Space Weather Service for Chinese Space Science Satellites

LIU Siqing[1,2], ZHONG Qiuzhen[1,2], GONG Jiancun[1], SHI Liqin[1,2], CHEN Dong[1], MIAO Juan[1], CAI Yanxia[1], BAI Meng[1], MA Wenzhen[1], LI Zhitao[1], LIU Fanghua[1], CHEN Yanhong[1]

1 (National Space Science Center, Chinese Academy of Sciences, Beijing 100190)
2 (University of Chinese Academy of Sciences, Beijing 100049)

E-mail: liusq@nssc.ac.cn

Abstract

Strategic Priority Research Program on Space Science has gained remarkable achievements. Space Environment Prediction Center (SEPC) affiliated with the National Space Science Center (NSSC) has been providing space weather services and helps secure space missions. Presently, SEPC is capable to offer a variety of space weather services covering many phases of space science missions including planning, design, launch, and orbital operation. The service packages consist of space weather forecasts, warnings, and effect analysis that can be utilized to avoid potential space weather hazard or reduce the damage caused by space storms, space radiation exposure for example. Extensive solar storms that occurred over Chinese Ghost Festival (CGF) in September, 2017 led to a large enhancement of the solar energetic particle flux at 1AU, which effected the near earth radiation environment and brought great threat to orbiting satellites. Based on the space weather service by SEPC, satellite ground support groups collaborating with the space Tracking, Telemetering and Command system (TTC) team were able to take immediate measures to react to the CGF solar storm event.

Key words

Space weather forecast, Space weather service, Space science satellites, Space radiation environment, Solar storm

1. Space Weather Service History in China

The Chinese space weather service has a long history stretching back to 1960s when National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS) provided space radiation environment forecast for China’s first artificial satellite Dongfanghong-1 (DFH-1. see Figure 1). The forecasters were called red forecaster by Qian Xuesen. In early 1970’s, NSSC compiled and published *The Artificial Satellite Environment Manual* for satellite design.

SEPC was formally established in 1992 in order to better support the China space exploration programs, especially the China Manned Spaceflight. The main frame of the forecasting team and operational system formed six years later, and SEPC started to issue space environment prediction every day via internet since 1998.

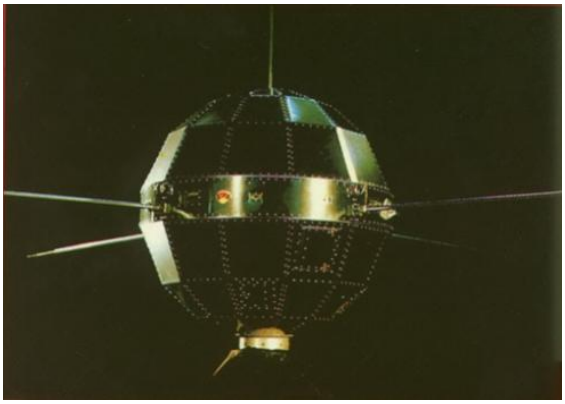

Fig.1 DFH-1 satellite, China’s first artificial satellite (Image by NSSC)

China’s manned spaceflight program has been very successful during the past two decades and is in rapid development. Eleven spacecraft, one cargo vehicle Tianzhou, and two experimental space stations were launched into space. From 1998 SEPC has provided space weather services for every step of the Chinese manned space missions as a portion complimenting the space application system (see Figure 2).

2. Space Weather Service Requirements by Chinese Space Science Missions

Strategic Priority Research Program on space science has implemented the following missions: Hard X-ray Modulation Telescope, Quantum Experiments at Space Scale, Dark Matter Particle Explorer, and Shijian-10[1]. These four space science satellites were launched in succession from 2015 to 2017.

The solar activities during Solar Cycle 24 have been at the lowest level in the space era as measured by the SunSpot Number(SSN). The occurrence of solar proton events is also very small compared to solar cycle 23[2]. Cycle 24 presents double-peaked characteristics, in March 2012 and April 2014 for example (Figure 3). Since the solar activities were in the declining phase from 2015 to 2017, the missions mentioned above were during an appropriate period to carry out space experiments.

However, orbiting satellites inevitably encounter radiation hazard in space. Each of the four space science satellites has a orbital height of about several hundred kilometers. The trajectory goes through the South Atlantic Anomaly (SAA) periodically, exposing the satellite to strong radiation. The South Atlantic Anomaly, a lower extension of the Van Allen radiation belts, lies above South America and the South Atlantic Ocean. To avoid the radiation risk the satellites and payloads designers need the total energetic particles flux of mission lifetime. For the satellites operators it is necessary to know when the satellites will pass through the SAA regions.

Fig. 2 Space weather forecast hall of SEPC

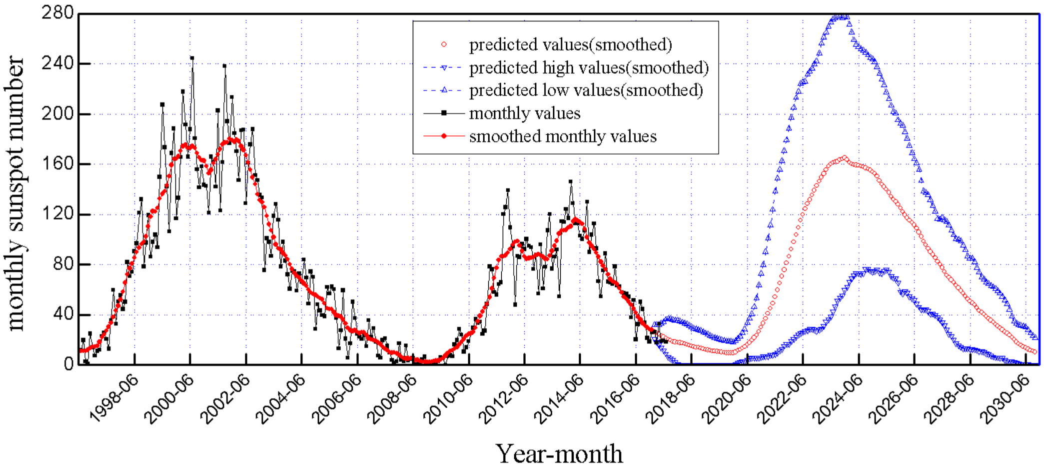

Fig. 3 Sunspot number of solar cycle 23, 24 and sunspot number prediction of the descending phase of solar cycle 24 and cycle 25

Besides the SAA region, solar proton events may increase the orbital radiation hazard during the solar storm. Shea and Smart[3] found that one third of the solar proton events occur during a two-to-three year period after sunspot maximum. In the declining phase of the solar cycle 23, Sun unleashed a series of large eruption, such as those events in October 2003, January 2005, September 2005, and December 2006. Thus, in the lifetime of space science satellites, solar proton events remain a high possibility threat. In general, most of the solar protons are guided by the Earth's magnetic field into the polar regions where the majority of the Earth's magnetic field lines enter and exit. These protons may affect both Quantum Experiments at Space Scale and Dark Matter Particle Explore satellites in polar orbits. The latitude that solar protons may reach depends on the cutoff latitude, which decreases when the Earth's geomagnetic field is strongly disturbed. Highly energetic solar proton may reach mid-to-low latitude[4]. Therefore, in evaluating the radiation level that Hard X-ray Modulation Telescope and Shijian-10 satellites may experience we should take into consideration the effect caused by solar proton events.

Space radiation may have serious effects on satellites and payloads. In the design stage, it is important to understand the space radiation environment so that reliable satellites can be designed at a reasonable cost. Some particles are so energetic that it can penetrate into the interior of a satellite and interact with its electronic circuit. Radiation effects in the interior of satellites are often grouped into three categories: total ionizing dose, displacement damage and single event effects. These effects may yield a consequence that ranges from unimportant ones to the shutdown of a vital system. To guarantee the safety of the space science missions, SEPC provides space radiation environment analysis and possible countermeasure. To reduce the radiation risk due to solar proton events SEPC monitors the space weather 24 hours per day, and provides daily space weather forecasts.

3. Space Weather Service for Space Science

The phases of space science mission development that must take into account space environment effects include planning, design, launch, operations, and anomaly resolutions. SEPC has provided a variety of space weather service for all the four space science missions.

During the mission planning phase, SEPC had participated in the assessment of scientific tasks, providing space environment analysis for designing orbit. The analysis assembled radiation environment specifications, plasma environment specifications, neutral atmospheric environment specifications, and debris meteoroid environment specifications. Moreover, SEPC had bundled into spatial environmental effect analysis the Total Ionizing Dose (TID), non-ionizing Displacement Damage Dose (DDD), Single Event Effects (SEE), and the orbital decay rate. Table 1 shows the analysis of orbital decay for different space conditions in the low orbit of the Shijian-10 satellite mission.

Table 1 Orbital decay rate for different space conditions

Solar and geomagnetic conditions	Orbital inclination	Orbital decay rate conditions (km/3 h)	
		350 km	250 km
Ap=10 $F_{10.7}$=70	0°	0.134	1.985
	45°	0.148	2.314
	90°	0.171	2.856
Ap=48 $F_{10.7}$=150	0°	0.653	4.855
	45°	0.715	5.557
	90°	0.833	6.828
Ap=300 $F_{10.7}$=260	0°	2.861	11.980
	45°	3.117	13.001
	90°	3.877	16.830

During the design phase, SEPC had provided support for satellite protection design by carrying out the analysis of space environment effect according to the special requirements of satellite development. For example, a single photon detector (avalanche diode), a crucial payload device of the Quantum Science experimental satellite, is very sensitive to proton irradiation and requires special protective measures. To fulfill the requirements by the satellite development sector, SEPC analyzed the reduction of orbital energetic proton fluxes with the orbit altitude decreasing from 600km to 500km, 450km, and 400km. A control group with different shielding layers was also provided. These environmental analyses helped to build an important basis for the final mitigation design scheme (see Figure 4 and 5).

During the launch phase, SEPC had provided safety period forecast for the launch windows 1 year, 6 months, 1 month, and finally 3 day in advance. Contents provided included medium and short term forecasts and possible

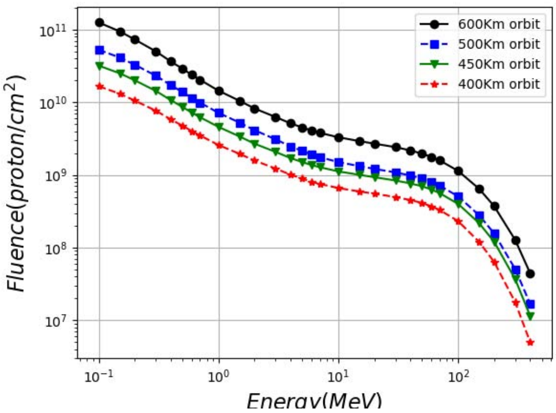

Fig. 4 Accumulated proton fluence of radiation belt in different altitude orbits

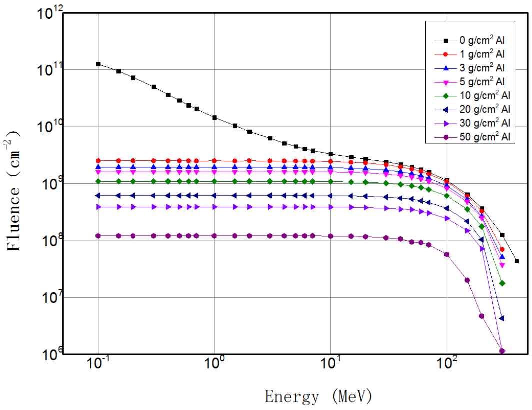

Fig. 5 Comparison of shielded proton flux in 500 km orbit

impact analyses of environmental elements such as solar activity, geomagnetic activity, high-energy radiation, *etc*.

During the operation phase, SEPC had provided daily forecasting and warning services for on-orbit satellites. Meanwhile, a real-time satellite orbital radiation environment calculation and 3D visualization system was developed. The system is driven by real-time monitoring data of geomagnetic activities and energetic particles. It can display the galactic cosmic rays, solar protons, and radiation belt environment on current mission orbits in an intuitive manner. Some scientific satellites, the Dark Matter satellite and the Hard X-ray satellite for example, carrying radiation-sensitive devices need to take some special mitigation operations when encountering severe radiation. In particular, when satellites with optoelectronic sensitive devices on board pass through SAA, measures like closing the lens protective cover, SAA data processing, algorithm correction, and annealing are needed to reduce and mitigate the effects of SAA[5-7]. For these scientific satellites, SEPC have provides accurate SAA contours, daily proton and electron energy spectra along orbit, and hazardous areas during proton events, to help ensure the safety of sensitive devices (see Figure 6).

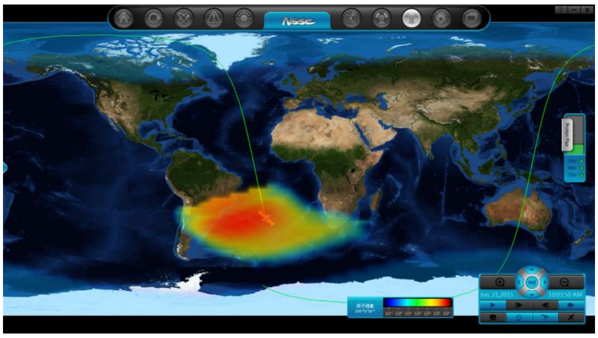

Fig. 6 Real-time orbital radiation environment calculation and 3D visualization system

In the orbital operation of scientific satellites, there are occasional anomalies of on-board equipment, such as star-sensitive resets, star-sensitive operating modes, on-board large-capacity memory abnormalities, and hardware CPU resets. Based on the time and location of the anomalies, we analyze the state of the space environment at the time of the anomaly and provide support for further anomaly diagnosis. The Figure 7 shows the soft errors detected by Error Detection And Correction (EDAC) on a scientific satellite. It is evidently shown that the errors mainly occur in the SAA center and polar regions.

4. Solar Storm Occurred in 2017

In September 2017 a spate of extensive solar activities, with the sun emitting 27 M-class and four X-class flares and releasing several powerful Coronal Mass Ejections (CMEs) were observed. The X9.3 flare on September 6th was the most intensive flare recorded during the current solar cycle (Figure 8). This event was named after the Chinese Ghost Festival (CGF) by NSSC since the traditional holiday was just one day before the eruption. When the CMEs plowed toward the Earth they sparked strong geomagnetic storms on September 7–8 (Figure 9). The major eruption on the Sun triggered two solar proton events with > 10MeV solar proton flux peaked at 1490PFU measured by GOES 15 satellite (Figure 9). Table 2 lists the start time, peak intensity, and end time for the two SPEs, respectively. The activity

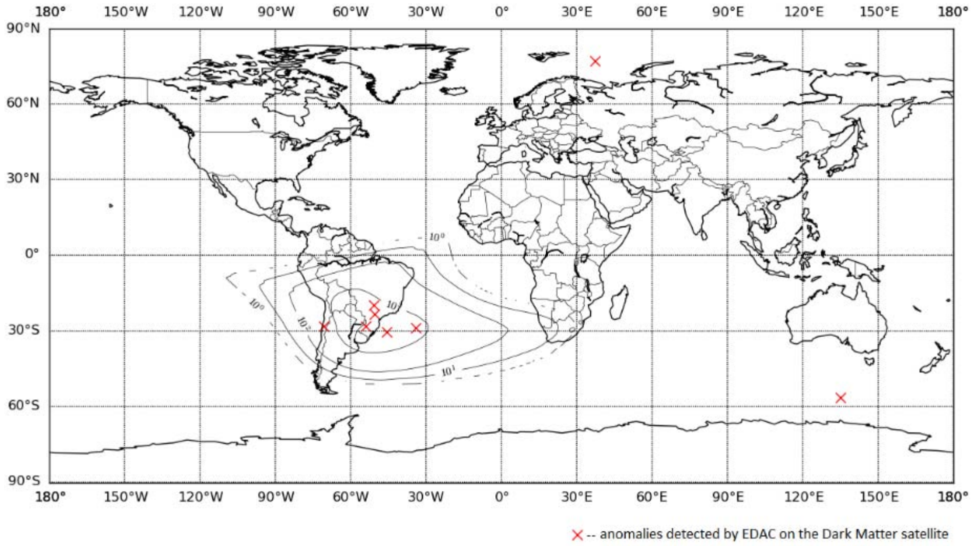

Fig. 7 Soft errors detected by EDAC on satellite

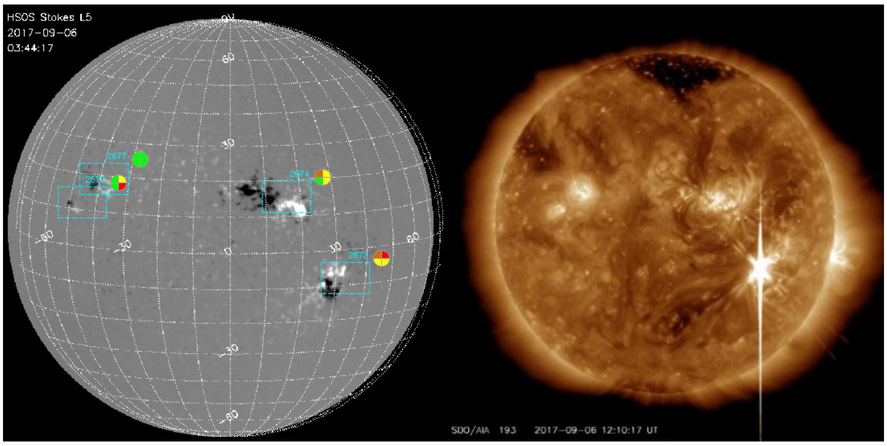

Fig. 8 SDO solar images, Left: SDO HMI magnetgram, right: SDO AIA 0193 image

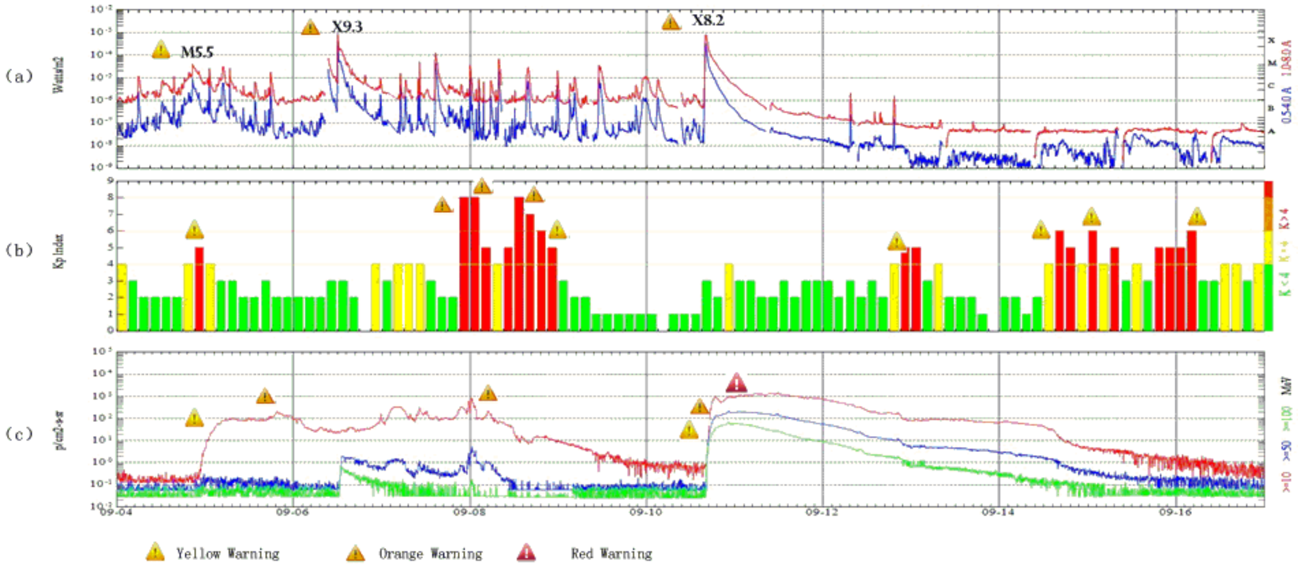

Fig. 9 (a) GOES 15 Xray flux, (b) Planetary *Kp* index, (c)GOES15 proton flux

Table 2 Two intensive SPEs

Events	Start time	Peak Intensity	End time
1	2017.9.5 00:40	844PFU	2017.9.9 00:05
2	2017.9.10 11:45	1490PFU	2017.9.14 17:25

originated in Region 2673, which rapidly grew into a much larger active region and attained ‘beta-gamma-delta’ magnetic configuration (Figure 8).

SEPC timely issued space weather alarms, nowcasts and forecasts through web, Email, SMS, microblog, Wechat and App for the Chinese Ghost Festival solar storm. Utilizing a number of operational model[8], $F_{10.7}$, Kp, Dst, AU/AL/AE model, 3D magnetopause model, the GEO relativistical electron flux model, regional ionosphere TEC model, and a solar wind model to name a few, SEPC had predicted the space weather throughout the whole event.

As mentioned earlier, single photon detector of Quantum Experiments at Space Scale and He Photomultiplier cathode of Hard X-ray Modulation Telescope are rather sensitive to space radiation. Besides, space radiation particles may charge the payload of Dark Matter Particle Explore to high voltage. SEPC analyzed the satellite orbital radiation environment and effects due to the two solar proton events on September 2017 based on the GOES15, NOAA satellites observations and geomagnetic transmission model.

Figure 10 illustrates the solar proton flux with energies >1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV, and >100 MeV. The proton fluxes of different channels possess an enhancement during the secondary solar proton event. Figure 11 depicts the orbital proton flux measured by NOAA satellites. While particles of low energies are usually blocked off by minial shielding, particles with energies >50 MeV can easily penetrate spacesuits and the skin of spacecraft. To assess the solar proton radiation effect, we calculated the orbital radiation environment for Quantum Experiments at Space Scale, Dark Matter Particle Explore, and Hard X-ray Modulation Telescope using *Ap* 9 model and proton transmission model based on the GOES15 proton measurements and geomagnetic *Kp* index. The orbital proton fluxes of Quantum Experiments at Space Scale and Dark Matter Particle Explore satellites increased significantly in the polar regions (Figure 12). The fluxes

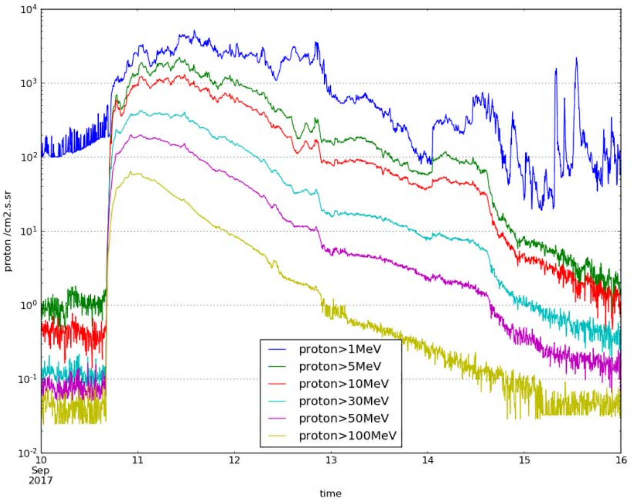

Fig. 10 GOES 13 solar proton fluxes at energies >1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV and >100 MeV

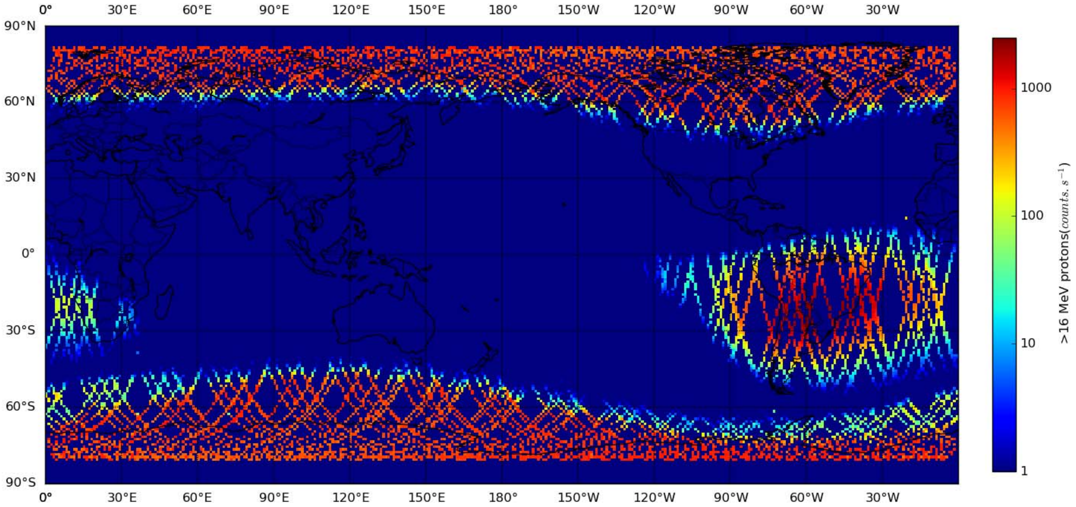

Fig. 11 >16 MeV Proton count rate measured by 5 NOAA Satellites on Sep. 11, 2017

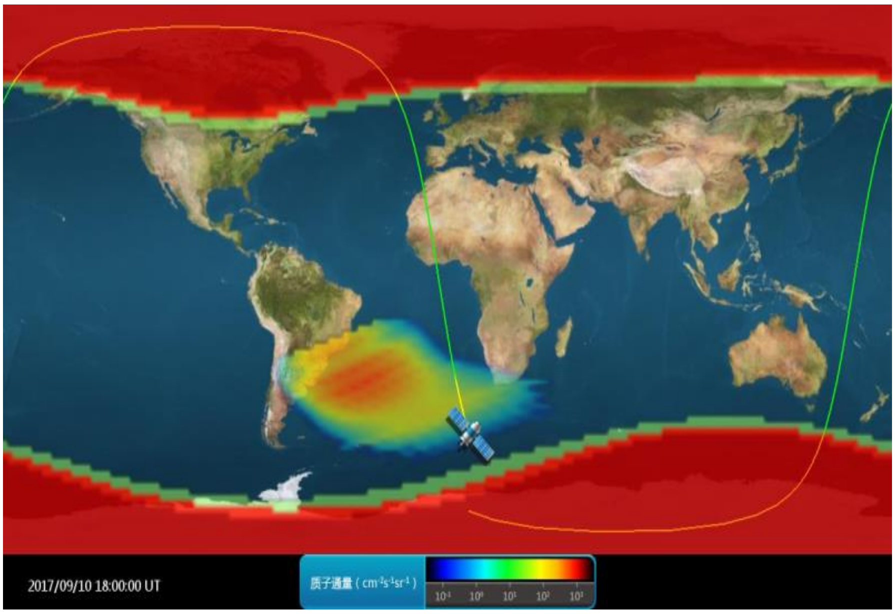

Fig. 12 Real-time model calculation of distribution of >10 MeV protons in orbits of dark matter satellite (Sept. 11, 2017)

are equivalent to the SAA radiation environment. As for the Hard X-ray Modulation Telescope the orbital proton fluxes increased only in the vicinity of the magnetic poles due to the low inclination angle of 43° (Figure 13).

Figure 14 gives the integral spectra at 500km height from a fitting method of three historical solar proton events, compared to the SAA central proton integral spectra at the same height using the AP9 Model[9]. It is noticeable that the entire spectrum during the CGF solar storm is higher than that in SAA central region, and lower than that of the SPE occurred on January 20th, 2005. The solar proton flux at energies >200MeV of the CGF solar storm is higher than that of the SPE occurred on October 28th, 2003. Due to the severe solar proton radiation condition, the TT&C team increased the tracking number to monitor the space science satellites.

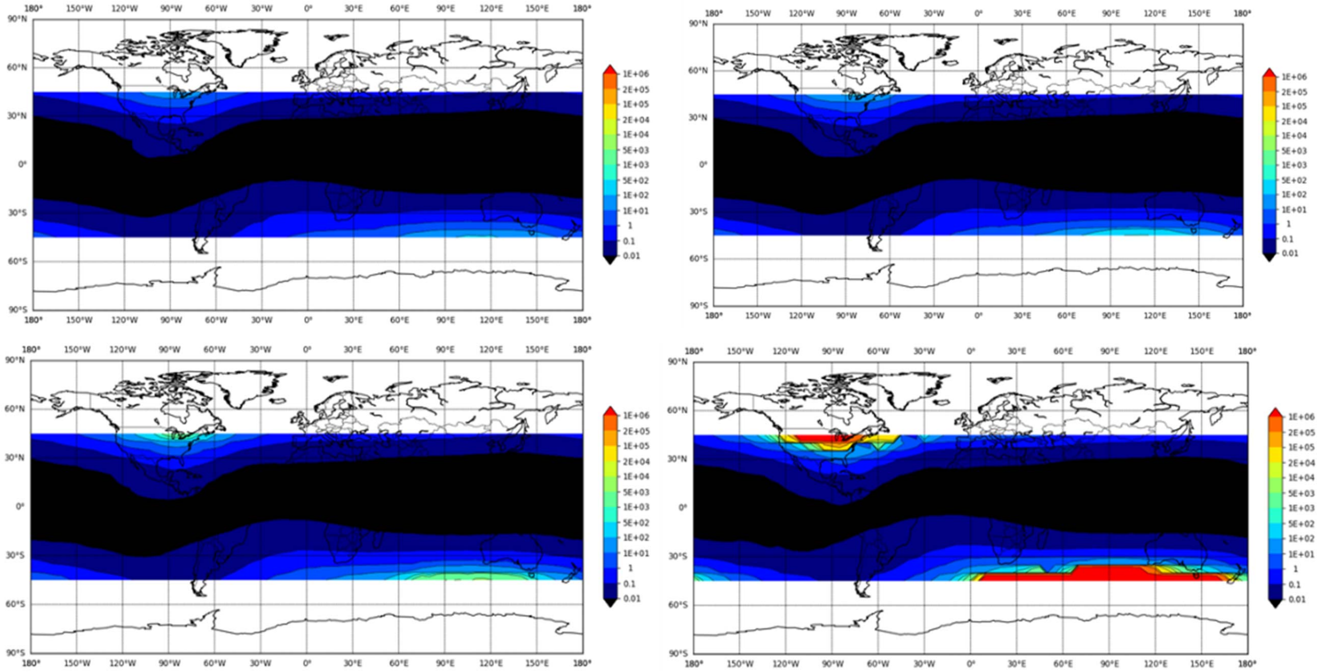

Fig. 13 Solar proton arrival area in the Hard X-ray satellite orbits under different geomagnetic conditions (*Kp*=1, 4, 5, 8)

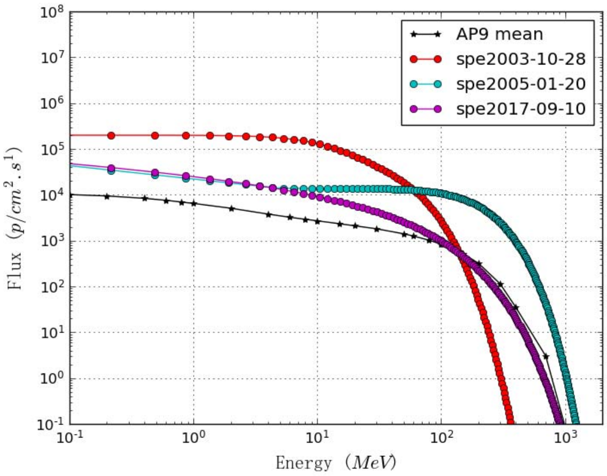

Fig. 14 Integral spectra of three SPE events and in SAA central portion

Quantum Experiments at Space Scale satellite suspended scientific experiments, and the experiment control payload was shut down. Hard X-ray Modulation Telescope was shut down, too. The two satellites returned to normal operation on September 13, 2017.

5. Future Chinese Space Science Satellites Plans and Space Weather Services

During the second phase of Strategic Priority Program on Space Science, the following missions are proposed and will be implemented: Einstein-Probe, Advanced Space-borne Solar Observatory, Water Cycle Observation Mission, Magnetosphere-Ionosphere-Thermosphere Coupling Exploration, Solar Wind Magnetosphere Ionosphere Link Explorer. These space science satellites may experience the peak phase of solar cycle 25. SEPC will continue to monitor the space weather 24 hours per day, providing space weather forecasts, environment analysis, and feasible countermeasures for Chinese space missions.

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