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STATISTICAL EVIDENCE FOR SYMPATHETIC FLARES

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ABSTRACT

Sympathetic flares are a pair of flares that occur almost simultaneously in different active regions, not by chance, but because of some physical connection. In this paper statistical evidence for the existence of sympathetic flares is presented. From *GOES* X-ray flare data, we have collected 48 pairs of near simultaneous flares whose positional information and *Yohkoh* soft X-ray telescope images are available. To select the active regions that probably have sympathetic flares, we have estimated the ratio R of actual flaring overlap time to random-coincidence overlap time for 38 active region pairs. We have then compared the waiting-time distributions for the two different groups of active region pairs ($R > 1$ and $R < 1$) with corresponding nonstationary Poisson distributions. As a result, we find a remarkable overabundance of short waiting times for the group with $R > 1$. This is the first time such strong statistical evidence has been found for the existence of sympathetic flares. To examine the role of interconnecting coronal loops, we have also conducted the same analysis for two subgroups of the $R > 1$ group: one with interconnecting X-ray loops and the other without. We do not find any statistical evidence that the subgroup with interconnecting coronal loops is more likely to produce sympathetic flares than the subgroup without. For the subgroup with loops, we find that sympathetic flares favor active region pairs with transequatorial loops.

Subject headings: Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

Sympathetic flares are defined as solar flares in different active regions that apparently occur as the common result of the activation of a coronal connection between the regions.[7] The sympathetic flares are compared with simultaneous flares, which are defined as unrelated solar flares that occur at nearly the same time. However, it is a difficult task to decide whether a pair of flares is physically connected or not. And even the existence of sympathetic flares is still being debated (Pearce & Harrison 1990; Bumba & Klvana 1993; Biesecker & Thompson 2000). Thus, it has been quite common in previous studies to use the term "sympathetic flares" naively to denote any pair of flares with close temporal and/or spatial proximity, without information on actual physical relations. Once we can somehow admit the existence of real sympathetic flares, another question is naturally raised as to what physical connection underlies almost simultaneous flaring. In the course of seeking an answer to this question, we first need to find observational features involved in the phenomena. Recent space missions such as *Yohkoh*, the *Solar and Heliospheric Observatory* (*SOHO*), and the *Transition Region and Coronal Explorer* (*TRACE*) have shown that solar active regions are intimately connected by coronal magnetic loops, which are identified by X-ray or EUV spectroheliograms. The coronal loops naturally come up as candidates for mediating physical relations between active regions bearing sympathetic flares. However, it remains unresolved whether or not the existence of coronal connections is important for sympathetic flares (Fritzova-Svestkova, Chase, & Svestka 1976). The purpose of our study is to tackle these problems from a statistical point of view. To avoid any ambiguity in terminology, we define the terms used in this paper as follows: Sympathetic flares are defined as a pair of successive flares that occur nearly simultaneously in different active regions having a certain physical connection, at least with statistical significance. Simultaneous flares are defined as a pair of successive flares, of which the second starts before the end of the first. Our definition of simultaneous flares is differentiated from the definition in the on-line Solar-Terrestrial Glossary in that we stick to the literal meaning of the term. Under our definition, the set of sympathetic flares is a subset of simultaneous flares, and simultaneous flares are either sympathetic or random-coincident flares.

There have been several reports on the existence of sympathetic flares. Fritzova-Svestkova et al. (1976) pioneered statistical investigation on this subject. They computed the frequency distribution of time intervals between flares in various active regions for two different groups. To one group belong active region pairs interconnected with visible X-ray loops, and to the other belong active region pairs without any visible interconnections. They found that there is no obvious difference between the two distributions, but that both show a slight excess for very short time intervals,

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[7] See, e.g., the High Altitude Observatory (a division of the National Center for Atmospheric Research) Glossary of Solar-Terrestrial Terms available at http://www.hao.ucar.edu/public/education/glossary.html#S.haogloss.

with statistical significances of 1.6 σ for the interconnection group and 1.9 σ for the nonconnection group. The statistical significance was only found for pairs of active regions separated by less than 3.6×10^5 km. This result was supported by Pearce & Harrison (1990), who examined the ratio of the actual flaring overlap time to the random-occurrence overlap time as a function of spatial separation for 15 flare-bearing active region pairs. There were also some observational studies of individual sympathetic flares in the aspect of temporal coincidence and/or physical connection (Gopalswamy et al. 1999; Zhang et al. 2000; Bagala et al. 2000; Wang et al. 2001). Specifically, by examining a series of high-resolution full-disk Hα data from Big Bear Solar Observatory (BBSO), Wang et al. (2001) showed that the propagation of a surge associated with filament eruption can be a cause of sympathetic flares.

The flaring-time interval, which is also called the "waiting time," is defined as the time span between two successive flaring events. The waiting-time distribution can provide us with statistical information on the probability of the next event occurring within a certain time interval after one event has taken place. If the number of sympathetic flares is not negligible, an overabundance will appear in short intervals of the waiting-time distribution relative to a Poisson distribution because sympathetic flares are regarded as having an interdependency, while a Poisson distribution implies a random process. This approach is conceptually the same as the method that Fritzova-Svestkova et al. (1976) employed. Biesecker & Thompson (2000) concluded that there is no evidence for sympathetic flares by comparing the distribution of solar X-ray flares in time with that expected of a time-varying (nonstationary) Poisson distribution. Moon et al. (2001) also showed that sympathetic flares are not significant in the statistical sense by examining the waiting-time distribution of *GOES* X-ray flares with short waiting times as well as the angular correlation function of simultaneous flares. These findings are in line with Chase et al. (1976), who found no evidence of sympathetic flares from *Skylab* X-ray observations of 94 interconnected active regions. However, it should be noted that these results do not absolutely deny the existence of sympathetic flares, but rather imply that sympathetic (or interdependent) flares, though they exist, are much smaller in number than independent flares.

Our major question is how to identify the existence of sympathetic flares with sufficient statistical significance. To answer this question, we take three steps as follows: First, we select simultaneous *GOES* flares, more exactly, pairs of successive flares greater than C1 class, of which the second flare occurs before the first flare ends. They must be either random-coincident flares or sympathetic flares. Second, to select active regions that are likely to have sympathetic flares, we estimate the ratio (R) of actual flaring overlap time to random-coincidence overlap time (Pearce & Harrison 1990). Third, we compare the waiting-time distributions with corresponding nonstationary Poisson distributions for two different groups of active region pairs: $R > 1$ and $R < 1$. For the $R > 1$ group we have found significant statistical evidence for sympathetic flares, i.e., a noticeable overabundance in short waiting times. To see the role of interconnecting coronal loops, we also conduct the same analysis for two different subgroups of the $R > 1$ group: one with loops and the other without. We then proceed to compare samples with transequatorial loops with those having longitudinal loops within the subgroup with loops. In § 2 a brief description is given of the data and the statistical procedure. In § 3 we report the results of our analysis performed according to the order described above. Finally, a brief summary and conclusion is delivered in § 4.

2. DATA ANALYSIS AND STATISTICAL PROCEDURES

We have considered simultaneous *GOES* X-ray flare pairs (greater than C1 class) whose positional information and *Yohkoh* SXT images are available. We found 71 successive flare pairs, most of which occurred between 1991 and 1994. Since then, the positional information of *GOES* flares has not been well compiled. About one-third (23 pairs) out of 71 flare pairs occurred in the same active regions. In this study, we only consider 48 successive flare pairs that occurred in 38 different active region pairs. To select active region pairs that have high a probability for sympathetic flaring, we have applied the statistical analysis of Pearce & Harrison (1990) to 38 active region pairs.

Let us consider a pair of active regions that simultaneously exist on the solar surface. If they are not linked together, the apparent flaring overlap time (or simultaneously flaring time) follows a probability rule for random-coincidence, which is given by

$$P_r = \frac{2 \sum t_a \sum t_b}{T_a T_b} \tag{1}$$

(Pearce & Harrison 1990), where $\sum t_a$ (or t_b) is the sum of the individual flaring time in each active region and T_a (or T_b) is the total crossing time on the solar disk for each active region. Equation (1) is valid only if each t_a (or t_b) is much less than T_a (or T_b). For solar flares, the maximum value of t_a/T_a is about 10^{-2}. Then the ratio (R) of actual flaring overlap time to random-coincidence overlap time between two active regions can be approximated as

$$R = \frac{\sum t_{ab}/T_{ab}}{P_r} , \tag{2}$$

where $\sum t_{ab}$ is the sum of each flaring overlap time for flare pairs occurring in two different active regions and T_{ab} is the total period over which two active regions coexist on the solar surface. The *GOES* X-ray flare data that we use here have a few advantages compared to the Hα data that Pearce & Harrison (1990) employed. First, the *GOES* data have no night-time gaps since they have been obtained nearly continuously without any remarkable interruption. Second, the timing uncertainty of *GOES* flares is much less than that of Hα flares because the starting and ending times of *GOES* flares are measured with 1 minute temporal resolution according to certain preset criteria. Third, the overlap time of Hα flares may involve an error due to the fact that the Hα emission is a chromospheric secondary effect of magnetic reconnection. Adopting an approximate timing uncertainty of Hα flares, Pearce & Harrison (1990) estimated about a 20% error in R for Hα flares. Taking a similar approach to *GOES* data yields only a few percent error in R. Such a small uncertainty is sufficiently tolerable in studies like ours because the value of R is only used for separating groups.

We have made two assumptions for the calculation of waiting times of the flare samples. First, observed X-ray flares are treated as discrete events in time. Second, the waiting time is defined as the time interval between the start of one event and the start of the next. If individual X-ray events are independent of each other and take place with a constant mean flaring rate m, the waiting-time distribution should be represented by a Poisson interval distribution in which the probability of an event occurring between time t and $t + dt$ is $P(t)dt$, where

$$P(t) = m \exp(-mt) , \quad (3)$$

with a mean frequency m. However, the mean flaring rate of major solar X-ray flares is not constant on a long timescale. It depends on the nature of each active region, the lifetime of a given active region, the distribution of active regions on the solar disk, the solar rotation, the solar cycle, etc.

The result of our statistical analysis is to be compared with a nonstationary Poisson distribution in which the mean frequency varies in time. For a slowly varying flaring rate, the waiting-time distribution of a nonstationary Poisson process with rates m_i and intervals t_i can be approximated by

$$\overline{P}(\Delta t) \approx \sum_i \phi(m_i) m_i \exp[-m_i \Delta t] , \quad (4)$$

where

$$\phi(m_i) = \frac{m_i t_i}{\sum_j m_j t_j} \quad (5)$$

is the fraction of events associated with a given rate m_i (Wheatland 2000; Moon et al. 2001).

The value of t_j should be a time unit that has the same potential to generate solar flares (Moon et al. 2001). If one selects too small a value of t_j, the number of flares during the interval would not be sufficient for statistics. Conversely, if one considers too large a value of t_j, the approximation as a nonstationary process loses its validity. To determine appropriate values of t_j, Wheatland (2000) used the method of Scargle (1998) based on Bayesian statistics and decomposed the *GOES* flares for 25 years into 390 Bayesian blocks. On the other hand, Moon et al. (2001) considered t_j as a constant free parameter and determined its value by comparing the observed waiting-time distributions with the corresponding nonstationary Poisson distributions. Here they found that 3 days is an appropriate value for all *GOES* flares stronger than C1 class during the last solar maximum from 1989 to 1991. They also showed that individual active regions can be approximated by a stationary Poisson distribution, which implies that the value of t_j should be about 14 days, the crossing time of an active region on the solar disk. Flare samples that we consider are not continuous and the number of flares that occurred in some active regions are not so large for Poisson statistics since we have selected active region pairs producing simultaneous flares. Thus, we assume that the value of t_j is the total crossing time on the solar disk of each active region pair, ranging from 15 to 25 days, which is close to the average value of t_j employed by Wheatland (2000).

In deciding whether a pair of active regions is linked together by SXT loops or not, personal subjectivity is likely to be involved. To avoid this problem, the reading of *Yohkoh* SXT daily images and the decision on the presence of loops was independently made by two of the authors.

TABLE 1
THE NUMBER OF ACTIVE REGION PAIRS WITH $R > 1$ AND $R < 1$

SXT Loop	Total Number	$R > 1$	$R < 1$
Yes.............	16 (5)	6 (4)	10 (1)
No	22 (9)	11 (4)	11 (5)
Total	38 (14)	17 (8)	21 (6)

NOTE.—The number of transequatorial active region pairs is given in parentheses.

3. RESULTS

We have computed the ratio (R) of actual flaring overlap times to random-coincidence overlap times between two active regions for 38 active region pairs. Table 1 summarizes the number of active region pairs that have $R > 1$ and $R < 1$, with and without SXT loop connections. We have found that 17 pairs have $R > 1$ and 21 pairs have $R < 1$. Figure 1 shows the waiting-time distribution for two different groups: one with $R > 1$ and the other with $R < 1$. For each group, we have estimated the statistical significance for the overabundance in the shortest waiting time. It is found that the $R > 1$ group has a noticeable overabundance

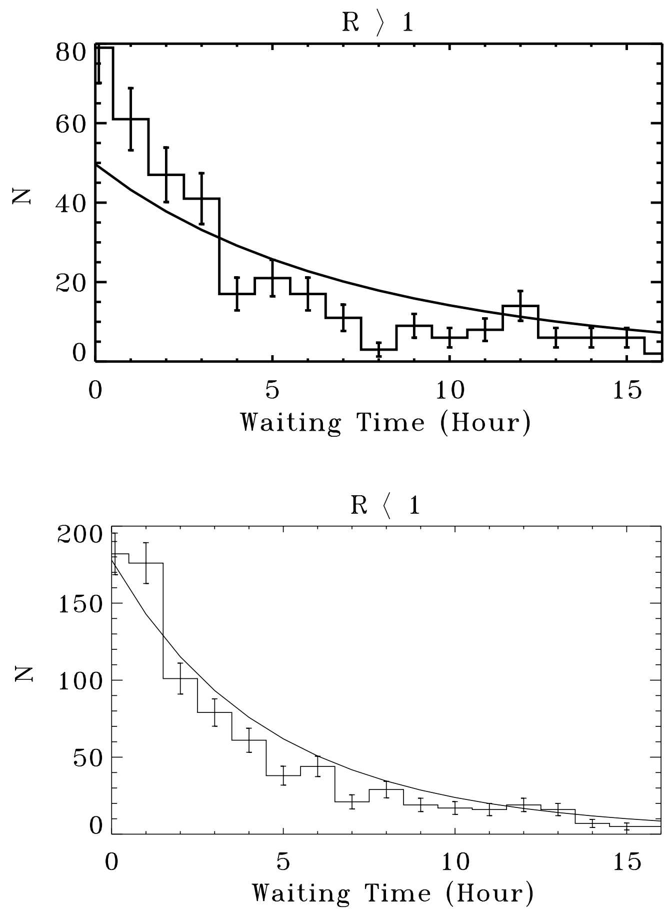

FIG. 1.—Waiting-time distributions for two different groups of active region pairs that produced simultaneous flares: one with $R > 1$ (*top*) and the other with $R < 1$ (*bottom*). The solid lines represent corresponding nonstationary Poisson distributions, and the error bars represent the square root of the number of waiting times in each bin.

TABLE 2
BASIC CHARACTERISTICS AND STATISTICS OF ACTIVE REGION PAIRS LIKELY TO HAVE SYMPATHETIC FLARES ($R > 1$)

NOAA AR 1	NOAA AR 2	Separation (deg)	P_r	$\sum t_{ab}/T_{ab}$	R	Loop	Type
6961	6964	32	1.9E−4	4.2E−4	2.3	Yes	Trans
7031	7032	10	5.5E−4	1.9E−3	3.4	Yes	Trans
7067	7069	22	1.2E−3	4.7E−3	3.9	Yes	Trans
7137	7138	32	6.5E−5	8.4E−4	12.8	Yes	Trans
7248	7257	36	7.9E−4	2.6E−3	3.3	Yes	Long
7276	7284	32	2.2E−4	1.3E−3	6.1	Yes	Long
6906	6908	87	6.3E−4	1.6E−3	2.5	No	Trans
6906	6915	84	1.4E−3	1.6E−3	1.2	No	Trans
7002	7005	64	2.1E−5	3.6E−3	169.3	No	Long
7042	7048	44	3.7E−4	3.6E−3	9.8	No	Long
7056	7067	128	4.2E−3	8.3E−3	2.0	No	Trans
7123	7126	108	4.7E−4	2.4E−2	50.8	No	Long
7150	7154	115	1.6E−3	4.5E−3	2.8	No	Long
7216	7218	65	4.3E−4	1.1E−3	2.6	No	Long
7227	7232	55	7.0E−5	4.9E−4	7.0	No	Long
7330	7334	60	7.9E−5	2.9E−3	36.2	No	Trans
7784	7786	69	2.3E−5	2.4E−4	10.3	No	Long

(3.3 σ), whereas the $R < 1$ group has a weak overabundance (0.3 σ). Basic information and statistics for the $R > 1$ group are tabulated in Table 2. Our results strongly indicate that sympathetic flares exist in a statistical sense. This conclusion is different from previous studies of waiting-time distribution (Biesecker & Thompson 2000; Moon et al. 2001). This difference is attributed to the fact that we have selectively considered active region pairs that are more likely to have sympathetic flares.

Figure 2 shows the waiting-time distributions for two subgroups of the $R > 1$ group: one with SXT loops and the other without loops. Our statistics yield the result that the subgroup with loop connections has a 1.5 σ overabundance, whereas the subgroup without loop connections has a 3.3 σ overabundance. It is very surprising that the statistical significance for the subgroup without SXT loop linkages is far greater than that with SXT loop linkages. This might be due to the contribution of some active region pairs with high values of R. However, Fritzova-Svestkova, Chase, & Svestka (1976) also reported a statistical excess of 1.6 σ for the interconnected pairs and 1.9 σ for the nonconnected pairs from *Skylab* observations. These results may imply that either the interconnecting coronal loops are insignificant for sympathetic flares or that there are other effective triggering agents for nonconnected sympathetic flares. However, we cannot absolutely exclude a possibility that invisible (low density) high coronal loops are associated with distant sympathetic flares.

Figure 3 shows the logarithmic ratio $\log R$ as a function of the angular separation between two active regions for two different data sets: 16 active region pairs with loops and 22 pairs without loops. Whereas Pearce & Harrison (1990) found that active region pairs with $R > 1$ only exist within 35° angular separation, we have found the pairs with $R > 1$ with much longer angular distances, even about 130°. But most of the active region pairs with high values of R (e.g., $R > 5$) have angular separations smaller than ~70°. It should also be noted that there is no systematic dependence between the value of R and the existence of SXT loops. As

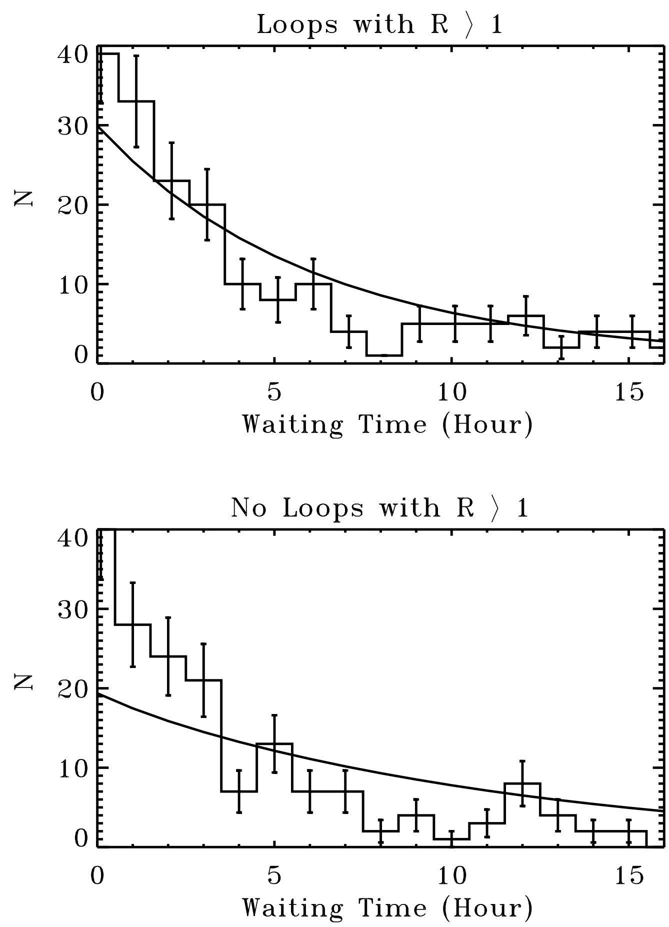

FIG. 2.—Waiting-time distributions for two different subgroups of the group with $R > 1$: with loop connections (*top*) and without loops (*bottom*). The solid lines represent corresponding nonstationary Poisson distributions, and the error bars represent the square root of the number of waiting times in each bin.

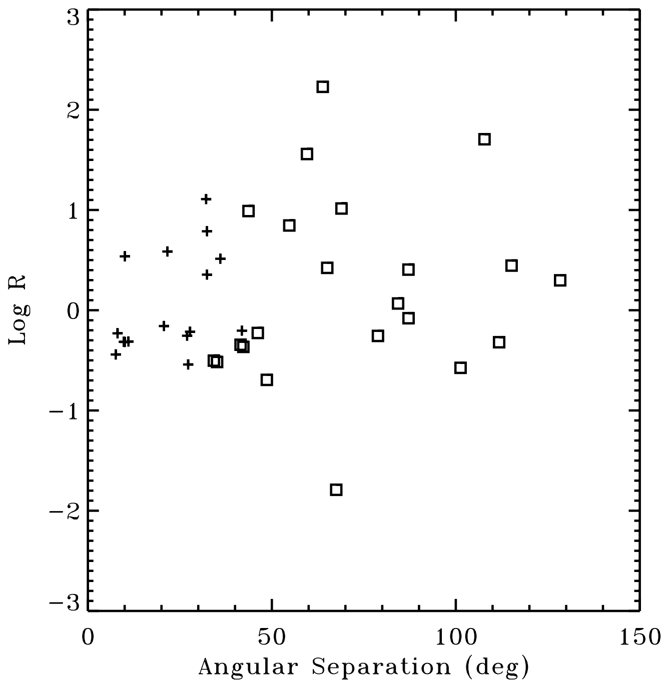

FIG. 3.—The log R of actual flaring overlap time to random-coincidence overlap time as a function of angular separation between two active regions for 38 data sets. The plus signs represent simultaneous flares with SXT loop connections, and the squares represent those without SXT loop connections.

seen in Table 1, the number of active region pairs with $R > 1$ is six out of 16 pairs with loop linkages and 11 out of 22 pairs without loop linkages. Also, these numbers do not support the idea that interconnecting coronal loops are significant for sympathetic flares. This conclusion is consistent with that drawn from Figure 2.

An interesting finding comes from the statistics involving transequatorial loops, which connect two active regions in opposite hemispheres (see numbers in parentheses of Table 1). According to Pevtsov (2000), about 30% of interconnected active regions have transequatorial connections and mostly the same chirality (more than two-thirds). For the data sets with loop linkages, we have also found five active region pairs with transequatorial loops out of 16 pairs with interconnecting loops (about 30%). Here four out of five active region pairs with transequatorial loops have R-values larger than unity. The median values of R for the data sets with transequatorial loops and longitudinal (non-transequatorial) loops are 3.5 and 0.6, respectively. For the data sets without loop linkages, nine out of 22 active region pairs are transequatorial in the sense that the active regions of a pair are located in opposite hemispheres. In this case, four out of the nine active region pairs that are transequatorial (without loops) have R values larger than unity. Our results show that the active region pairs with transequatorial loops have a higher probability of sympathetic flaring than those with longitudinal loops that connect two active regions in the same (northern or southern) hemisphere. Why transequatorial loops are more favorable to sympathetic flaring is quite puzzling. Farnik, Karlicky, & Svestka (1999) argued that very long transequatorial loops are formed by reconnection between two shorter transequatorial loops. Such magnetic reconnection can produce sympathetic flares. However, the examination of this scenario is beyond the scope of the present study.

In Figure 4, the delay time between two simultaneous flares is plotted versus their angular separation for all 38 active region pairs (*top*) and for pairs with $R > 1$ only (*bottom*). As seen in the figures, there is no obvious correlation between the two quantities. Our results show that the second flare can start at any time while the first flare is occurring. For the group with $R > 1$, about 90% of the active region pairs have time delays of less than 70 minutes and 60%, less than 30 minutes.

Zhang et al. (2000) found only 1–2 minutes of time delay in three sympathetic Hβ flares of NOAA AR 6240 and attributed the time delay to the heat conduction time. However, this case might be considered as one flaring event because only one reconnection process seem to generate a pair of Hβ flarings (see *GOES* data). It is also notable that Wang et al. (2001) observed propagation of a surge at a speed of ~80 km s^{-1}, which they suggested triggered a sympathetic flare. The speed is comparable to the MHD wave propagation speed in the chromosphere. As seen in the bottom panel of Figure 4, most delay times of simultaneous flares are located below the upper solid line, which corresponds to the information propagation speed of 100 km s^{-1}. For majority of sympathetic flares, the information propagation speed is even higher. This suggests that the information propagation in the chromosphere, for example, in the

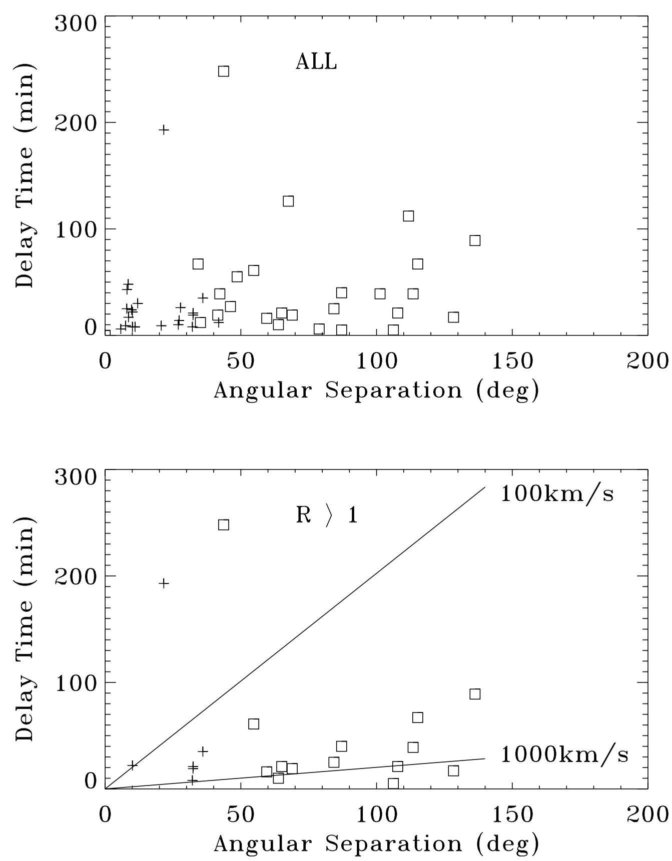

FIG. 4.—Delay time between two simultaneous flares vs. their angular separation for the whole data set (*top*) and the data subset with $R > 1$ (*bottom*). The symbols are the same as Fig. 3. In the bottom panel, two solid lines correspond to information propagation speeds of 100 and 1000 km s^{-1}, respectively.

form of a surge, may be involved for sympathetic flares having relatively large waiting times rather than near simultaneous sympathetic flares. Therefore, we still need to further investigate coronal connections in sympathetic flares, although they may not be so visible. As alternative mechanisms of sympathetic flaring, we also have to consider subphotospheric connections suggested by Fritzova-Svestkova et al. (1976) and large-scale convective motions proposed by Bumba & Klvana (1993).

4. SUMMARY AND CONCLUSION

In this paper, we have presented statistical evidence for the existence of sympathetic flares. For this work, we have collected 48 sets of simultaneous flares, for which both positional information and *Yohkoh* SXT images are available. Because we suspect that the negative conclusions of previous studies (Biesecker & Thompson 2000; Moon et al. 2001) on the existence of sympathetic flares is due to the effect of sampling, we divided the data into two groups according to the value of R, the ratio of actual flaring overlap time to random-coincidence overlap time. We have then derived the waiting-time distributions for two different groups of active region pairs, $R > 1$ and $R < 1$, and compared them with corresponding nonstationary waiting-time distributions. As a result, we have found clear statistical evidence for the existence of sympathetic flares, i.e., a noticeable overabundance in short waiting times in the waiting-time distribution for the $R > 1$ group.

As for the role of interconnecting X-ray loops, we do not find any statistical evidence for the significance of loop presence in sympathetic flares. However, it is found that transequatorial loops are more favorable to sympathetic flares than longitudinal loops. Finally, the delay time between successive flares is, in most cases, shorter than the chromospheric wave transit time and a few times the coronal wave transit time. This suggests unobservable coronal connections between flaring active regions, but we also pay attention to the possibility of subphotospheric connections.

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