0254-6124/2019/39(6)-809–07 *Chin. J. Space Sci.* 空间科学学报

HUANG Cong, LIU Dandan, GUO Jing, ZHANG Xiaoxin. SZ-5 cabin's height changes during three super-storms in 2003. *Chin. J. Space Sci.*, 2019, **39**(6): 809-815. DOI:10.11728/cjss2019.06.809

SZ-5 Cabin's Height Changes during Three Super-storms in 2003*

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Abstract In this work, the daily height variations of SZ-5 (Shenzhou-5) cabin from 22 October to 28 November in 2003 are analyzed, which includes the period of the Halloween Storm and the Great November Storm. The significant orbital decays have been observed at the end of October and in late November due to the great solar flares and the severe geomagnetic storms. According to the equation of the air-drag-force on a spacecraft and the SZ-5 orbital decay information, the relative daily average thermospheric density changes during the three 2003 super-storms are derived and the results are compared with the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar Extended Model (NRLMSISE-00). The results show that the daily average thermospheric density (at the altitude of SZ-5, about 350 km) in storm time enhances to approximately 200% as much as that in the quiet time but the empirical model may somewhat underestimate the average thermospheric density changes and the daily contributions of geomagnetic storms to the density enhancements during these severe space weather events.

Key words Thermosphere density, Orbital decay, Geomagnetic storm, Empirical model

Classified index V 556

0 Introduction

It is well known that the thermospheric density changes caused by intense solar activity have great impacts on the atmospheric drag force to LEO (Low Earth Orbit) spacecraft. The increasing of the air drag can lead to the dramatic orbital decays of the spacecrafts[1,2]. There are two main ways to input the energy of solar activity into thermosphere: one is the solar EUV (Extreme Ultra-Violet) radiation, the other is the solar wind particle deposition in the polar region. The solar EUV radiation is the main contributor to the thermosphere heating, which accounts for 80% of the energy input into the thermosphere[3]. Another way to input solar energy into the thermosphere is dominated by Joule (particle) heating, which is associated with geomagnetic activity and determined by the level of geomagnetic activity[4]. The solar EUV radiation drives relative long-term density perturbations in thermosphere[5,6], while the Joule/particle heating causes significant impacts on the thermospheric density during severe geomagnetic storms. The thermospheric density may enhance as much as 134% with the raising of the Kp index from 1 to 6[7].

Many studies about the thermospheric density responses to geomagnetic storms have been carried out[5,8−23]. Liu *et al.*[5] and Sutton *et al.*[16] utilized the measurements from the STAR (Spatial Triaxial Accelerometer for Research) accelerometer

* Supported by the Natural Science Foundation of China (41574178, 41874187, 41774152, 41774195) and Grant from CAS Key Laboratory of Geospace Environment, University of Science and Technology of China
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on the CHAMP (Challenging Mini-satellite Payload) to investigate the relationship between thermospheric density variations and strong geomagnetic storms in 2003. Bruinsma *et al.*[17] applied CHAMP and GRACE (Gravity Recovery and Climate Experiment) accelerometer data to analyze the thermospheric density responses to the 2003 great geomagnetic storm in November compared with the NRLMSISE-00 model. Kim *et al.*[6] analyzed atmospheric drag effects using KOMPSAT-1 satellite's track data and drew a conclusion that the Joule heating driven by geomagnetic storms makes more effects on thermospheric density increasing than the solar EUV radiation. Park *et al.*[24] compared the KOMPSAT-1 drag derived density with the MSIS model to show that the model underestimates the thermosphere density changes during the strongly disturbed geomagnetic intervals. Lei *et al.*[21] utilized the CHAMP and the GRACE measurements to study the impact of solar forcing on the thermosphere density and the related effect on the satellite orbit. Using the CHAMP data, Chen *et al.*[22,23] compared the impacts of the geomagnetic activity caused by different origins on thermosphere densities and spacecraft orbits. However, there still exist difficulties in accurately describing the relationship between thermospheric density disturbances and geomagnetic activity by empirical models[25].

The Halloween Storms of 2003 are a series of severe space weather events that occurred from late October to early November in 2003. During the Halloween Storms, there exist two super-storms[5] that occurred on October 29 and 30 with the daily Ap indices reaching to about 200. The Great November Storm is an isolated severe geomagnetic storm with the daily Ap index increasing to about 150, which occurred on November 20. These three storms made significant impacts on LEO spacecraft orbits and provide us a good chance to study the thermospheric density responses to these super-storms.

In this work, we present the height changes of SZ-5 (Shenzhou-5, in the near-circular orbit with a 42° inclination at the altitude of about 350 km) cabin during the geomagnetic storms of October and November in 2003 and compare the relative thermospheric density variations calculated from the height changes of SZ-5 with the NRLMSISE-00 model to analyze the differences between observations and model during the severe space weather events, and also discuss the geomagnetic storm daily contributions to the thermospheric density increasing compared with the solar EUV radiation.

1 Data and Methodology

The SZ-5 height data used here is the daily average height data. H_n is defined as the daily average height on Day n, and ΔH_n is the daily average height change on Day n. Considering the space weather event on Day n may have relative hysteretic impacts on the day after Day n, we define the equation: $\Delta H_n = H_n - H_{n+1}$. The daily average height and height change datasets of SZ-5 have been plotted in Figure 1 from October 22 to November 2 (Day 295 to 306) and November 17 to 28 (Day 321 to 332) including the periods of the three super-storms in 2003. According to the paper of Montenbruck *et al.*[26], the air drag force on a spacecraft is given by $F_{\rm drag} = \frac{1}{2}\rho v^2 C_{\rm d} S$, where ρ is the atmospheric density, v is the spacecraft's orbital velocity relative to the atmosphere, $C_{\rm d}$ is the dimensionless drag coefficient and S is the spacecraft's cross-sectional area perpendicular to the direction of the motion. Applying the Law of Conservation of Energy and Kepler's Laws, we can derive the relation $\Delta H \propto \rho$ (see the details in the next paragraph), which can be used to calculate the relative atmospheric density changes. The ρ calculated from the orbital ΔH of SZ-5 can be adjusted to 350 km by the equation: $\rho_z = \rho_{350} \times (\rho_{\rm model_}z / \rho_{\rm model_350})$, where ρ_z is the ρ at the altitude of z km, ρ_{350} is the ρ at the altitude of 350 km, $\rho_{\rm model_}z$ is the ρ calculated by the model (NRLMSISE-00) at the altitude of z km and $\rho_{\rm model_350}$ is the ρ calculated by the model (NRLMSISE-00) at the altitude of 350 km.

The details for deriving the relation $\Delta H \propto \rho$.

First, according to the paper of Montenbruck *et al.*[23], the air drag force on a spacecraft is given by $F_{\rm drag} = \frac{1}{2}\rho v^2 C_{\rm d} S$, where ρ is the atmospheric densi-

ty, v is the spacecraft's orbital velocity relative to the atmosphere, $C_{\rm d}$ is the dimensionless drag coefficient and S is the spacecraft's cross-sectional area perpendicular to the direction of the motion. Second, the energy of the spacecraft is given by

$$E = \frac{1}{2}mv^2 - \frac{GM_{\rm e}m}{r} = -\frac{GM_{\rm e}m}{2r},$$

m is the mass of the spacecraft, $M_{\rm e}$ is the mass of the Earth, v is the spacecraft's orbital velocity relative to the atmosphere, r is the orbital radius and G is the constant of universal gravitation. Third, the energy changes by the air drag is given by

$$\dot{E} = \frac{GM_{\rm e}m}{2r^2}\dot{r} = -F_{\rm drag}v = -\frac{1}{2}\rho v^3 C_{\rm d}S,$$

and we use

$$\frac{GM_{\rm e}m}{r} = mv^2,$$

then we get the equation:

$$\dot{r} = -\rho\frac{C_{\rm d}S}{m}(GM_{\rm e}r)^{1/2}.$$

Then, we assume $C_{\rm d}$ and S are constant in the daily average calculation and r changes little in the short-term, finally, we have the relation $\Delta H \propto \rho$.

In this work, the NRLMSISE-00 model is applied to make the comparison between the observations and the model. The development of the NRLMSISE-00 model is based on the series versions of MSIS models[27−29] including new drag data of satellites and the additional calculations of atmospheric anomalous oxygen. The details about the NRLMSISE-00 model can be found in the paper of Picone *et al*[30]. The space weather indices used in this work are Ap and $F_{10.7}$, which can be derived at the World Data Center for Geomagnetism, Kyoto* and NASA's Goddard Space Flight** Center.

2 Results

Figure 1 shows the daily heights and height changes of SZ-5 during Day 295 to 306 and Day 321 to 332 in 2003, including the storms on Day 302 (October 29), 303 (October 30) and 324 (November 20). From Figure 1, we found the orbital heights of SZ-5 changed

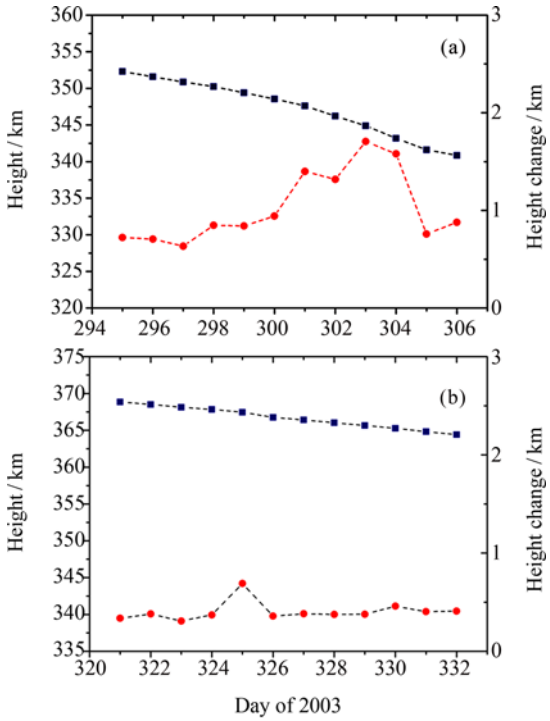


Fig. 1 SZ-5 orbital heights (blue squares connected by dash lines) and the orbital height changes (red spots connected by dash lines) in October (a) and November (b)

significantly after the storm days. Using the method mentioned in Section 1 and assuming the $C_{\rm d}$ and S of SZ-5 are constants in one day average, we calculated the relative ρ_n (ρ_n is the daily average ρ on Day n) from the ΔH_n of SZ-5 (ΔH_n is the daily average ΔH on Day n), which refers to the daily average ρ of the first day (Day 295 in October panel and Day 321 in November panel, in Figure 2). In other words, the relative daily change of ρ_n equals ρ_n/ρ_1. Using the relative daily variations of ρ_n in this analysis is for our convenience to easily derive the relative daily density changes while we assume the values of the $C_{\rm d}$ and S of SZ-5 are constants. Figure 2 shows the space weather indices, the relative ρ_n changes calculated from the SZ-5 data and the NRLMSISE-00 model in the 2003 October and November events. For the October event in Figure 2(a), we found that the peaks of relative daily density changes calculated from the SZ-5 data are on Day 303 and 304, where exist 1 day delay to the storm days of 302 and 303, the density changes are

*http://wdc.kugi.kyoto-u.ac.jp/index.html
**https://omniweb.gsfc.nasa.gov/form/dx1.html

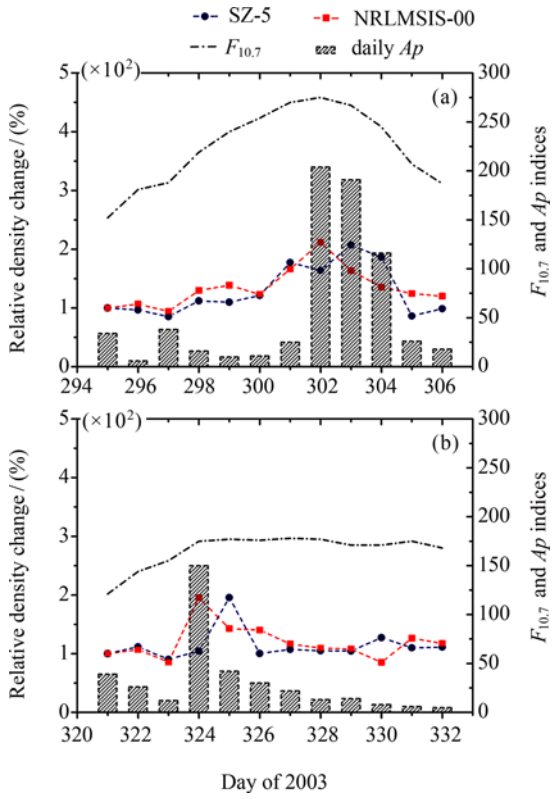


Fig. 2 Calculated by the SZ-5 orbital height changes and the NRLMSIS-00 model in October (a) and November (b) Events (densities have been adjusted to the altitude of 350 km)

are about 207% (Day 303) and 186% (Day 304) of the first day (Day 295) during the storms at the end of October. The model outputs show the density changes are about 211% of the first day (Day 295) on Day 302 and 164% on Day 303 during the October storms. In addition, an X17 solar flare occurred on Day 301, which made great impacts on the thermosphere. From the SZ-5 data, the density enhanced to 146% (Day 301) and 135% (Day 302) of the day before (Day 300). The impacts on the thermospheric density by this X17 flare have been investigated in the previous studies[31−33], in which the thermosphere density increases by about 50%∼70% at 400 km from low to mid-latitudes. Our results are in some agreement with these previous studies and coincide with the model on Day 301. For the November event in Figure 2(b), it was found that the geomagnetic storm occurred on Day 324 caused the 196% atmospheric density change of the first day (Day 321) calculated from the SZ-5 orbital height changes on Day 325 but the model shows the 195% atmospheric density change of the first day (Day 321) on Day 324. It is interesting to see obvious daily average density depressions on the days after the density significant enhancement days, which are on Day 305 in October event and Day 326 in November event. This situation has been reported in previous studies[17,19].

We plotted the daily average orbital height changes of SZ-5 during the two periods (Day 295 to 306 and Day 321 to 332) in Figure 3(a). All height changes have been adjusted to the altitude of 350 km by the adjustment equation like ρ mentioned in Section 1. From Figure 3(a), in the October events, the average height changes are about 1.29 km·d^{-1} during the flare-influenced intervals (Day 301, 302) and 1.48 km·d^{-1} on the storm days (Day 303, 304). To the November event, the daily average height changes are about 0.94 km in the storm and 0.51 km during the reference days (Day 327, 328, 329). The differences in daily height changes between the October and November events are due to the different solar EUV flux. The solar EUV flux made great impacts on the orbital height changes of SZ-5 in the October storms. In Figure 3(b), the daily average mass densities at 350 km calculated by the NRLMSISE-00 model during the storm day, the flare day and the reference days are also plotted, in October and November, respectively. From the model predictions, we found that the solar EUV has obvious impacts on the thermospheric density enhancements in the October events but the November storm caused more relative density increases in the November event like the results of SZ-5 data analysis.

Figure 3(c) shows the daily contributions of geomagnetic storms (hereafter, CoGS) to the density enhancements in the October and November storms calculated by the SZ-5 data and the NRLMSISE-00 model. We made the CoGS calculations from Figure 3(a) (b). To calculate the CoGS in Figure 3(a), we define $\Delta H_{\rm s}$ and $\Delta H_{\rm r}$ are the average relative height changes on the storm days and the reference days, respectively. Then, we have the equation: $C_{\rm SZ\text{-}5} = (\Delta H_{\rm s} - \Delta H_{\rm r})/\Delta H_{\rm r}$ (the $C_{\rm SZ\text{-}5}$ is the CoGS

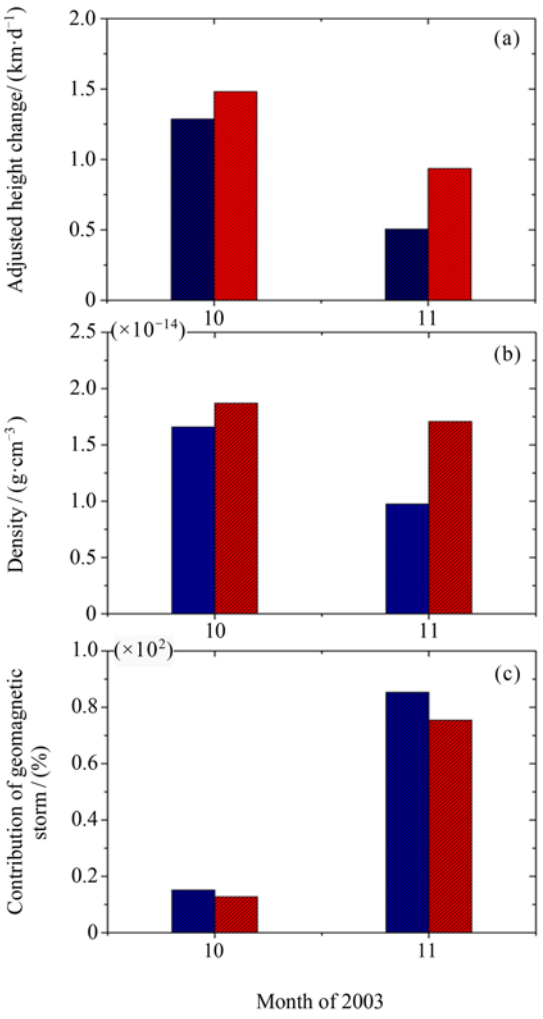


Fig. 3 (a) The relative daily average orbital height changes. The blue columns denote the daily average height changes on the flare-influenced days (Day 301, 302) in October and the reference days (Day 327, 328, 329) in November, and the red columns denote the daily average height changes on the storm-affected days (Day 303, 304 in October and Day 325 in November). All height changes have been adjusted to the altitude of 350 km. (b) The daily average mass density at 350 km calculated by NRLMSIS-00. The blue columns denote the daily average mass density on the flare days (Day 301 in October and the reference days (Day 327, 328, 329) in November, and the red columns denote the daily average mass density on the storm days (Day 301, 302 in October and Day 324 in November. (c) The daily contributions of geomagnetic storms to the density enhancements compared with the solar EUV in October and November calculated from the SZ-5 data (blue) and the NRLMSIS-00 model (red)

calculated by the SZ-5 data). For the October event in Figure 3(a), we suppose the storm effects are superimposed on the solar EUV effects during the storm days (Day 303, 304) and therefore choose the Day 301 and 302 as the reference days due to the $F_{10.7}$ indices were almost at the same level on Day 301 to 304. For the November event in Figure 3(a), we define Day 325 as the storm day and select Day 327, 328, 329 as the references day (excluding Day 326 due to the density depression) owing to the same level of $F_{10.7}$ during this period. To do the CoGS calculations in Figure 3(b), we define $\Delta D_{\rm s}$ and $\Delta D_{\rm r}$ to be the average density changes on the storm days and the reference days, respectively. Then, we have the equation: $C_{\rm Model} = (\Delta D_{\rm s} - \Delta D_{\rm r})/\Delta D_{\rm r}$ (the $C_{\rm Model}$ is the CoGS calculated by the NRLMSISE-00 model). In the CoGS calculations of Figure 3(b), by applying the similar choosing method above, we define Day 302, 303 and 324 are the storm days and choose Day 301, 327, 328, 329 as the reference days in the October and November events, respectively. From Figure 3(c), in the October storms, the $C_{\rm SZ\text{-}5}$ is about 15% but the $C_{\rm Model}$ is about 13%. For the November storm, $C_{\rm SZ\text{-}5}$ and $C_{\rm Model}$ are about 85% and 75%, respectively. The NRLMSISE-00 model may somewhat underestimate the geomagnetic storm daily contributions to the thermospheric density enhancements compared with the solar EUV effects in these storms, especially in the November storm.

3 Conclusions and Discussions

In this work, we utilized the daily average orbital height data of SZ-5 to analyze the daily thermospheric density changes during three storms in October and November 2003. The NRLMSISE-00 model is also applied to do the variance comparison between the observations of SZ-5 and the model predictions. The geomagnetic storm daily contributions in these space weather events to the thermospheric density enhancements compared with the solar EUV effects have been discussed. According to the results in this study, we drew conclusions below.

(1) During three severe geomagnetic storms in

2003, the SZ-5 orbital heights present significant changes. According to the daily average atmospheric density changes calculated from the SZ-5 data, the daily average atmospheric density enhancements at the altitude of 350 km exhibit about 207% (Day 303), 186% (Day 304) and 196% (Day 325) of the relative quiet days (Day 295 in October and Day 321 in November) before the storms, respectively. There exist density depressions on the days after the storm-induced density enhancements, which are on Day 305 and 326, respectively.

(2) From the comparisons of daily average atmospheric density changes between the storm days and the reference days in October and November, based on the SZ-5 data, we derive the geomagnetic storm daily contributions to the atmospheric density enhancements compared with the solar EUV effects, which are 15% and 85% in the October and November storms, respectively.

(3) The NRLMSISE-00 model may somewhat underestimate the geomagnetic storm's impacts in these three super-storms. The daily average atmospheric density enhancements at 350 km calculated by the NRLMSISE-00 model are about 212% (Day 302), 164% (Day 303) of Day 295 in October and 195% (Day 324) of Day 321 in November. The NRLMSISE-00 model predicts that the daily contributions of geomagnetic storms to the atmospheric density enhancements are about 13% and 75% of the solar EUV effects in the October and November events, respectively.

The results about the density enhancements during the 2003 super-storms in this work are in some agreement with the previous studies[5,16,17,34,35]. These studies show that the thermospheric density increased significantly with the geomagnetic indices such as *Ap*, *Kp*, *etc.*, and the density enhancements reached over 200% of the quiet intervals at 410 km during the 2003 severe October and November storms but the empirical models (MSISE-90, NRLMSISE-00) underestimate the geomagnetic storm impacts on the thermospheric density. Due to that the density calculated by the daily average orbital heights are approximate to two days' average density, the peak time of the density changes may be different between the SZ-5 data and the NRLMSIS model. From these previous studies, it is found that the relative thermospheric density changed more significantly in the November storm compared with the October Storms. Our results coincide with the findings of these previous studies and provide new cases at 350 km. However, due to the limit of SZ-5 orbital data used in this work, our results are only about the daily average density changes that can't accurately describe the temporal and spatial density variations in one day. So, we hope to use the observations from the in-situ atmospheric density detectors onboard Chinese satellites in future studies. This work proved that the energy input by the particle precipitations during storms is another main energy source leading to the density disturbance in the thermosphere. So, the Magnetosphere-Ionosphere-Thermosphere (MIT) connecting observations and the related investigations are desired to be carried out in the future.

Acknowledgements Thanks for the SZ-5 orbit data from Beijing Aerospace Command and Control Center.

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