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A cyclic behavior of CME accelerations for accelerating and decelerating events *

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Abstract We investigate the cyclic evolutionary behavior of CME accelerations for accelerating and decelerating CME events in cycle 23 from 1997 January to 2007 December. It is found that the absolute values of semiannual mean accelerations of both accelerating and decelerating CME events roughly wax and wane in a cycle, delaying the sunspot cycle in time phase. We also investigate the semiannual number of CMEs with positive and negative acceleration and find that there are more decelerating CME events than accelerating CME events during the maximum period of a cycle (about three years), but there are more accelerating CME events than decelerating CME events during the rest of the time interval of the cycle. Our results seem to suggest that the different driving mechanisms may be acting accelerate and decelerate CME events: for accelerating CME events, the propelling force ($F_{\rm p}$) statistically seems to play a significant role in pushing CMEs outward; for decelerating CME events, the drag ($F_{\rm d}$) statistically seems to play a more effective role in determining CME kinematic evolution in the outer corona. During the maximum period of a cycle, because of the V^2 dependence, $F_{\rm d}$ is generally stronger; because of the magnetic field dependence, $F_{\rm p}$ is also generally stronger. Thus, the absolute values of both the negative and positive accelerations are generally larger during that time. Because of the V^2 dependence, $F_{\rm d}$ may be more effective during the maximum period of a cycle. Hence, there are more decelerating CME events than accelerating CME events during that time. During the minimum time interval of a cycle, CMEs have relatively small speeds, and $F_{\rm p}$ may be more effective. Therefore, there are more accelerating CME events than decelerating CME events during that time.

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

1 INTRODUCTION

Coronal mass ejections (CMEs) are among the largest energy releases in the solar system and can directly affect space weather in the near-Earth environment. In spite of such practical importance, the physical mechanisms responsible for CME initiation, acceleration, and propagation remain unclear.

All CMEs have positive acceleration in the beginning as they lift off from rest — the propelling force ($F_{\rm p}$) exceeds gravity ($F_{\rm g}$) and other restraining forces (Gopalswamy 2004). It is accepted that magnetic reconnection plays a major role in the origin of CMEs, which are driven through the ambient

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solar wind by magnetic and pressure forces (Vršnak 1990; Chen 1996). The moment a CME lifts off, it is subject to an additional retarding force — the drag, given by $F_{\rm d} = CA\rho(V_{\rm cme} - V_{\rm sw})|V_{\rm cme} - V_{\rm sw}|$, where C is the drag coefficient, A is the surface area of the CME, ρ is the plasma density, $V_{\rm cme}$ is the CME speed and $V_{\rm sw}$ is the solar wind speed (negligible close to the Sun) (Chen 1989; Cargill et al. 1996; Gopalswamy 2004). The results of Chen & Krall (2003) suggest that the propelling force fades at heights below $\sim 4R_{\odot}$. Some similar conclusions were drawn by Vršnak (2001), Gallagher et al. (2003) and Zhang & Dere (2006). Therefore, drag must play a significant role within the LASCO C2 and C3 FOV (2.1–$32R_{\odot}$). The telescope C1 was disabled in 1998 June. Previous reports (Yashiro et al. 2004; Gopalswamy 2006) suggested that the interactions between CMEs and the solar wind are the most important mechanism that determines CME kinematic evolution in the LASCO C2 and C3 FOV. That is to say, slower CMEs tend to accelerate and faster CMEs tend to decelerate. The CME acceleration over the entire Sun-Earth distance also has a similar relation to the CME initial speed (Lindsay et al. 1999; Gopalswamy et al. 2000, 2001). Their results suggest that the interaction between CMEs and the solar wind is important for CME propagation models in the interplanetary medium.

In this paper, we will investigate the cyclic evolutionary behavior of CME accelerations and the semiannual number of CMEs for accelerating and decelerating CME events in cycle 23 from 1997 January to 2007 December.

2 THE CYCLIC EVOLUTIONARY BEHAVIOR OF CME ACCELERATION

The CME data used here come from SOHO/LASCO[1]. This CME catalog, generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory, covers the period from 1996 January to the present. For each CME event, the catalog gives height-time plots, plane-of-sky speeds, the central position angle (CPA), and so on. The CME speeds are obtained by linearly fitting the height-time measurements. In order to determine whether the CME is accelerating or decelerating, a quadratic fitting to the CME height-time plots was also made. A minimum of three height-time measurements is needed for an estimate of the acceleration, but the accuracy increases when there are more measurements. We exclude some CMEs because their accelerations are uncertain due to either poor height measurements or a small number of height-time measurements (See sect. 3.4 of Yashiro et al. (2004) for details). Thus, we obtain accelerations for 4366 CMEs out of the 12916 detected. In our study, we analyze the accelerations obtained from the quadratic fit and the speeds obtained from a linear fit of these CMEs.

We divide the CMEs into accelerating and decelerating events according to their acceleration signs determined from the quadratic fit and then plot the semiannual mean accelerations of SOHO/LASCO CMEs as a function of time for the interval 1997–2007. We also plot the semiannual mean speeds of SOHO/LASCO CMEs as a function of time for the interval 1997–2007 for the two groups, as is shown in Figures 1 and 2. Error bars represent the uncertainty in the mean ($\sigma/(n)^{1/2}$, where σ is the standard deviation and n is the number of data points included in the average). Figures 1 and 2 also show the corresponding quadratic fits. From Figures 1 and 2, we can find that the absolute values of semiannual mean accelerations of both accelerating and decelerating CME events roughly wax and wane in a cycle, having the same cyclic phase as the semiannual mean speeds. However, for accelerating CME events, the semiannual mean acceleration and speed peaked during the periods 2002 July to December and 2002 January to June respectively; for decelerating CME events, the absolute value of semiannual mean acceleration and speed peaked during the periods 2003 January to June and 2002 July to December respectively, well after the maximum of the sunspot cycle (2000 July 10 to August 6).

Figure 3 shows a scatter plot between the measured acceleration and speed of accelerating and decelerating CME events for which the acceleration estimate was possible. As we know, some results (Gopalswamy et al. 2000, 2001; Yashiro et al. 2004; Gopalswamy 2006) suggested that an interaction between the CMEs and solar wind was the most important mechanism that determines CME kinematic evolution in the outer corona. Wang & Sheeley (1990) found that the solar wind speed ranged from

[1] *http://cdaw.gsfc.nasa.gov/CME_list*

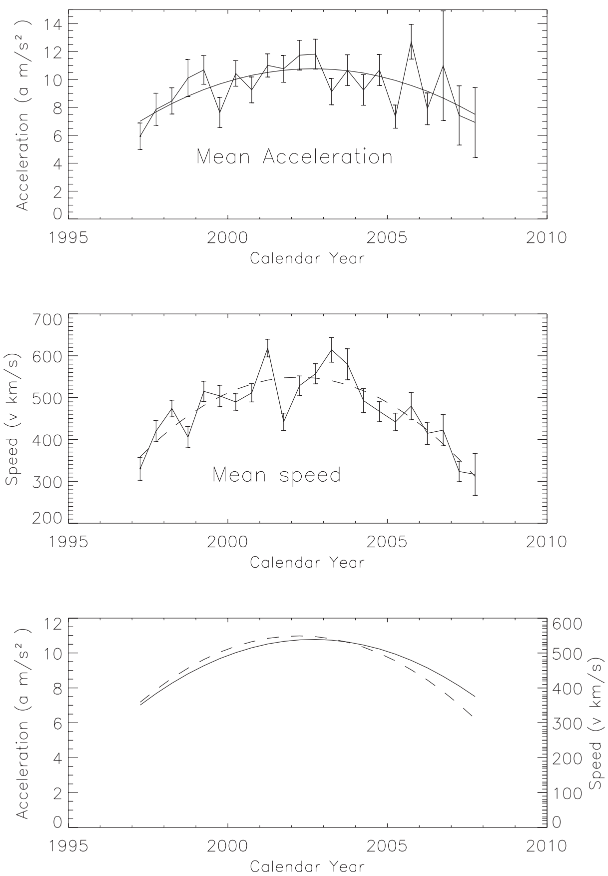

Fig. 1 Semiannual mean accelerations (*top panel*) and speeds (*middle panel*) of SOHO/LASCO accelerating CME events from 1997 to 2007. The solid line in the top panel and the dashed line in the middle panel show the corresponding quadratic fits, which are repeated in the bottom panel.

350 km s^{-1} to 550 km s^{-1}. Their results suggest that slow CMEs (v <350 km s^{-1}) accelerate, CMEs of intermediate speed (350 km s^{-1} < v <550 km s^{-1}) statistically should have no appreciable acceleration, and fast CMEs (v >550 km s^{-1}) decelerate. However, from 1997 to 2007, SOHO/LASCO observed 337 decelerating CMEs, or 15.3% of all the 2200 decelerating CMEs recorded, which are slow CMEs (v < 350 km s^{-1}), and 713 accelerating CMEs, or 32.9% of all the 2166 accelerating CMEs recorded, which are fast CMEs (v >550 km s^{-1}).

The absolute values of semiannual mean accelerations of both accelerating and decelerating CME events roughly wax and wane in a cycle, having the same cyclic phase as the semiannual mean speeds. That is to say, for accelerating CME events, slower CMEs tend to have little acceleration and faster CMEs tend to have large acceleration; for decelerating CME events, slower CMEs tend to have little deceleration and faster CMEs tend to have large deceleration. We can find that our results about the cyclic evolutionary behavior of CME accelerations for accelerating and decelerating CME events are different from the general consensus that slower CMEs tend to have large acceleration and faster CMEs tend to have large deceleration in the corona. Also from Figure 3, we find that there is a significant fraction of fast CMEs (v >550 km s^{-1}) showing acceleration and a significant fraction of slow CMEs (v < 350 km s^{-1}) showing deceleration. Our results seem to suggest that, within the LASCO C2 and C3 FOV, the different driving mechanisms may be acting in accelerating and decelerating CME events:

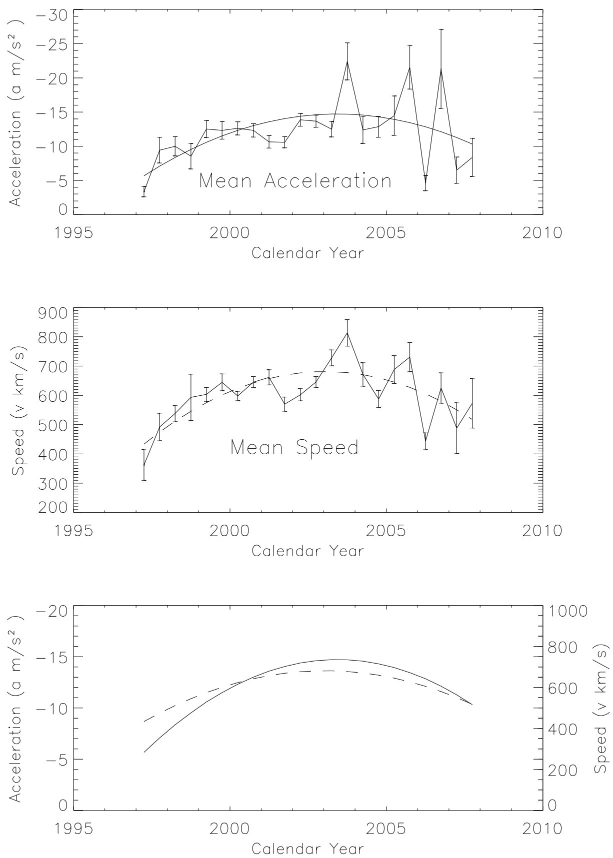

Fig. 2 Semiannual mean accelerations (*top panel*) and speeds (*middle panel*) of SOHO/LASCO decelerating CME events from 1997 to 2007. The solid line in the top panel and the dashed line in the middle panel show the corresponding quadratic fits, which are repeated in the bottom panel.

for accelerating CME events, the propelling force ($F_{\rm p}$) statistically seems to play a significant role in pushing CMEs outward; for decelerating CME events, the drag ($F_{\rm d}$) statistically seems to play a more effective role in determining CME kinematic evolution in the outer corona. As we know, CMEs are generally faster during the maximum period of a cycle. Because of the V^2 dependence, $F_{\rm d}$ is generally stronger. In addition, it is well known that the magnetic field is generally stronger during that time. Because of the magnetic field dependence, $F_{\rm p}$ is also generally stronger. Thus, the absolute values of both the negative and positive accelerations are generally larger during that time. However, we do not know why the cycle of the absolute values of semiannual mean accelerations and speeds of both accelerating and decelerating CME events delay the sunspot cycle in time phase.

3 SOLAR-CYCLE VARIATION OF THE SEMIANNUAL NUMBER OF CMES

We also investigate the semiannual number of CMEs with positive and negative acceleration, as shown in Figure 4 and Table 1. We can find that there are more decelerating CME events than accelerating CME events during the maximum period of a cycle (about three years), by a percentage of 31, but there are more accelerating CME events than decelerating CME events during the rest of the time interval of the cycle, by a percentage of 26.

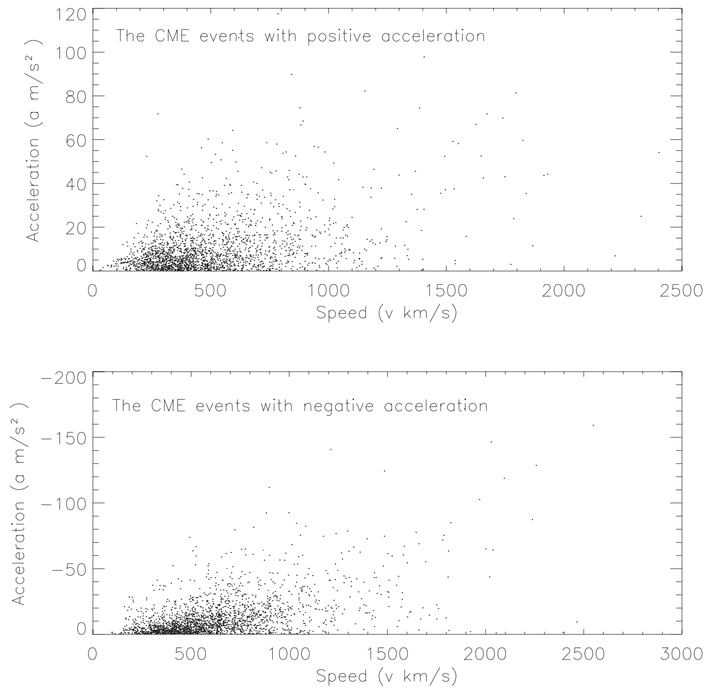

Fig. 3 Scatter diagram of CME acceleration and speed for accelerating and decelerating CME events.

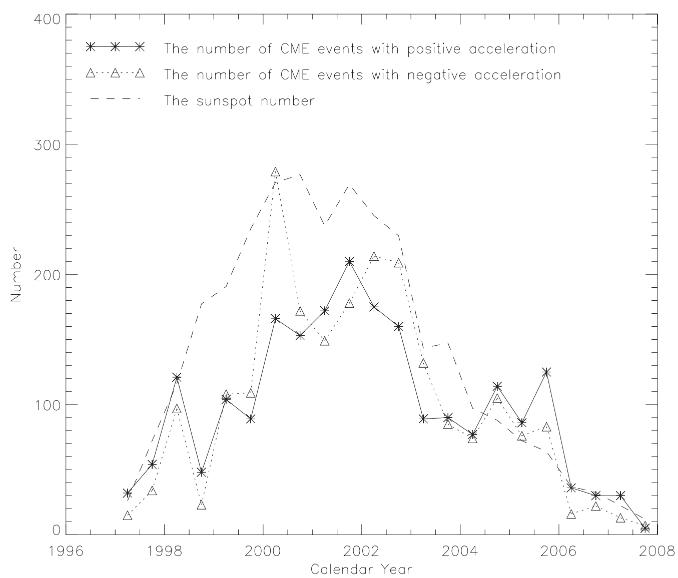

Fig. 4 Semiannual number of SOHO/LASCO accelerating (*solid line*) and decelerating (*dotted line*) CME events from 1997 to 2007. The semiannual sunspot number (*dashed line*) is divided by a factor of 80 to fit the scale.

Table 1 Semiannual Number of CMEs with Positive and Negative Acceleration

Time	Semiannual Number of Accelerating Events	Semiannual Number of Decelerating Events	Probability	Preference
1997 Jan – Jun	32	15	9.31×10^{-3}	Accelerating event
1997 Jul – Dec	54	34	2.11×10^{-2}	Accelerating event
1998 Jan – Jun	121	97	5.95×10^{-2}	-
1998 Jul – Dec	48	23	2.03×10^{-3}	Accelerating event
1999 Jan – Jun	104	108	0.418	-
1999 Jul – Dec	89	109	8.83×10^{-2}	-
2000 Jan – Jun	166	279	4.72×10^{-8}	Decelerating event
2000 Jul – Dec	153	172	0.159	-
2001 Jan – Jun	172	149	0.109	-
2001 Jul – Dec	210	178	5.77×10^{-2}	-
2002 Jan – Jun	175	214	2.69×10^{-2}	Decelerating event
2002 Jul – Dec	160	209	6.17×10^{-3}	Decelerating event
2003 Jan – Jun	89	132	2.30×10^{-3}	Decelerating event
2003 Jun – Dec	90	85	0.381	-
2004 Jan – Jun	77	74	0.435	-
2004 Jul – Dec	114	105	0.294	-
2005 Jan – Jun	86	76	0.239	-
2005 Jul – Dec	125	83	2.17×10^{-3}	Accelerating event
2006 Jan – Jun	36	16	3.89×10^{-3}	Accelerating event
2006 Jul – Dec	30	22	0.165	-
2007 Jan – Jun	30	13	6.85×10^{-3}	Accelerating event
2007 Jul – Dec	5	7	0.387	-

To be sure that solar-cycle variation of the semiannual number of CMEs cannot be obtained purely by chance, we check by calculating the actual probability of obtaining a result. Let us consider a distribution of n objects (CMEs) in two classes. The probability that one CME (one object) is an accelerating or decelerating event (class 1 or 2) by chance is $p = 1/2$. We use the following binomial formula to derive the probability $P(k)$ of getting k objects in class 1 and $n - k$ objects in class 2 (Vizoso & Ballester 1990; Carbonell et al. 1993; Li et al. 1998; Joshi et al. 2006):

$$P(k) = \binom{n}{k} p^k (1-p)^{n-k}. \tag{1}$$

The probability of finding more than d objects in one class is:

$$P(\geq d) = \sum_{k=d}^{n} P(k). \tag{2}$$

In general, when $P(\geq d) > 10\%$, this implies a statistically insignificant result, when $5\% < P(\geq d) < 10\%$, it is marginally significant, and when $P(\geq d) < 5\%$, we have a statistically significant result. The results are given in Table 1. From Table 1, we find a statistically significant result that there are more decelerating CME events than accelerating CME events during the maximum period of a cycle, but there are more accelerating CME events than decelerating CME events during the minimum time interval of a cycle.

As we know, magnetic reconnection plays a major role in determining F_p (Vršnak 1990; Chen 1996). The solar wind speed wanes and waxes during a solar cycle, peaking around the solar minimum (Wang & Sheeley 1990); the CME speed waxes and wanes during a solar cycle, peaking around the solar maximum (Gopalswamy 2004, 2006; Yashiro et al. 2004), and the CME speed varies roughly linearly with the magnetic field in their original active regions (Qiu & Yurchyshyn 2005; Chen et al. 2006). During the maximum period of a cycle, because of the V^2 dependence, F_{d} is generally stronger; because of the magnetic field dependence, F_{p} is also generally stronger. Thus, the absolute values of both the negative and positive accelerations are generally larger during that time. Both F_{d} and F_{p} are generally stronger in fast CMEs than in slow CMEs. However, because of the V^2 dependence, F_d may be more effective during the maximum period of a cycle. Hence, there are more decelerating CME events than accelerating CME events during that time. During the minimum time interval of a cycle, CMEs have relatively small speeds, and F_p may be more effective. So, there are more accelerating CME events than decelerating CME events during that time.

We also show the semiannual sunspot number in Figure 4. We can find that, during 2001 January to June, there is a low point in sunspot number. That is to say, statistically, the magnetic field becomes weaker. The drag of CMEs, F_d, and the propelling force of CMEs, F_p, all become lower. CMEs have relatively small speeds. The F_p force may be more effective during this time. So, around the year 2001, there are more accelerating CME events than decelerating CME events, by a percentage of 17. During the interval 1998 June to 1999 February, when there were large data gaps, there are some low points in the semiannual number of SOHO/LASCO accelerating and decelerating CMEs.

4 CONCLUSIONS AND DISCUSSION

In this paper, we investigate the cyclic evolutionary behavior of CME accelerations for accelerating and decelerating CME events in cycle 23 from 1997 January to 2007 December. It is found that the absolute values of semiannual mean accelerations of both accelerating and decelerating CME events roughly wax and wane in a cycle, delaying the sunspot cycle in time phase. We also investigate the semiannual number of CMEs with positive and negative accelerations and find that there are more decelerating CME events than accelerating CME events during the maximum period of a cycle (about 3 years), but there are more accelerating CME events than decelerating CME events during the rest of the time interval of the cycle.

All CMEs have positive acceleration in the beginning as they lift off from rest. However, within the LASCO C2 and C3 FOV, drag ($F_\mathrm{d} = CA\rho(V_\mathrm{cme} - V_\mathrm{sw})|V_\mathrm{cme} - V_\mathrm{sw}|$) is believed to play a significant role (Vršnak 2001; Chen & Krall 2003; Gallagher et al. 2003; Zhang & Dere 2006). Some conclusions (Gopalswamy et al. 2000, 2001; Yashiro et al. 2004; Gopalswamy 2006) suggested that an interaction between the CMEs and the solar wind was the most important mechanism that determines CME kinematic evolution in the outer corona. That is to say, slower CMEs tend to have large accelerations and faster CMEs tend to have large decelerations. However, our results — for accelerating CME events, slower CMEs tend to have little acceleration and faster CMEs tend to have large acceleration; for decelerating CME events, slower CMEs tend to have little deceleration and faster CMEs tend to have large deceleration, and there is a significant fraction of fast CMEs ($v >$550 km s^{-1}) showing acceleration and a significant fraction of slow CMEs ($v < 350$ km s^{-1}) showing deceleration — seem to suggest that the different driving mechanisms may be acting in accelerating and decelerating CME events: for accelerating CME events, the propelling force (F_p) statistically seems to play a significant role in pushing CMEs outward; for decelerating CME events, the drag (F_d) statistically seems to play a more effective role in determining CME kinematic evolution in the outer corona. During the maximum period of a cycle, because of the V^2 dependence, F_d is generally stronger; because of the magnetic field dependence, F_p is also generally stronger. Thus, the absolute values of both the negative and positive accelerations are generally larger during that time. Because of the V^2 dependence, F_d may be more effective during the maximum period of a cycle. So, there are more decelerating CME events than accelerating CME events during that time. During the minimum time interval of a cycle, CMEs have relatively small speeds, and F_p may be more effective. Hence, there are more accelerating CME events than decelerating CME events during that time.

It must be pointed out that, in this paper, we adopt the plane-of-sky speeds and accelerations when we investigate the cyclic evolutionary behavior of CME accelerations and the semiannual number of CMEs with positive and negative accelerations. Recently, by identifying solar surface source regions of CMEs using X-ray and Hα flare and disappearing filament data, and through considerations of CME trajectories in three-dimensional (3-D) geometry, Howard et al. (2008) devised a methodology to correct for the projection effect and obtained the real CME speeds and accelerations. 1961 CME events can be selected from the time period 1996–2005, or 18.7% of all the 10512 CMEs recorded. They concluded that while using the plane-of-sky measurements may be suitable for studies of general trends in a large sample of events, correcting for projection effects is mandatory for those investigations which rely on a numerically precise determination of the properties of individual CMEs. In our study, we exclude some CMEs because their accelerations are uncertain due to either poor height measurement or a small number of height-time measurements. We also analyze a great many events (4366), which should reduce the uncertainty of plane-of-sky speeds and accelerations. Moreover, in Section 3, we investigate the semiannual number of CMEs with positive and negative acceleration. That is to say, we investigate the sign of CME acceleration. Figure 5(b) of Howard et al. (2008) shows the relationship between deprojected and the sky-plane projected acceleration. It is found that, for almost all of the CMEs, the sign of deprojected acceleration is coincident with that of the sky-plane projected acceleration. So, the results of this paper should show the general solar cycle trends.

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