs are identified as indicated by the closed curves in Fig. 1a. The areas of them are 16.2 and 5.5 gr, respectively. Fig. 1b and 1c show the soft X-ray image from the Yohkoh/SXT and magnetogram from the SOHO/MDI as comparisons. It is obvious that the dark regions in SXT image are similar to the EIT 284Å. The magnetogram from the SOHO/MDI shows that the magnetic fields inside the two dark regions were all weak and monopolar that are both the properties of a CH. This example suggests that the brightness gradient method does well determine CHs viewed in EIT 284Å.

3. STATISTICAL RESULTS

Since SEP events are affected by many factors, slow narrow CMEs, the bad producers of SEP events, can not be used to study the CH effect. Thus we focus on frontside fast (projected speed ≥ 1000 km/s) halo (span angle $\geq 130°$) CMEs. Based on the CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/), 89 fast halo CMEs are identified as definite frontside events. Statistical results are represented in Fig. 2 – 5.

Fig. 2 suggests that the occurrence probability, P, of (major) SEP events depends on the CH-proximity. For the all SEP events (Fig. 2a), P reaches the maximum 80% when $0.5R_\odot < D \leq 1.0R_\odot$. When CMEs are near or far away from CHs, the occurrence probabilities both becomes smaller. For near-CH CMEs, i.e., $D \leq 0.5R_\odot$, P is about 58%, and for CMEs far away from CHs, i.e., $D > 1.0R_\odot$, P is $\sim 50\%$. For the major SEP events (Fig. 2b), the variation of occurrence probability is more significant. For CMEs

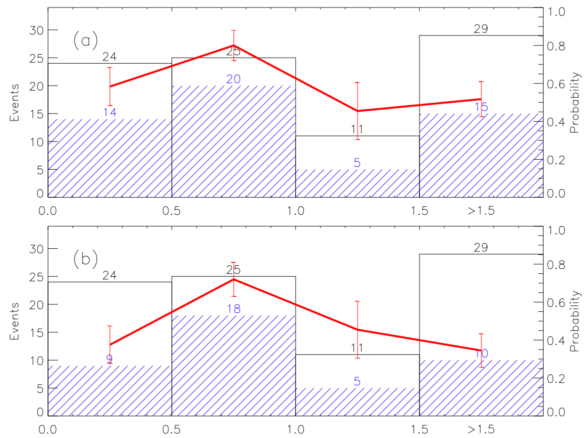

Figure 2. Distribution of the CH-proximity, D, to the CME for all events. (a) Histogram represents the events with D within some bin of distance. Open bars indicate the CME events, and solid bars indicate the SEP events. The polyline with 1-σ standard deviation denotes the ratio (P) of the number of SEP events to CME events, which means the occurrence probability of SEP events. (b) The same as (a) but solid bars indicate the major SEP events.

near or far away from CHs, P is both 38% approximately. When $0.5R_\odot < D \leq 1.0R_\odot$, P reaches the maximum 72%. These results suggest that occurrence probability of SEP events is relatively low when CMEs are near or far away from CHs, and especially, a nearby CH has significant negative effect on the production of SEP events.

Further, we divide the all SEP events into two groups: Group I contains the events approaching to CHs ($D \leq 0.5R_\odot$), and Group II contains the other events. It is found that the fitted line for Group I is roughly below that for Group II, and its slope is evidently smaller (Fig. 3). This result implies that

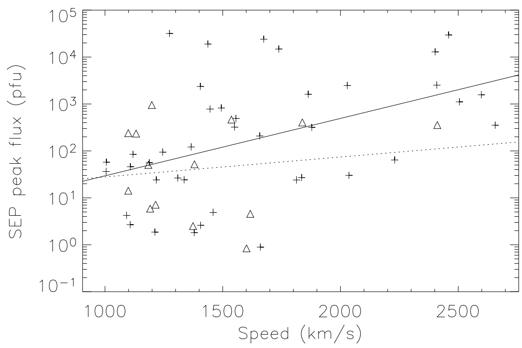

Figure 3. Scatter plot of SEP peak fluxes vs CME projected speeds. '△' indicate the near-CH ($D \leq 0.5R_\odot$) SEP events (Group I), and '+' indicate the other SEP events (Group II). The dotted and solid lines are the linear fits for Group I and II, respectively.

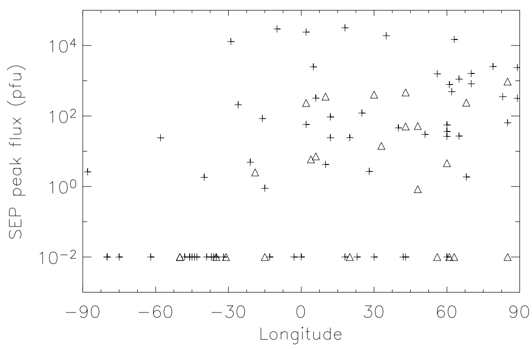

Figure 4. Scatter plot of SEP peak fluxes vs CME longitudes.

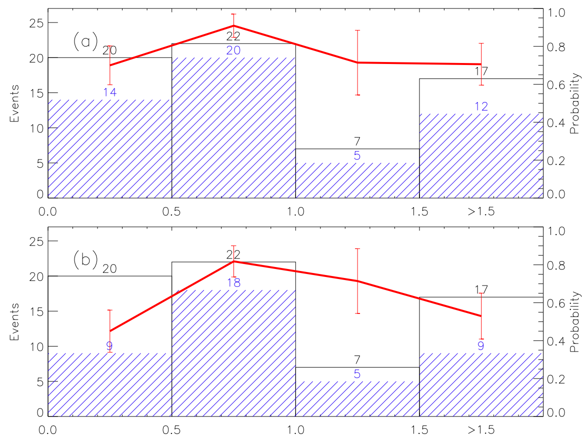

Figure 5. Distribution for the events from E30° to solar west limb. Only the probability of the major SEP events is analyzed here.

a near-CH CME seems required to be faster to produce a major SEP event. Particularly, none of Group I CMEs was slower than $\sim$ 1100 km/s or produced a SEP flux $\geq$ 1000 pfu. These facts are both consistent with the results obtained from Fig. 2 that CHs do have an evident negative effect on SEP events, especially on major ones.

CME longitude is an important factor in producing SEP events. Near east-limb CMEs are difficult to produce SEP events due to interplanetary spiral magnetic field. This fact perhaps makes the statistical results obtained above be illusion. To distinguish whether the longitude effect distorts the results, Fig. 4 is plotted. The non-SEP-associated CMEs are marked at 10^{-2} pfu. Clearly, the near-CH CMEs did not concentrate on the solar east-hemisphere. Thus the results concerning the occurrence probability of SEP events is not distorted by the CME longitude effect.

Further an additional examination on the CMEs originating from $E30°$ to solar west limb is performed. Figure 5 represents the results of this data set. Since the longitudes from $E30°$ to solar west limb are favorable to produce SEP events, the occurrence probabilities obtained here are all somewhat higher than those for all CMEs. But the similar statistical results are got. For the all SEP events (Fig. 5a), P reaches the maximum 91% when $0.5R_\odot < D \leq 1.0R_\odot$. When CMEs are near or far away from CHs, the occurrence probabilities both becomes smaller ($\sim$ 70%). For the major SEP events (Fig. 5b), the maximum probability P is $\sim$ 82% when $0.5R_\odot < D \leq 1.0R_\odot$. $P \sim 45\%$ for near-CH CMEs and $P \sim 58\%$ for CMEs far away from CHs.

4. CONCLUSIONS AND DISCUSSION

The investigation of 89 frontside fast halo CMEs from 1997 through 2003 suggests that the occurrence probability of SEP events is relatively low when CMEs are near or far away from CHs, and especially, big nearby CHs are evidently against the production of SEP events. The following conclusions are obtained:

(1) The occurrence probability of SEP events depends on the CH-proximity to the CME location. A nearby CH has significant negative effect on the production of SEP events, especially for major SEP events.

(2) When the CH-proximity within the range of 0.5 – 1.0 $R_\odot$, a CME has the largest probability of 80% (72%) to produce a (major) SEP event. For the CMEs near or far away from CHs, the occurrence probability becomes much lower ($\sim$ 50% – 58% for SEP events and $\sim$ 38% for major ones).

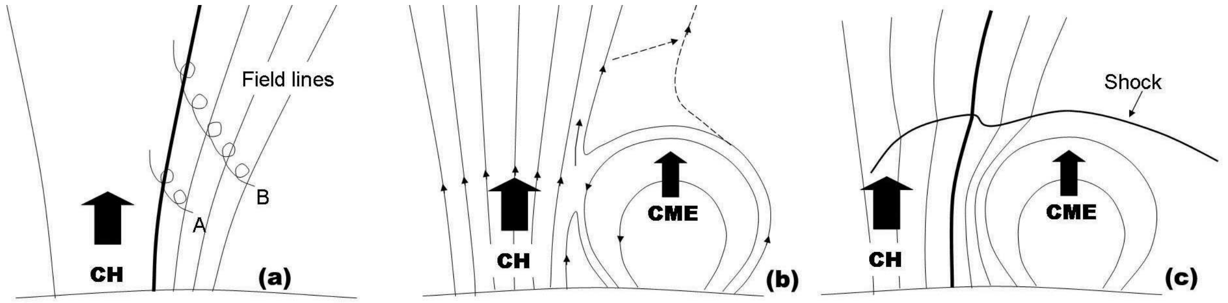

Figure 6. Schematic diagram of three possible interpretations of CH-proximity effect on major SEP events.

(3) For the CMEs from $E30^\circ$ to west limb, the results are similar except that the probabilities become somewhat higher. The occurrence probability of (major) SEP events reaches the maximum value of 91% (82%) when $0.5R_\odot < D \leq 1.0R_\odot$. When a CME is near or far away from a CH, the occurrence probability of (major) SEP events drops to $\sim 70\%$ ($\sim 45\% - 58\%$).

(4) A near-CH CME seems required to be faster ($\gtrsim 1100$ km/s) to produce a major SEP event, and is very difficult to produce an extreme intense (> 1000 pfu) SEP event.

Conceptually, a CH has two properties, (1) the fast flow and MHD wave speeds and (2) the opened and relatively straight magnetic field lines, against the formation of SEP events. The above statistical results suggest that big nearby CHs are evidently against the production of SEP events. However, CMEs is a phenomenon outside of CHs. How do these interior properties of CHs affect their CME neighbors? We propose the following three possibilities as illustrated in Fig. 6. (a) Particles being accelerated diffuse across coronal field lines until they reach the open straight lines from CHs, then escape quickly without sufficient accelerations. (b) Particles escape from acceleration region along the CH field lines through slow magnetic field reconnections. (c) The shock strength is weakened in a fast solar wind stream which connects with the Earth.

On the other hand, why is the occurrence probability of SEP events also low when CMEs are far away from CHs? The reason is not known yet, which needs more work to answer.

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