Proton belt variations traced back to Fengyun-1C satellite observations

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Key Points:
- Variations of proton during the 6 April 2000 storm were analyzed using Fengyun-1C satellite measurements
- Proton trapping and loss were affected by the disturbance differently depending on the energy and L location
- Several mechanisms, rather than a single mechanism, might explain the variations during the disturbance

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Abstract: We used historical data to trace trapped protons observed by the Fengyun-1C (FY-1C) satellite at low Earth orbits (~800 km) and chose data at 5–10 MeV, 10–40 MeV, 40–100 MeV, and ~100–300 MeV from 25 March to 18 April 2000 to analyze the proton variations. Only one isolated strong storm was associated with a solar proton event during this period, and there was no influence from previous proton variations. Complex dynamic phenomena of proton trapping and loss were affected by this disturbance differently depending on the energy and L location. The flux of 5–10 MeV protons increased and created new trapping with a maximum at L ~2.0, and the peak flux was significantly higher than that at the center of the South Atlantic Anomaly. However, at higher L, the flux showed obvious loss, with retreat of the outer boundary from L ~2.7 to L ~2.5. The increase in the 10–40 MeV proton flux was similar to that of the 5–10 MeV flux; however, the peak flux intensity was lower than that at the center of the South Atlantic Anomaly. The loss of the 10–40 MeV proton flux was closer to the Earth side, and the outer boundary was reduced from L ~2.3 to L ~2.25. For the higher energy protons of 40–100 MeV and 100–300 MeV, no new trapping was found. Loss of the 40–100 MeV protons was observed, and the outer boundary shifted from L ~2.0 to L ~1.9. Loss was not obvious for the 100–400 MeV protons, which were distributed within L <1.8. New proton trapping was more likely to be created at lower energy in the region of solar proton injection by the strong magnetic storm, whereas loss occurred in a wide energy range and reduced the outer boundary on the Earth side. Similar dynamic changes were observed by the NOAA-15 satellite in the same period, but the FY-1C satellite observed more complex changes in lower energy protons. These results revealed that the dynamic behavior of protons with different L-shells was due to differences in the pitch angle. Possible mechanisms related to new trapping and loss are also discussed. These mechanisms are very important for understanding the behavior of the proton belt in the coming solar cycle.

Keywords: high-energy proton; trapping; loss; disturbance; inner radiation belt

1. Introduction

Normally, radiation belt protons have their origin in the cosmic ray albedo neutron decay phenomenon, known as CRAND, and are regarded as fairly stable in the inner zone radiation belt (Albert et al., 1998). However, disturbances produced by the Sun that interfere with the Earth can sometimes drive spatial and temporal variations in the proton radiation belt. Most variations are associated with two important factors: magnetic storms and solar energetic particles (Lorentzen et al., 2002; Selesnick et al., 2007, 2010, 2014). The high-energy protons ejected from solar energetic particles are always regarded as the main source of the new proton population. They can be transported deep into the magnetosphere during periods of magnetic activity and captured to create a new proton belt. At the same time, part of the inner belt particles near the outer boundary will be lost during storms.

Proton variations include the creation of new trapping and loss near the outer boundary. The CRRES (Combined Release and Radiation Effects) satellite observed significant trapping, which was unique and created a new proton belt with a very high energy of
35 MeV at \( L < 2.5 \) (Pavlov et al., 1993). Several new trapping variations with lower energy (~10 MeV) at a wide range of \( L = 2–3.5 \) were observed in the 23rd solar cycle (Gussenhoven et al., 1994; Hudson et al., 1998; Lorentzen et al., 2002). In the 24th solar cycle, there have been very few reports of new trapping, which was mentioned only after the 7 March 2012 solar proton event observed by the RBSP (Radiation Belt Storm Probes) satellite (Selesnick et al., 2016). Obvious proton loss was observed from October to November 2003, and protons of 19–29 MeV and 86–120 MeV all disappeared beyond \( L = 2 \), based on observations of the SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer) satellite (Looper et al., 2005). Other proton losses effected by large geomagnetic storms were reported from the HEO-3 (Highly Elliptical Orbit-3) satellite and National Oceanic and Atmospheric Administration (NOAA) satellites (Selesnick et al., 2010; Zou H et al., 2011). Lorentzen et al. (2002) found that proton variations in different orbits sometimes did not correspond to each other and that variations were more likely to be observed at low Earth orbits. Variations related to new trapping or loss of protons have been rare for this solar cycle since 2009 because of the absence of large magnetic storms and the injection of solar energetic particles. Although the variations in the inner radiation belt have gained some attention, we still do not fully understand how complex variations in the proton flux occur at different energies in different \( L \)-shells during a disturbance.

At the altitude of a low Earth orbit, satellites can pass through the South Atlantic Anomaly (SAA), which allows observation of the inner proton belt. The Fengyun-1C (FY-1C) satellite was in a polar orbit with an altitude of \( \sim 800 \) km and an inclination of 98°. The Space Particle Composition Monitor (SPCM) instrument onboard the satellite collected data on the radiation belt during most of the 23rd solar cycle and recorded several significant typical changes in the SAA caused by extreme events. Such extreme events rarely happened during the 24th solar cycle, which just ended recently. Our aim was to reveal the complex proton variations in energy and location during periods of activity and provide reference on proton variations for the incoming solar cycle.

We used historical data to trace trapped protons observed by the FY-1C satellite. We then analyzed the proton data in four channels from 5 to 300 MeV from 25 March to 18 April 2000. Only one isolated strong storm was associated with a solar proton event during this period, and no obvious variations occurred within at least 2 months before this period. Therefore, these data show clearer variations in response to the disturbance. The contents are organized as follows. In Section 2, we describe the basic properties of the FY-1C satellites, the SPCM instrument, and the proton data selected. Detailed features of the proton variations and a comparison of results with the NOAA-15 observations in the same period are given in Section 3. Finally, two potential mechanisms are presented to explain the variations and our conclusions are discussed in Section 4.

2. Instrument and Data
The FY-1 satellites were launched into a Sun-synchronous orbit at an altitude of 830 km with an inclination of 98°. The SPCM was flown on the FY-1 satellites beginning in 1999; it was on board the FY-1C from 1999 to 2007 and on board the FY-1D from 2002 to 2009.

The SPCM consisted of a 15-μm light-blocking layer, the collimator, and a three-element semiconductor telescope. These semiconductor units utilized a 100-μm-thick gold silicon surface barrier detector for the front piece and two 3,500-μm-thick lithium silic-on drift detectors. The SPCM had a field of view of 60°. It was able to measure protons on five energy channels (3–300 MeV), heavy ions on six energy channels (12–2,800 MeV), and electrons on one channel (> 1.6 MeV).

The method used to identify the energy of each proton channel can be described as follows:

\[
\{ \text{D}_1 + \text{D}_2 \} \text{ deposition energy}_1 \cdot \{ \text{D}_1 + \text{D}_2 \} \text{ deposition energy}_2 \cdot \text{D}_3 \text{ deposition energy}_3 \text{ (or D}_1 \},
\]

where \( D_1, D_2, D_3 \) represent the three detectors, respectively. The proton channel was identified by setting the threshold of deposition energy at \(( D_1 + D_2 \)). Deposition energy, and deposition energy, in \(( D_1 + D_2 \)) determined the lower limit and upper limit of each proton channel. The coincidence and anti-coincidence from the outputs of the third detector distinguished between high- and low-energy protons with the same deposition energy in \(( D_1 + D_2 \)). Electronic processing of the signal from the solid-state detector required particle deposits of at least 2.5 MeV in the front two detectors \(( D_1 + D_2 \)) to be counted as an event. It was almost impossible to deposit electrons larger than 2.5 MeV in \(( D_1 + D_2 \)). Thus, contamination by electrons was likely small and could be ignored.

Laboratory calibration was completed for the energy channels, counting scales, and response time resolution. The geometric factor was 0.255 cm²·sr⁻¹. The SPCM mainly measured the trapped energetic particle fluxes with pitch angles of 60°–120° because the instrument was mounted perpendicular to the orbital plane of the satellite. The SPCM detector data were accumulated over 8-s intervals and collected on a 1°(latitude) × 2°(longitude) grid. Articles related to the FY-1 SPCM can also be found in Wang SJ et al. (2001).

Geomagnetic indices and solar wind parameters with a time resolution of 1 min, solar proton event data from GOES-10 (Geostationary Operational Environmental Satellite-10) with a time resolution of 1 min, solar proton event data from GOES-10 (Geostationary Operational Environmental Satellite-10) with a time resolution of 1 min, and proton data from NOAA-15 were used for this study and were obtained from the Coordinated Data Analysis Website (http://cdaweb.gsfc.nasa.gov/).

3. Features of the Variations
In this section, we provide an overview of typical proton variations observed from 25 March to 18 April 2000. In Figure 1, environmental parameters varying with time showed an obvious disturbance on 06 April 2000. Upstream solar wind data from the ACE (Advanced Composition Explorer) satellite showed an obvious jump in the solar wind speed from ~360 km/s to ~570 km/s and an accompanying large solar wind density enhancement, which induced a significant solar wind dynamic pressure up to
~22 nPa. Subsequently, the influence of the solar wind on the Earth’s magnetosphere led to the development of a magnetic storm, with the disturbance storm time index (Dst) minimum reaching approximately –280 nT later on 06 April 2000. During the disturbance period, the flux of the solar energetic particle source was observed by GOES-10, but with a lower flux intensity and a very soft spectrum, being short of protons > 30 MeV.

The dependence of typical proton variations on the geographic coordinates and on the L-shells at various energies is shown below. L-shells were calculated by using the IGRF-2005 (International Geomagnetic Reference Field-2005) model. Only a few tracks of data were available per day owing to limited satellites resources, and it would have taken nearly 10 days to determine the global distribution. Taking this into account, we averaged the data from 10 days before and after the disturbance at every interval of 0.05 L between 1 < L < 5, which encompassed the entire inner belt.

### 3.1 Proton Flux Variations at Geographic Coordinates

#### 3.1.1 Observations of the FY-1C

Figure 2 displays proton fluxes in the energy range from 5 to 300 MeV during the time periods from 25 March to 05 April 2000 and 08 March to 18 April 2000 immediately before and after the disturbances described above. The regions of proton registration near L ~1.8, 2.0, and 3.0 are marked on the image. We observed that protons from the inner belt were detectable mainly in the SAA at these altitudes. The higher the energy, the lower the flux and the smaller the area covered.

Before the disturbance, all proton channels showed one central peak (referred to here as the center of the SAA). However, after the disturbance, the spatial extent of this region was very different among all the proton channels. In the lower energy proton channels, the flux level was elevated within the southeast region of the SAA corresponding to L > 1.8. The flux of 5–10 MeV protons increased significantly. The enhanced flux intensity was even greater than that at the center of the SAA and formed obvious new trapping. Satellites that traverse the region should take extra precautions to operate safely and avoid contamination. The flux of 10–40 MeV protons showed a relatively small increase and less than the flux at the center of the SAA. No flux increased at the higher energies of 40–100 MeV and 100–300 MeV.

In addition to the flux enhancement affected by the disturbance, the proton channels at 5–10 MeV, 10–40 MeV, and 40–100 MeV showed a flux decrease at the southeast edge of the SAA corresponding to L ~2–3, which indicated that losses were still occurring during this period. These losses were clearer at the higher energies of 10–40 MeV and 40–100 MeV. No obvious loss of protons occurred at 100–300 MeV, located below L ~2.

#### 3.1.2 Comparison of observations with the NOAA-15

The NOAA-15 is one of the satellites in the POES (Polar Operational Environmental Satellite) series, having an orbital altitude and inclination similar to that of the FY-1C. The SEM2 (Space Environment Monitor) was mounted on the NOAA-15 to monitor high-energy particles. The SEM2 consisted of one total energy detector (TED) and two medium-energy proton and electron detectors.
Figure 2. Geographic coordinates of proton flux variations in the energy range from 5 to 300 MeV during the time periods from 25 March to 05 April 2000 and 08 March to 18 April 2000 immediately before and after the disturbances on 06 April 2000. The $L$ regions of proton registration near $L \sim 1.8, 2.0,$ and $3.0$ are marked.

(MEPED-90 and MEPED-0). The field of view of the MEPED-90 telescope and MEPED-0 telescope was $\pm 15^\circ$, whereas that of the TED was $\pm 60^\circ$. The field of view of the MEPED-0 was outward along the local zenith, parallel to the Earth center-to-satellite radial vector. The MEPED-90 was mounted approximately perpendicular to the MEPED-0, and the TED was mounted parallel to the MEPED-0 (Rodger et al., 2010). This meant the detectors observed protons from different pitch angles, which influenced the intensity and spatial distribution.

Figure 3 shows proton fluxes at 2.5–6.9 MeV from the MEPED-90 and MEPED-0 during the same time periods described in Figure 1. Before the disturbance, the protons were mainly in the SAA, corresponding to $L < 1.8$, whereas protons at 5–10 MeV observed by FY-1C showed a wider $L$ range, up to $L \sim 3$. (Here we ignored the difference in energy). Variations in new proton trapping similar to the FY-1C observations were observed at 2.5–6.9 MeV by the MEPED-0. Figure 4 shows proton fluxes of $> 16$ MeV and $> 36$ MeV from the TED. Note that variations in proton decreases at lower energies were observed by FY-1C only because of its wider $L$ range distribution. The pitch angle distribution of particles observed by FY-1C was concentrated in the vicinity of 90° along the satellite orbit, whereas a wider range in the pitch angle distribution of particles was observed by NOAA-15, from 10°–170°. In the range of $L \sim 2–3$, the pitch angle observed by the MEPED-0 was approximately 150°, and the pitch angle observed by the MEPED-90 was approximately 50° (Wang CQ et al., 2013). Protons at a low altitude were anisotropic. The proton intensity around 90° was the highest (Kuznetsov et al., 2012). Therefore, the difference in pitch angle is suggested to play a leading role in the differences in proton flux distribution among the FY-1C, MEPED-0, and MEPED-90 observations. In addition, the dynamic variations in the FY-1C observations were more significant than those by the NOAA-15.

3.2 Proton Flux Variations on $L$-shells
Proton fluxes depending on the $L$-parameter were found to cor-
The new peak intensity of 5–10 MeV protons greatly exceeded the peak flux in the center of the SAA. The increase in the proton flux distributions are shown in Figure 3.

The figure clearly shows the profile variations. Before the disturbance, all the channels showed one peak structure corresponding to the center of the SAA. The proton flux distributions are shown with the boundary at $L \sim 2.7$ for 5–10 MeV, at $L \sim 2.3$ for 10–40 MeV, at $L \sim 2.0$ for 40–100 MeV, and at $L \sim 1.8$ for 100–300 MeV. We defined the boundaries where the average flux decreased to $1 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. After the disturbance, an increase in the proton intensity was clearly visible for 5–10 MeV and 10–40 MeV around $L \sim 1.8$, and a new peak structure formed with a peak intensity around $L \sim 2$. The new peak intensity of 5–10 MeV protons greatly exceeded the peak flux in the center of the SAA. The increase in the $L$ range for 5–10 MeV was limited, from $L \sim 1.8$ to $\sim 2.3$.

We could clearly see the proton flux dropout and that the outer boundary shrank. The 5–10 MeV protons decreased from around $L \sim 2.3$ to $L \sim 2.25$, and for the 40–100 MeV protons, the boundary shifted from $L \sim 2$ to $L \sim 1.9$. No obvious dropout was seen for 100–300 MeV protons, with the distribution boundary at $L \sim 1.8$. Note that the flux dropout occurred even lower at $L \sim 1.9$, for the flux distribution profile of 40–100 MeV protons after the disturbance, in contrast to the obvious increase for lower energy protons at 5–10 MeV and 10–40 MeV around $L \sim 2$. We suggest the increase in protons was greater than the decrease.

Figure 3. Geographic coordinates of proton flux variations at 2.5–6.9 MeV during the time periods from 25 March to 05 April 2000 and 08 March to 18 April 2000 immediately before and after the disturbances on 06 April 2000. (Left) For the MEPED-0 on board NOAA-15, the field of view was outward along the local zenith. (Right) For the MEPED-90 on board NOAA-15, the field of view was approximately perpendicular to that of the MEPED-0.

Figure 4. Geographic coordinates of proton flux variations at $> 16$ MeV (left) and $> 36$ MeV (right) during the time periods from 25 March to 05 April 2000 and 08 March to 18 April 2000 immediately before and after the disturbances on 06 April 2000.
4. Discussion and Conclusions

In the given event, we found that inner belt protons showed more complicated variations. Significant changes in proton intensity were apparent across a wide range of energy. We classified the variations by trapping and loss during the disturbance.

On the basis of the FY-1C measurements, we found that increases obviously occurred for lower energy protons at 5–10 MeV and 10–40 MeV, which formed trapping, with a new peak flux located at \( L \approx 2 \). We also found a similar proton variation when using measurements at 2.5–6.9 MeV from the MEPED-90 on NOAA-15. Dropouts occurred at a wide \( L \) range, even as low as \( L \approx 2 \), and they significantly changed the proton distribution at the outer boundary except for 100–300 MeV protons. Note that complex physical processes might be involved in these variations.

We propose two mechanisms to explain the trapping events. For both mechanisms, solar energy particles are considered an important source of trapping, and both emphasize the important contribution of a magnetic storm to the proton injection depth. One mechanism is storm sudden commencement injection (SC-injection), by which particles might be resonantly accelerated and injected inward by the electric field (E-field) pulse induced by impulsive compression of the magnetosphere during the sudden commencement of a geomagnetic storm. In SC-injection, trapping appears at the beginning of the storm, with trapped proton energy not less than 15 MeV (Blake et al., 1992; Li XL et al., 1993; Pavlov et al., 1993). This mechanism has been effective in explaining the trapping that occurred in a 1991 event. The other mechanism is direct-trapping, by which the solar protons penetrate directly deep into the inner magnetosphere during the main phase and trapping appears when the penetration boundary retreats at the storm recovery phase. During recovery of the magnetic field at the magnetic storm recovery phase, protons will find themselves at closed shells if the recovery time is less than the magnetic drift period. The typical time of magnetosphere reconstruction is equal to several minutes (Lazutin et al., 2007). The particle magnetic drift period can be expressed as \( T = 44/LE \), where \( T \) is in minutes and \( E \) is the particle energy in MeV. For 2 MeV protons, \( T \) is about 11 min at \( L \approx 2 \), and for 50 MeV protons, \( T \) is about 20 s at \( L = 2 \). This means the lower energy protons may remain at closed drift shells before they are able to leave the magnetosphere because of the rapid recovery of the magnetosphere configuration. In contrast, high-energy protons will trace the retreat of the proton belt boundary owing to recovery of the magnetosphere configuration (Lazutin et al., 2007).

Radial profiles of 2.5–6.9 MeV proton data from NOAA-15 are shown in Figure 6. One profile was registered before the storm on 05 April 2000, when solar protons occupied the region down to \( L \approx 3.5–4 \). The penetration of solar protons approached \( L \approx 2–3 \) during the main phase of the storm on 06 April 2000. In the recovery phase of the storm, a new maximum at \( L \approx 2 \) was created, which was significant stronger than that at the center of the SAA. At the same time, the solar protons retreated to \( L \approx 3.5–4 \). The appearance of the new maximum still remained on 08 April 2000. It is clear from the radial profile described above that during the main phase of the storm, the protons penetrated lower, to \( L \approx 2–2.5 \), because the cutoff was suppressed the most during the main phase of the storm when the Dst reached a minimum.

New trapping was created and accelerated in the recovery phase of the magnetic storm, rather than by SC-injection. The strong flux of new trapping was not only from the direct injection of solar protons, but also from other acceleration mechanisms, such as waves.
Losses were considered because distortion of the magnetic field can lead to the destruction of adiabatic motion (Hudson et al., 1997; Selesnick et al., 2010; Zou H et al., 2011). An increase in the curvature of the magnetic field lines, which induces destruction of the first adiabatic invariant, can explain the loss at $L > 2$ for protons at $> 36$ MeV (Zou H et al., 2011). During this disturbance, losses occurred not only at higher energies, but also at 5–10 MeV. Moreover, losses occurred lower, below $L \sim 2$. The distortion of the magnetic field cannot effectively explain these losses, which may be related to the third adiabatic invariant (Selesnick et al., 2010). During a large magnetic storm, the bending and diffusion of the magnetic field lines will cause the position of the geomagnetic cutoff to expand inward. At the same time, a decrease in the magnetic field at the magnetic equator will result in a decrease in the magnetic flux in the trapping shell. To ensure the conservation of the third adiabatic invariant, the trapped protons will move outward to a weaker region of the magnetic field. In the large $L$ region, protons with certain energy are more likely to be lost because of bending and diffusion of the magnetic field lines. Therefore, the outward motion-related conservation of the third adiabatic invariant will lead to additional loss of the trapped protons and to loss in a larger range. The decrease in intensity of the magnetic field is greater in a large $L$ range, which corresponds to the capture region of lower energy protons.

In this article, we showed the complex proton variations as depending on energy and $L$ location. We can conclude that during the disturbance, new proton trapping was more likely to be created at a lower energy in the region of solar proton injection associated with the strong magnetic storm, whereas proton loss occurred in a wide energy range and induced the outer boundary to shift closer to the Earth side, which depended on the $L$ value of the distribution. Several mechanisms, rather than a single mechanism, might better explain the variations during a disturbance. A detailed discussion of such mechanisms will require further in-depth study in the future.

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