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CHARACTERISTIC SOLAR WIND DYNAMICS ASSOCIATED WITH GEOSYNCHRONOUS RELATIVISTIC ELECTRON EVENTS

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ABSTRACT

We have investigated characteristic solar wind dynamics associated with relativistic electron events at geosynchronous orbit. Most of the events for April, 1999 through December, 2002 are found to be accompanied by a prolonged solar quiet period which is characterized as low solar wind density, weak interplanetary magnetic field (IMF), and fast alfvenic fluctuations in IMF B_z. In a typical relativistic event, electron fluxes begin to increase by orders of magnitude when solar wind parameters drop to low values (e.g., $n_{sw} \sim 5$ cm^{-3} and $|B_{IMF}| \sim 5$ nT) after sharp peaks. Then the elevated electron fluxes stay at the high level during the solar quiet period. This observation may suggest the following scenario for the occurrence of a geosynchronous relativistic event: (i) Quiet solar winds can yield a stable and more dipole-like magnetospheric configurations in which the geosynchronous orbit locates well inside the trapping boundary of the energetic electrons. (ii) If a large population of MeV electrons are generated (by whatever acceleration process(es)) in the inner magnetosphere, they can be trapped and effectively accumulated to a high intensity. (iii) The high electron flux can persist for a number of days in the geosynchronous region as long as the solar wind dynamics stays quiet. Therefore the scenario indicates that the occurrence of a relativistic event would be a result of a delicate balance between the effects of electron acceleration and loss. In addition, the sensitive dependence of a relativistic event on the solar wind conditions makes the prediction of solar wind variability as important as understanding of electron acceleration processes in the forecast of a relativistic event.

Keywords: solar winds, relativistic electron events, geosynchronous orbit

1. INTRODUCTION

The relativistic electron fluxes in the inner magnetosphere exhibit large fluctuations in both long (~days) and short (~minutes to hours) time scales. Although sudden large increases and decreases of electron fluxes occur irregularly, some pronounced events, such as a long duration high electron flux after sudden enhancements by orders of magnitudes, which is so-called *relativistic electron*

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events, are easily identified. It has been reported that the relativistic electron events are linked to some fatal failures of satellite operations through the known as "deep dielectric charging effect" (Baker et al. 1994, Gussenhoven et al. 1991).

High variability of the electron fluxes are strongly associated with geomagnetic activities. It is well known that the large flux drops during the storm main phase are in part attributed to the Dst effect. In the Dst effect, the electron flux decreases due to the adiabatic response of energetic electrons to the magnetic field weakening for a storm development in a way to conserve all three adiabatic invariants (Kim & Chan 1997, Kim et al. 2002). Despite its simplicity, for some cases the adiabatic loss process can explain a significant portion of the observed decreases. It is also not rare that large increases of relativistic electron intensity are observed during the storm recovery phase. However, the association of the flux increase with the storm activity is not as obvious as for the main phase flux decrease, for the large flux enhancements do occur even when there is no strong magnetic storms. Besides, not all large magnetic storms produce substantial enhancements of energetic electrons. Kim & Lee (2003) have demonstrated that only about 50% of the geosynchronous relativistic events during April, 1999 through December, 2002 occurred in association with a geomagnetic storm of $Dst_{min} \leq -70$ nT. In addition, their statistics showed that roughly 30% of the large geomagnetic storms ($Dst_{min} \leq -100$ nT) do have a relativistic event. Reeves (1998, 2003) has obtained similar results in their analysis of electron flux data for 1998 trough 2002.

Some studies have paid an attention to the relationship between solar wind parameters and relativistic flux changes (e.g., Paulikas & Blake 1979). In particular, Li et al. (2001) have shown that some of the geosynchronous flux changes for energetic electrons can be predicted using the solar wind velocity, its variability, and the north-south component of the interplanetary magnetic field (IMF). Also, O'Brien et al. (2001) have examined a number of solar wind and magnetospheric parameters to determine the parameters that might influence the large increases of relativistic fluxes occurring during geomagnetic storms. They showed that solar wind speed, storm duration, recovery phase Pc 5 power, and recovery phase AE are associated with magnetic storms that produce relativistic electrons at geosynchronous orbit.

The present study examines more rigorously the association of solar wind dynamics with the relativistic electron events especially at geosynchronous orbit. We do not restrict the relativistic events to the ones that occurred during geomagnetic storms. We aim to look for characteristics in solar wind variations which are statistically similar in a large number of events. Analysis of solar wind parameters and MeV electron fluxes shows that the occurrence of a relativistic event is strongly correlated with specific solar wind conditions. Most of our examined events occurred during the intervals of extremely quiet solar wind dynamics (usually more than several days). In the intervals, the solar wind density is low, the interplanetary magnetic field is weak, and the IMF B_z exhibits fast south-north turnings. By providing the stable and less disturbed inner magnetosphere, such prolonged quiet solar winds can help geosynchronous relativistic electrons to be kept in the trapping region. So that the geosynchronous measurements can report the days-long high electron intensities if there takes place a massive generation of MeV electrons by some acceleration processes.

2. DATA PREPARATION

We analyze > 2 MeV electron fluxes measured by GOES-10 satellites for April, 1999 through December, 2002. Five-minute averaged electron fluxes are obtained from the coordinated data analysis web (CDAWeb) whose URL is http://www.cdaweb.gsfc.nasa.gov. Then they are averaged over an hour to make a hourly data set of electron fluxes along with solar wind parameters and Dst index.

To find geosynchronous relativistic electron events, this study adopts the same definition of the relativistic event as that used in Kim & Lee (2003) (denoted as paper I hereafter). In the definition, a daily average flux must be continuously larger than $2 \times 10^3/\text{cm}^2/\text{s}/\text{sr}$ for at least 3 days. The daily average flux is calculated by taking an average over the fluxes measured at local noon and midnight of each day. If the time interval between the two events is less than 2 days, they are counted as one event. With this criteria, we can identify total 34 events – 10 events for 1999, 11 events for 2000, 4 events for 2001, and 9 events for 2002.

As stated in Paper I, the determination of the electron flux base level refers to the approximate flux values at the times of two spacecraft failures in 1998 as introduced in Figure 1(a) of Baker (2000). Such criteria is relatively rigorous compared with other studies in which an event is usually defined by the amount of the flux increase with respect to the pre-enhancement (e.g., O'Brien et al. 2001). The number of relativistic electron events for a given time intervals can vary depending on the definition of the event. Besides, it depends on the satellites utilized in the data analysis. As different satellite would detect slightly larger or smaller fluxes at the same local times depending on their orbital locations, one must adjust the base level of the electron flux in the definition of relativistic electron event in order to get the same number of the events as that obtained by using GOES-10 data.

In order to investigate characteristic solar wind behavior, we collect the hourly solar wind parameters, such as solar wind number density, solar wind speed, and the magnitude of IMF B, measured by the ACE satellite from the CDAWeb. We also obtain the 16-second resolution IMF B_z in GSE coordinate systems from ACE/SWEPAM Level 2 Data website of http://www.srl.caltech.edu/ACE. Using the IMF B_z data, we calculate a number of crossings at $z = 0$ per an hour which can be a proxy of the frequency of IMF B_z oscillations. For brief comparison of the geomagnetic storm association with that of solar wind conditions in relativistic electron flux changes, we analyze 1-hour Dst index provided by Kyoto World Data Center (WDC-C2). Using the prepared hourly data sets of > 2 MeV electron flux, solar wind parameters, and Dst index, we examine the characteristic solar wind variations and geomagnetic activities for the intervals of events and non-events separately.

3. RESULTS

We look for characteristics in solar wind dynamics associated with relativistic events. Figure 1 depicts the hourly evolution of electron flux and some solar wind parameters for two typical examples of a relativistic event. Plots for the two events are overlapped in the figure.

Figure 1(a) shows the drastic changes of electron flux levels for 13 day period. The electron fluxes at local noon for the first two days are at a constant level around $100/\text{cm}^2/\text{s}/\text{sr}$ for both cases. They then drop to near or below $1/\text{cm}^2/\text{s}/\text{sr}$ at $\sim$23 UT on Dec. 2 for the case of Event I and at $\sim$19 UT on Apr. 6 for Event II. The electron fluxes stay low for about one day, which are followed by the large flux enhancements of more than 3 orders of magnitude. In 1 or 2 days after the flux enhancements, the daily average flux becomes $> 2000/\text{cm}^2/\text{s}/\text{sr}$; i.e., the relativistic electron events began on Dec. 5, 1999 for Event I and on Apr. 10, 2000 for Event II. The elevated electron fluxes persist at the high level for a number of days (8 days for Event I and 6 days for Event II) with no large fluctuations except for diurnal variations. Both events then cease with sudden large flux drops to around the pre-enhancement flux levels.

In association with the flux evolution patterns, the solar wind parameters exhibit some characteristic behavior. Changes of the magnitude of IMF B in Figure 1(b) and the solar wind number density in Figure 1(c) resemble to each other. Sharp peaks appear at the time of the electron flux drops (e.g., solar wind density peaks for the end of Apr. 6 to the beginning of Apr. 7). Following the peaks, there exist a long interval of weak interplanetary magnetic field ($\sim$ 5 nT) and small solar wind number density ($\lesssim 5\text{cm}^{-3}$). When compared with the electron fluxes in Figure 1(a), the large

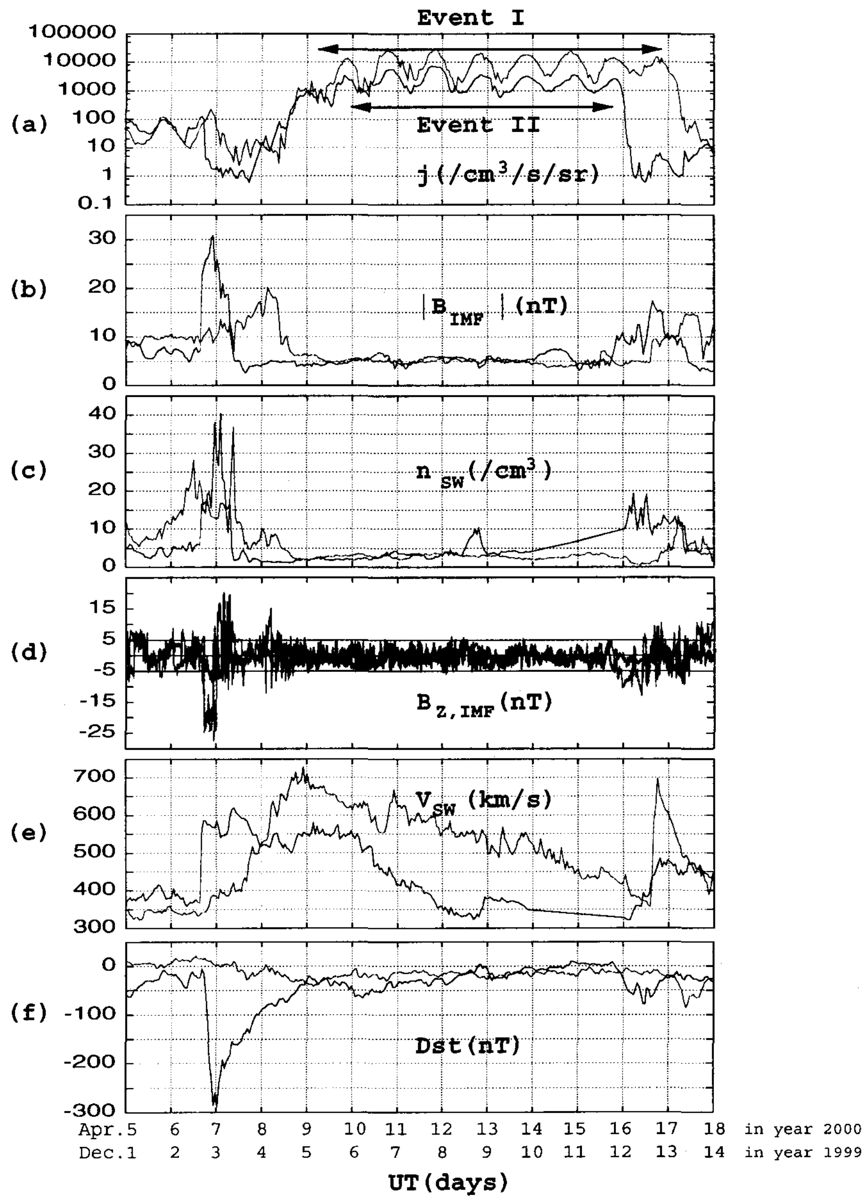

Figure 1. Two examples of relativistic electron events. Hourly variations of electron flux of E>2 MeV in (a), magnitude of interplanetary magnetic field in (b), solar wind number density in (c), 4-minute resolution IMF B_z data in GSE coordinates in (d), solar wind velocity in (e), and Dst index in (f).

electron flux enhancements occur right after the solar quiet interval begins. And the electron fluxes are continuously high until the solar quiet intervals cease. In other words, the quiet solar winds prevail throughout the time period of the substantial flux enhancements and the relativistic events. In fact, one can identify another peak in solar wind density and the magnitude of IMF B around the

Table 1. Average values for event times, for non-event times, and for the entire period.

time	j	$\|B_{\rm IMF}\|$(nT)	$n_{\rm sw}$(cm^{-3})	$v_{\rm sw}$(km/s)	$P_{\rm sw}$(nP)	$\|B_z\|$(nT)	B_z fr.(/hr)	Dst(nT)
events	4733	5.7	4.0	495	1.65	2.3	10.5	−21
n-events	302	7.4	5.8	385	2.10	3.3	7.5	−15
total	913	7.2	5.5	400	2.03	3.1	8.1	−16

end of the events. Here one need to note the odd straight lines (for example, from $\sim$ 00 UT on Apr. 14 to $\sim$ 24 UT on Apr. 15 in Figure 1(c)) are erroneous due to the data gap.

Figure 1(d) plots the IMF B_z changes using 4-minute average data, which present another characteristic solar wind behavior associated with the geosynchronous relativistic events. It is easy to match the large south–north turnings to the IMF B peaks in Figure 1(b). Corresponding to the period of the relativistic electron events, IMF B_z shows fast fluctuations with the small amplitude.

Figure 1(e) shows the solar wind speed. The solar wind speed peaks appear before (for Event II) or around (for Event I) the large electron enhancements, jumping from about 400 km/s to $\sim$600 km/s for Event II and to $\sim$700 km/s for Event I. It then slowly declines from the maximum throughout the event. It is roughly true in our examination that a relativistic event accompanies a solar wind speed bump whose maximum is over 500 km/s.

Figure 1(f) shows the variations of Dst index. While solar wind parameters behave similarly for both events, Dst index shows a big difference especially prior to the events. Event II took place during the recovery phase of a large geomagnetic storm ($\text{Dst}_{\min} = -288$ nT), while Event I is associated with the weak geomagnetic disturbance. Paper I has discussed that only about 30% of the events during the years 1999 to 2002 occurred during the recovery phase of a geomagnetic storm with $\text{Dst}_{\min} < -100$ nT. These results indicate that solar wind conditions may be more relevant to the occurrence of a relativistic event than a magnetic storm activity is.

Not all relativistic events exhibit the same characteristics as the ones described in Figure 1. However, most of our examined events show the qualitatively same behavior in their association with solar wind dynamics. Specifically, the occurrence of a geosynchronous relativistic event is closely correlated with the appearance of a prolonged solar quiet period. Table 1 provides the quantitative comparison among the average electron fluxes and the solar wind parameters for events (2nd row), for non-events (3rd row), and for the entire time period (4th row).

The average electron flux for events is $\sim$4700/cm^2/s/sr, which is more than 15 times larger than the non-event average, and about 5 times larger than the average over the entire period. Considering the time fraction of the events (189 days) and the non events (1182 days), the total average is in a reasonable range. The average $|B_{\rm IMF}|$ for events is smaller than the non-event average by about 75%. Similarly, the event average solar wind density is $\sim$70% of the non-event average. A solar wind speed bump usually appears along with a relativistic event, and it gradually decays during the event. This makes the average solar wind speed for events a bit larger compared with the non-event average. The average speed of $\sim$495 km/s for events is consistent with the results by O'Brien et al. (2001) which found that sustained solar wind velocity in excess of 450 km/s is a strong indicator of the subsequent enhancements of energetic fluxes. Owing to the smaller solar wind density, the average solar wind dynamic pressure for events is roughly 70% weaker than the non-event average.

The 8th column gives the average number of zero crossings in IMF B_z per an hour, calculated using 16-sec resolution data, which is used as a proxy of the frequency of the B_z fluctuations. The average frequency for events is 1.5 times the non-event average. As demonstrated in Figure 1(d), the rapid fluctuations of IMF B_z with the small amplitude (the average $|B_z| \sim 2.3$ nT in the 7th

Table 2. Comparison among the average values for storm-time events and for non-storm-time events.

time	j	$n_{sw}(cm^{-3})$	v_{sw}(km/s)	P_{sw}(nP)	$\|B_{IMF}\|$(nT)	Dst(nT)
with storm	4723	4.1	489	1.70	5.9	−25
w/o storm	4756	3.8	509	1.53	5.5	−11

column) is one of the features for the quiet solar wind dynamics. The south-north turnings in IMF B_z faster than the time scale of the loading-unloading process will not effectively drive substorm activities in the inner magnetosphere. Therefore together with the low solar wind dynamic pressure, the fast fluctuations of IMF B_z with the small amplitude would contribute to the formation of the stable and more dipole-like magnetospheric configurations during the relativistic events.

In Figure 1(e) we see that not all relativistic events occurred during a large magnetic storm. Table 2 presents that the average solar wind features are similar among the events which are and which are not associated with a geomagnetic storm ($Dst_{min} \leq -50$ nT). The difference in the average electron flux and the solar wind parameters for the events with and without storms are within only several percent. Again, this result demonstrates that the occurrence of a geosynchronous relativistic event is more strongly correlated with specific solar wind conditions than with storm activity levels.

Although most of our examined events occurred during the intervals of quiet solar wind variations, such intervals do not always accompany a relativistic event. Figure 2 provides an example of that case. There can be found two intervals of relatively quiet solar winds: 10 UT on Sep. 23 ~ 10 UT on Sep. 26 for Interval 1 and 18 UT on Sep. 27 ~ 00 UT on Oct. 3 for Interval 2. The solar wind changes for both intervals are similar to each other. The quiet intervals are preceded by the large peaks in the solar wind number density, in the interplanetary magnetic field, and in the solar wind speed. On the other hand, the electron fluxes do not evolve in the same manner for Intervals 1 and 2. At about 01 UT on Sep. 22 the electron flux drops almost to the back ground level and never recovers during the solar quiet period (Interval 1), except for the temporal large pre-noon flux on Sep. 22 which disappears next day. On the contrary, for Interval 2 we can clearly see the large flux enhancements and the long duration of the high electron intensity. It is indeed an intriguing question why we observe an event only in Interval 2 under the similar solar wind conditions. Seeking for the explanation remains as our future work. At least we can learn from this study that the prolonged quiet solar wind dynamics are necessary but not sufficient for the occurrence of a geosynchronous relativistic event.

4. DISCUSSION

We have investigated characteristic variations of solar wind parameters in association with geosynchronous relativistic events. Most of the examined events occurred during the intervals of extremely quiet solar winds which are usually preceded by large peaks in the solar wind density and the interplanetary magnetic field. In the intervals, the solar wind density is $\sim 5cm^{-3}$, the magnitude of the interplanetary magnetic field is $\sim$ 5 nT and the solar wind velocity is in a declining phase from its peak. IMF B_z shows the fast fluctuations with the small amplitude with respect to $z = 0$. So the extremely quiet solar wind means no strong solar wind dynamic pressure and no significant southward turnings of IMF B_z.

The quiet solar wind dynamics can lead to relatively undisturbed inner magnetosphere. Then in the stable and more dipole-like magnetospheric configurations, the outer radiation belt may extend well outside the geosynchronous orbit so that the geosynchronous satellites can measure stably-

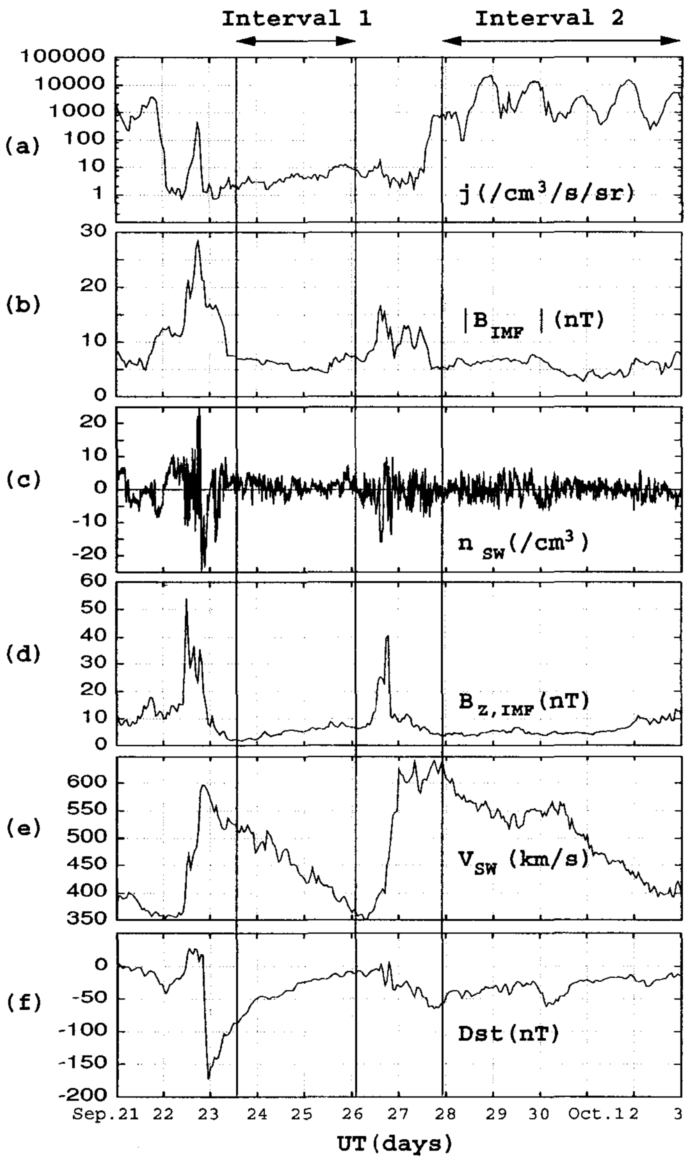

Figure 2. An example of no relativistic electron event for a solar quiet interval. Solid lines denote the approximate time of the beginning and the end of the two intervals. (a) electron flux (b) magnitude of IMF B (c) IMF B_z (d) solar wind density (e) solar wind speed (f) hourly Dst index.

trapped particles. So if there is a large generation of MeV electrons under this quiet solar wind conditions, they can be trapped and effectively accumulated to a high level. And the high flux intensity will persist for several days as long as the solar wind dynamics keeps quiet. According to this scenario, the occurrence of an event is not only a matter of electron accelerations, but also a matter of loss in the geosynchronous region. In other words, even though there takes place a massive generation of the energetic electrons, we can not observe a relativistic event unless the generated electrons are trapped for a long time period experiencing no significant loss. Therefore the occurrence of a relativistic event would be a result of a delicate balance between the effects of electron acceleration and loss.

As the geosynchronous orbit is close to the trapping boundary of MeV electrons, the relativistic fluxes in the geosynchronous region is more sensitive to the solar wind conditions. Depending on solar wind conditions, it may be possible that the relativistic events occur at lower L values (e.g., $L \sim 5$) while the geosynchronous electron fluxes are still low. If some satellite data exhibit such observations, it could be an evidence for the close association of quiet solar winds with the geosynchronous relativistic events as discussed in this paper.

In no doubt, the most important question in the studies of the relativistic electron events is how the relativistic electrons can be accelerated. The results of our study are in a line with the recent work by a team of space scientists. The team from Boston University and the National Oceanic and Atmospheric Administration (NOAA) proposed that relativistic electrons may be accelerated by magnetic waves driven by the solar wind. When the solar wind density is high and comes up against the Earth's magnetosphere, it compresses the magnetosphere. When the solar wind density is low, the magnetosphere expands. Kepko & Spence (2003) have discovered that the solar wind contains periodic structures of high and low density, generating global magnetic waves. It is well known that if the frequency of these waves matches the frequency of the electrons in their motion in the outer radiation belt, the electrons can be accelerated to a significantly high energy. Despite that the detailed calculations remain to be done, the proposed mechanism can explain the high correlation between the solar wind conditions and the occurrence of relativistic electron events.

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