A comparison of the effects of CIR- and CME-induced geomagnetic activity on thermospheric densities and spacecraft orbits: Case studies

Guang-ming Chen,1 Jiyao Xu,1 Wenbin Wang,2 Jiuhou Lei,3 and Alan G. Burns2

Received 30 March 2012; revised 1 June 2012; accepted 28 June 2012; published 16 August 2012.

[1] So far studies of the effect of geomagnetic storms on thermospheric density and satellite orbits have been mainly focused on severe storm events caused by Coronal Mass Ejections (CMEs). The effect of long-duration, less intensive geomagnetic activity that is related to Corotating Interaction Regions (CIRs) has not been fully explored. In this paper, thermospheric densities observed by the CHAMP satellite and its orbit parameters are used to compare the responses of satellite orbital altitudes to geomagnetic activity caused by CMEs and CIRs. Three cases are investigated in this paper. Each case had one or two CME storm(s) and one CIR storm that occurred successively. In these cases three out of four CME-storms were stronger than their corresponding CIR-storms, but the durations of these CME-storms were much shorter. Thus, the satellite orbit decay rates during CME-storms are usually larger than those during CIR-storms. However, CIR-storms often had long durations that perturbed satellite orbits for longer periods of time. As a result, the total thermospheric density changes and satellite orbit decays for the entire periods of CIR-storms were much greater than those for the CME-storms since these parameters were related to the total energy deposited into the thermosphere/ionosphere, which depended on both the strengths and the durations of the storms. This study indicates that more attention should be paid to CIR storms during the declining phase and during solar minimum, when they occur frequently and periodically. Whereas fewer CME storms occurring under these conditions. We also found that changes in thermospheric densities and CHAMP orbit decay rates correlated well with variations of auroral hemispheric power, but lagging by about 3–6 h.


1. Introduction

[2] Aerodynamic drag, which is directly related to thermospheric densities, is the largest uncertainty in determining and predicting the orbits of satellites operating below about 600 km [Storz et al., 2002]. The prediction of the lifetime and the re-entry date of a low Earth orbit (LEO) satellite depend upon an accurate knowledge of the variations of thermospheric densities. Changes in thermospheric density occur when there are variations in solar EUV radiation [Xu et al., 2011, and references therein] and/or geomagnetic activity [Knipp et al., 2004].

[3] Under geomagnetic disturbed conditions, large amounts of energy that is generated as the solar wind interacts with the magnetosphere is dissipated into the upper atmosphere at high latitudes by particle precipitation and Joule heating, leading to the expansion of the global thermosphere and the enhancements of thermospheric density at the orbit heights of LEO satellites [Wilson et al., 2006]. The enhancements of thermospheric densities and thus satellite drag under geomagnetic disturbed conditions often bring difficulties for tracking and predicting the trajectories of thousands of space objects [Wright, 2007; Anderson et al., 2009]. There have been many studies on the variations of thermospheric densities during geomagnetic storms [e.g., Wilson et al., 2006; Bruinsma et al., 2006; Forbes et al., 2005, 2008; Sutton et al., 2005; Sutton, 2009; Bruinsma and Forbes, 2007a, 2007b; Lathuillère et al., 2008; Thayer et al., 2008; Guo et al., 2010; Lei et al., 2008, 2011a, 2011b]. These studies, however, are
mostly focused on storm-time, instantaneous changes of thermospheric densities or periodic variations of these changes. There have not been many studies on the total thermospheric density changes during the entire period of a storm event, which determine total satellite orbit decays that are critical for satellite tracking.

[4] There are significant differences between geomagnetic storms driven by coronal mass ejections (CME) and by corotating interaction regions (CIRs)/high speed solar wind streams [Borovsky and Denton, 2006]. Denton et al. [2006] pointed out that the strength of magnetospheric convection electric field of a CME-storm is often stronger than that of a CIR-storm. However, the duration of a CIR-storm is usually much longer [Tsurutani and Gonzalez, 1987]. The long-duration, less-intense CIR storms thus can deposit roughly the same amount of energy as or even more energy into the upper atmosphere than most of moderate CME-storms do over the entire periods of storm events [Turner et al., 2009; Emery et al., 2009]. Energy inputs to the upper atmosphere causes increases in global mean neutral temperature and thermal expansion, as well as changes in neutral circulation and composition, and thus enhancements of neutral density at a particular altitude. So far people have mainly focused on the effect of severe CME-storms on thermospheric density [e.g., Sutton et al., 2005; Bruinsma et al., 2006; Lei et al., 2011a]. Recently, there have been some investigations on the effects of long-duration CIR storms on thermospheric density and ionospheric plasma densities [e.g., Lei et al., 2008, 2011b; Burns et al., 2012; Solomon et al., 2012]. However, there have been no studies comparing the effects of these two types of storms on thermospheric densities and satellite orbits. The effect of CIR-storms on satellite orbits are of particular importance during the declining phase and near solar minimum of a solar cycle, when large CME storms are almost absent, whereas high speed solar wind streams and their resultant CIRs occur frequently and periodically and produce large effects on the thermosphere-ionosphere system [e.g., Lei et al., 2008; Wang et al., 2011; Burns et al., 2012; Solomon et al., 2012, and references therein].

[5] In this paper, thermospheric densities observed by the CHAMP satellite and its orbit parameters are used to investigate the response of the satellite orbital altitudes to geomagnetic storms caused by different drivers. In Section 2 we introduce data set and analysis method used in this study. Results and discussion are in Section 3 and Section 4. The summary is given in the last section.

2. Data and Method

[6] The CHAMP satellite was launched on July 15, 2000 to a near-circular orbit with an inclination of 87.3° initially at 454 km [Reigber et al., 2002]. The orbit period is about 93 min. The CHAMP satellite carried the STAR accelerometer, which measures the non-gravitational accelerations acting on the satellite. Many papers [e.g., Liu and Lühr, 2005; Sutton et al., 2005; Sutton, 2009; Bruinsma et al., 2006; Bruinsma and Forbes, 2007a, 2007b] have described the retrieval of thermospheric densities from the accelerometer measurements on CHAMP. In the present work, we use the data set from Sutton [2009].

[7] The CHAMP satellite orbit is not circular; there are tens of kilometers differences in orbit heights between satellite apogee and perigee. Thus, the distance $r$ between the satellite and the Earth’s center varies along the satellite orbit. In addition, since gravity varies along the satellite orbit, there is a fluctuating component of satellite orbit height that is associated with both the satellite orbit period and the Earth rotation period. To address this issue and to thus analyze geomagnetic storm effects, the mean atmospheric density (MDPR) and the mean semi-major axis $a$ (see Appendix A) per revolution are used instead of the distance $r$ in our analysis. The orbit decay rates $\frac{\text{d}a}{\text{d}t}$ per revolution (ODPR) are calculated according to $\frac{\text{d}a}{\text{d}t}$. The geomagnetic activity induced total orbit decays are calculated by subtracting the background atmospheric effects from the variations of $\frac{\text{d}a}{\text{d}t}$.

[8] Global auroral precipitation is computed by using data from the Defense Meteorological Satellite Program (DMSP) and National Oceanic and Atmospheric Administration (NOAA) satellites intercalibrated with each other by Emery et al. [2009]. For the present study, we use the hourly averaged hemispheric power (HP) from both the northern and southern hemispheres as a proxy for the total energy inputs to the thermosphere and ionosphere from the magnetosphere and solar wind during the storm.

3. Results

[9] In this section, three cases of geomagnetic storms in 2002 and 2006 are analyzed to study their effects on atmospheric density and satellite orbit. Each case had both CME- and CIR-storm event (s) which occurred successively. For each event, the total satellite orbit decay in response to geomagnetic disturbances is calculated by integrating the differences between the storm-time ODPR and the mean value of pre- and post-storm ODPR. Thus the effects of season and satellite precession (local time), as well as the 27-day variation of solar rotation on our results are expected to be small as the longest duration of the events studied in this paper is about 6 and half days (c.f. Table 1, Storm 5).

[10] The onset time of a CIR or ICME storm is associated with the arrival of interplanetary shocks or other abrupt changes in solar wind and IMF conditions. In this paper, the onset time of each storm is determined by the arrival time of CIRs or ICMEs observed by the ACE or Wind satellite, which is listed in the table of Jian [2008], and the propagation time from the satellite to the magnetopause based on solar wind speed. To study the effect of a storm on thermospheric densities and satellite orbits, the end time of the storm is defined as the time when the AE index becomes quiet, and MDPR becomes steady and approaches minimum. The threshold value of AE for the quiet condition is defined as the 60-day mean value around the storm period with AE values larger than 400 nT being removed. Thus, the storm ending is defined by three conditions: AE has fallen below its 60-day mean value; the thermospheric density is no longer changing; and the thermospheric density is approaching a minimum.

[11] Note that we determine the occurrence of CME/CIR storm events using changes in solar wind and interplanetary magnetic field conditions following Jian’s [2008] method. We do not use the AE index for this purpose. Instead, we only use this index as one of the proxies for the duration of
Table 1. A Summary of the Storm Effects on Thermosphere Densities and Spacecraft Orbits

<table>
<thead>
<tr>
<th>Storm</th>
<th>Start Time (YYYYdd hh:mm)</th>
<th>End Time (YYYYdd hh:mm)</th>
<th>Driver</th>
<th>Geomagnetic Activity</th>
<th>Dist Minumum Bz (nT)</th>
<th>Solar EUV Radiation (F10.7)</th>
<th>Maximal MDPR (GW)</th>
<th>Maximal ODPR (10^-15 J m/day)</th>
<th>Maximal Decay Rate (m/day)</th>
<th>Duration (day)</th>
<th>Total Auroral Energy (10^15 J)</th>
<th>Total Decay Rate (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2002143:11:16</td>
<td>2002144:18:58</td>
<td>CME</td>
<td>Strong</td>
<td>−109</td>
<td>high</td>
<td>90.9</td>
<td>7.77</td>
<td>148</td>
<td>1.32</td>
<td>1.42</td>
<td>32.6</td>
</tr>
<tr>
<td>2</td>
<td>2002146:19:58</td>
<td>2002151:14:24</td>
<td>CIR</td>
<td>Moderate</td>
<td>−64</td>
<td>high</td>
<td>58.0</td>
<td>6.61</td>
<td>129</td>
<td>4.77</td>
<td>4.34</td>
<td>96.5</td>
</tr>
<tr>
<td>3</td>
<td>2002077:14:23</td>
<td>2002079:05:46</td>
<td>CME</td>
<td>Weak</td>
<td>−37</td>
<td>high</td>
<td>49.6</td>
<td>7.48</td>
<td>145</td>
<td>1.64</td>
<td>1.61</td>
<td>26.5</td>
</tr>
<tr>
<td>4</td>
<td>20020807:12:25</td>
<td>20020808:00:58</td>
<td>CME</td>
<td>Strong</td>
<td>−100</td>
<td>high</td>
<td>70.5</td>
<td>8.19</td>
<td>167</td>
<td>2.52</td>
<td>4.25</td>
<td>70.5</td>
</tr>
<tr>
<td>5</td>
<td>2002146:19:58</td>
<td>2002151:14:24</td>
<td>CIR</td>
<td>Strong</td>
<td>−41</td>
<td>high</td>
<td>53.8</td>
<td>7.02</td>
<td>134</td>
<td>6.13</td>
<td>7.34</td>
<td>80.7</td>
</tr>
<tr>
<td>6</td>
<td>2006327:03:40</td>
<td>2006332:19:12</td>
<td>CIR</td>
<td>Weak</td>
<td>−30</td>
<td>low</td>
<td>62.1</td>
<td>2.80</td>
<td>51</td>
<td>5.65</td>
<td>8.37</td>
<td>38.0</td>
</tr>
<tr>
<td>7</td>
<td>2006333:05:54</td>
<td>2006335:17:31</td>
<td>CME</td>
<td>Moderate</td>
<td>−71</td>
<td>low</td>
<td>121.0</td>
<td>3.65</td>
<td>79</td>
<td>2.48</td>
<td>4.07</td>
<td>36.7</td>
</tr>
</tbody>
</table>

*aBold values are associated with CIR storms, and the rest deal with CME storms.
calculations of the total thermospheric density variation and satellite orbit decay during interested storm periods the effect of these pre-storm variations has been removed by subtracting the storm-time ODPR with the mean value of pre- and post-storm ODPR.

The second storm (Storm 2) also had a large southward Bz excursion with a maximum amplitude of about 12 nT. This storm was caused by high speed solar wind streams and the resultant co-rotating interaction region (CIR) that encountered the Earth at about 2000 UT on day 146 [Jian, 2008]. The solar wind velocity increased from \( \sim 450 \text{ km}^{-1} \) to \( \sim 750 \text{ km}^{-1} \) on day 147. The minimum of Dst for this storm was \(-64 \text{ nT}\) on day 147 which was a moderate geomagnetic storm [Loewe and Prölls, 1997]. The maximum values of ap, AE index and HP reached 39, 1111 nT and 58.0 GW, respectively. The MDPR and orbit decay rate

**Figure 1.** F10.7, hourly averaged Bz (nT), hourly averaged solar wind density (\( \text{cm}^{-3} \)) and speed (km/s), Dst, ap, hourly averaged AE (nT), averaged hemispheric auroral power (HP) and atmospheric densities per revolution (MDPR), CHAMP orbit decay rates (ODPR) and geomagnetic activities induced total orbit decays for day 140–153, 2002. ST and OV show the start and the end of the storms.
also increased rapidly and reached maximum values of $\sim 6.6 \times 10^{-12} \text{ kg m}^{-3}$ and 129 m/day from their pre-storm values of $\sim 5.5 \times 10^{-12} \text{ kg m}^{-3}$ and 109 m/day, respectively. 

[15] Unlike the case of Storm 1, in which IMF Bz became steadily northward and AE, HP as well as thermospheric density, recovered rapidly after 0200 UT on day 144, Storm 2 had an oscillating IMF Bz that lasted for several days with high AE and HP values. Thermospheric density also stayed enhanced till day 152. This is related to Alfvenic fluctuations in IMF and high speed streams that followed the CIR interval as discussed by Tsurutani and Gonzalez [1987] and Tsurutani et al. [1995, 2006].

[16] Based on our definition of storm beginning and ending times, the duration of Storm 1 was 1.32 days, and that of Storm 2 was 4.77 days. Storm 2 persisted for a much longer period of time, which produced sustained perturbations to thermospheric densities and, consequently, satellite orbits.

[17] It can be seen that HP, AE, MDPR and ODPR all had similar variations. Two peaks of HP occurred on days 143 and 147 for Storms 1 and 2, respectively. Responding to this geomagnetic activity, two peaks of MDPR and ODPR also occurred on days 143 and 147. The variations of MDPR and ODPR both followed those of HP and AE. This is not a surprise as HP and AE are directly related to auroral activity and thus energy deposition into the upper atmosphere. It is also interesting to note that the variations of orbit decay rates were very similar to those of density variations.

[18] The total changes of orbit mean semi-major axis caused by these two storms in case 1 are then calculated by subtracting the observed variations in the semi-major axis from presumed semi-major axis variations as a result of the drag by the quiet time, background thermosphere. For Storm 1, the storm-induced total variation of the semi-major axis was 32.6 m. For Storm 2, the corresponding variation was 96.5 m, about a factor of 3 larger than that in Storm 1. Storm 1 is evidently stronger, with deeper Dst minimum, stronger auroral activity and larger density changes and bigger orbital decay rates, than Storm 2. However, it lasted a much shorter time. Thus, its cumulated effect on thermospheric density and satellite orbit is less than that of Storm 2. In this case, the total orbit decay caused by a moderate CIR-storm was larger than that by a strong ICME-storm.

3.2. Case 2: Storms on Days 74–96 in 2002

[19] In this case, two CME storms (Storms 3 and 4) and one CIR storm (Storm 5) under the equinox condition (day 74–96, 2002) occurred. The storm classification (i.e., CME or CIR storm) and their onset time are again obtained from the list of Jian [2008]. Solar wind and IMF conditions, geomagnetic indices, auroral hemispheric power and thermospheric density changes during this case are shown in Figure 2, with the same format as that in Figure 1. Solar F$_{10.7}$ flux was steady during first two CME storms, oscillating around 170, whereas during the CIR storm F$_{10.7}$ increased from $\sim$180 to $\sim$220.

[20] Three geomagnetic storms occurred according to Dst. Among them, a weak storm was caused by a CIR event, one weak and one strong storm were caused by ICMEs. The disturbed period was divided into three storms according to the same method as in Case 1.

[21] The first CME event produced a minor storm (Storm 3), during which Dst decreased to the minimum of $\sim 37$ nT on day 78. During the storm, ap, AE and HP increased, with maximum magnitudes of about 50, 600 nT and 49.6 GW, respectively. Thermospheric density per revolution increased from $\sim 5.8 \times 10^{-12} \text{ kg m}^{-3}$ before the storm on day 77 to $\sim 7.5 \times 10^{-12} \text{ kg m}^{-3}$ on day 78. Then it recovered gradually and reached a minimum value of $6.3 \times 10^{-12} \text{ kg m}^{-3}$ in the early morning of day 79, which was still larger than the pre-storm value. This is probably related to the fact that this storm was followed by a moderate disturbed condition on day 79 which, according to Jian [2008], was caused by a very minor CME event. Thus the thermosphere did not have time to fully recover to its pre-storm state, although ap, AE and HP already became very small at the night of day 78 and in the morning of day 79. The ODPR had the similar variations to the thermospheric densities. The ODPR increased from 113 m/day, before the storm on day 77, to $\sim 145$ m/day on day 78. The weak CME event occurring on day 79 only brought a very small disturbance to Dst, which had a minimal value of $\sim 13$ nT. Nevertheless, ap, AE and HP still enhanced noticeably. The thermospheric densities and ODPR also enhanced. They reached the peaks of $6.8 \times 10^{-12} \text{ kg m}^{-3}$ and 133 m/day during this minor event, respectively.

[22] Storm 4 was caused by the CME event that occurred on day 82, which had a longer period of southward IMF conditions than the other two CME storms (Storms 1 and 3). Thus Storm 4 was a strong storm with Dst reaching a minimum value of $\sim 100$ nT on day 83. ap, AE and HP were all enhanced with maximum values of 80 nT, 1025 nT, and 70.5 GW, respectively. This storm also lasted relatively longer (2.5 days) than the other two CME storms and had broader peaks of ap, AE and HP, indicating continuous energy input to the upper atmosphere. Thus there was a large thermospheric density enhancement, from $5.7 \times 10^{-12} \text{ kg m}^{-3}$ before the storm to a peak value of $8.2 \times 10^{-12} \text{ kg m}^{-3}$ during the storm. ODPR increased to the maximum of 167 m/day from the pre-storm value of 113 m/day, ap, AE, HP, MDPR and ODPR, appeared to fully recover to their pre-storm condition at about 0000 UT on day 85, but Dst recovered to its quiet time value on day 86.

[23] In response to the CIR/high speed solar wind stream event starting on day 88, a minor geomagnetic storm occurred between day 88 and 94. Dst increased to $\sim 38$ nT on day 88 and a SSC (sudden storm commencement) occurred. Dst then decreased rapidly to be negative and fluctuated till the midnight of day 94. The minimum value of Dst was $\sim 41$ nT on day 92. During this long disturbed period, ap, AE and HP were all enhanced and reached maximum values of 39 nT, 800 nT and 53.8 GW on day 89. The thermospheric densities and ODPR reached the maximum of $7.0 \times 10^{-12} \text{ kg m}^{-3}$ and 134 m/day on day 89. Then they decreased gradually. ap, AE, HP, MDPR and ODPR remained elevated for almost 6 days during this minor geomagnetic storm.

[24] Storm 3 and Storm 4 were caused by CME events and persisted for about 1.64 and 2.52 days, respectively. Storm 5 was a CIR storm and persisted for 6.13 days. The peaks of AE and HP were larger in Storm 4 than those in the other
storms. The maximum of ODPR in Storm 4 reached 167 m/day, which were also larger than those in the other two storms.

The total variations of satellite orbit altitudes during Storm 3, Storm 4 and Storm 5 were 26.5 m, 70.5 m and 80.7 m, respectively. Storm 3 had a weaker strength and shorter duration, so the total variation of the orbit altitude was also smaller. Though the CME-induced Storm 4 was stronger and brought large thermospheric density enhancements and orbit disturbances, the total orbit decay during that storm, which persisted for a shorter duration, was less than that in Storm 5. The weak CIR-storm in Storm 5 had the longest period and thus led to the largest total orbit decay over the entire storm event.

It is worth noting here that the $F_{10.7}$ value was larger during the Storm 5 period. Enhanced solar EUV radiation might also contribute to the increase of thermospheric density and thus total orbit decay in this period. However, a close examination of the variation of thermospheric density shows that this may not be the case. As shown by the first

**Figure 2.** Same as Figure 1, but for day 74–96, 2002.
and eleventh panels in Figure 2, the enhancement of thermospheric density decreased gradually with time from midday of day 89 as the storm progressed, as compared to the steady increase of $F_{10.7}$ during the same period. In addition, MDPR was even slightly smaller near 0000 UT on day 95 (post-storm) than at 0000 UT on day 89 (pre-storm), suggesting that solar radiation plays an insignificant, if any, role in the observed thermospheric density and satellite orbit variations. In fact, Xu et al. [2011] showed clearly that the effect of changes in solar EUV radiation on thermospheric density and satellite orbit is only significant for periods around a solar rotation or longer.

![Figure 3](image.png)

**Figure 3.** Same as Figure 1, but for day 324–339, 2006.

### 3.3. Case 3: Storms on Days 324–340 in 2006

[27] In this case, we study storm effects under low solar activity conditions. Figure 3 shows the same parameters as Figure 1, but for days 324–340 in the winter of 2006. It can be seen that $F_{10.7}$ was low and varied from 74.6 on day 324 and increased to about 100 on day 339 (first panel). A CIR event occurred in the later morning of day 327 and the IMF $B_z$ component oscillated between southward and northward till the morning of day 333. Responding to this CIR/high solar wind stream event, a weak geomagnetic storm (Storm 6) occurred on day 327 and the minimum value of
Dst was only $-31$ nT. However, its duration was very long and AE, $ap$ and Dst did not recover to their pre-storm, quiet time values even on day 333 when a CME event occurred. This CME event produced a moderate storm (Storm 7) with Dst decreasing from positive to $-71$ nT at 1200 UT on day 334.

During Storm 6, $ap$, AE and HP increased rapidly in the early phase of the storm, then oscillated during the entire period of the storm. MDPR increased to a peak value of $\sim2.8 \times 10^{-12}$ kg m$^{-3}$ in the early morning of day 328 from a pre-storm value of $\sim2.0 \times 10^{-12}$ kg m$^{-3}$. Then it decreased gradually to $\sim2.1 \times 10^{-12}$ kg m$^{-3}$ on day 333, but didn’t recover to its quiet time value because its recovery was interrupted by Storm 7. ODPR was enhanced from 34 m/day in the early morning of day 327 to a maximum of 51 m/day on day 328. Then it decreased on day 333 to 42 m/day, which was also larger than its pre-storm value. During the latter part of the storm, the enhancements of AE, $ap$ and HP were much larger than those in Storm 6. The atmospheric density per revolution was enhanced to a peak value of $\sim3.7 \times 10^{-12}$ kg m$^{-3}$ in the afternoon of day 334. Then it decreased gradually to $\sim2.3 \times 10^{-12}$ kg m$^{-3}$ in the afternoon of day 335, which was close to the pre-storm value of about $2.1 \times 10^{-12}$ kg m$^{-3}$. The ODPR increased to 79 m/day from 42 m/day. Then it decreased to 48 m/day in the afternoon of day 335.

Comparing thermospheric densities at midday on day 326 and day 338, which were both quiet, MDPR increased from about $1.8 \times 10^{-12}$ kg m$^{-3}$ to $2.0 \times 10^{-12}$ kg m$^{-3}$, or by about 11%. This increase in density was probably caused directly by changes in solar EUV radiation, although HP and AE were still higher on day 338 than on day 326. The $F_{10.7}$ values on days 326 and 338 were 75 and 95, respectively. The difference between the two was about 27%. Thus, thermospheric density variation caused by solar EUV was most likely a minor factor, compared with the storm caused by geomagnetic storms. This is also consistent with our conclusion in Case 2.

From Figure 3, it can be seen that HP, MDPR and ODPR have similar variations. Two peaks of HP occurred on day 327 and day 334, respectively. Two peaks of MDPR occurred in the early morning of day 328 and the afternoon of day 334, respectively. Two peaks of ODPR for Storms 6 and 7 occurred nearly at the same time, when MDPR reached maximum. The peaks of HP, MDPR and ODPR in Storm 7 were larger than those in Storm 6. The times when the two peaks appeared were very close to those for MDPR. The variations of ODPR and MDPR both followed those of HP.

During Storm 6 and Storm 7, the total variation of CHAMP orbit altitude was 38.0 and 36.7 m, respectively. The geomagnetic disturbance and thermospheric density variation during Storm 6 were caused by the CIR event on day 327, and those during Storm 7 were caused by the CME event on day 334. The latter geomagnetic storm was much stronger than the former, and the maximum of thermospheric density enhancement was also larger. But the durations of the former event and its associated thermospheric density perturbations were much longer. The total orbit decay caused by the CIR-storm was roughly the same as that caused by the CME-storm, although the peak value of orbit decay rates during the CME-storm was again higher than that during the CIR-storm.

### 4. Discussion

The change of mean semi-major axis $\bar{a}$ is caused by thermospheric drag that is proportional to thermospheric density $\rho$. This density can be thought of having two components. The first one is the background thermosphere density $\rho_b$ and the other is the storm-induced thermospheric density $\rho - \rho_b$. The total variation of satellite orbit heights (semi-major axis) are caused by the storm effect ($d\bar{a}_{\text{storm}}$) and the background effect ($d\bar{a}_{\text{b}}$):

$$\frac{d\bar{a}}{dt} = \frac{d\bar{a}_{\text{b}} + d\bar{a}_{\text{storm}}}{dt} = -C_D\frac{A}{m}\sqrt{GM\bar{a}}(\rho + \rho_b - \rho_b)$$

where $C_D$ is the drag coefficient, $m$ is the satellite mass, $M$ is the mass of the Earth, $G$ is the gravitation constant and $A$ is the surface area of the satellite.

Equation (1) indicates that the time derivative of the satellite orbit (semi-major axis) is correlated with $\rho$ and $\bar{a}$. The area to mass ratio of CHAMP with an elongated shape is $0.00138$ m$^2$/kg. $\bar{a}$ can be regarded as a constant for a short period of time (a few months) since $\bar{a}$ is more than 6700 km and the decay rate is about 0.1 km per day. As a result, $d\bar{a}/dt$ for CHAMP is determined mainly by thermospheric densities that can change by 20% to more than a factor of two during storms (c.f. Figures 1–3) [Prößl, 1980]. Then the total variation of the satellite orbit during the entire period of a storm is described by

$$\Delta \bar{a} = \Delta \bar{a}_{\text{b}} + \Delta \bar{a}_{\text{storm}} = -C_D\frac{A}{m}\sqrt{GM\bar{a}}\left(\int \rho_b dt + \int (\rho - \rho_b) dt\right)$$

Thus the total variations of the satellite orbit induced by geomagnetic storms can be expressed by

$$\Delta \bar{a}_{\text{storm}} = -C_D\frac{A}{m}\sqrt{GM\bar{a}}\int (\rho - \rho_b) dt$$

In section 3, 7 geomagnetic disturbance events in 3 cases under different solar activity conditions are examined to investigate their effects on thermospheric densities and satellite orbits. These geomagnetic disturbances are separated into two categories: CME storms (Storms 1, 3, 4 and 7) in which their strengths were strong but their duration were short; and CIR storms (Storms 2, 4 and 6) in which their strengths were weak, but their duration were long. In every case, the storms of different types occurred successively. The total time periods of the three cases examined in the paper is limited to less than three weeks, thus the effects of long-term variations, such as seasonal variations, and satellite precession (local time change) are mostly excluded from our analysis. The influences of the 27 day variations caused by solar rotation were insignificant and negligible comparing to those by geomagnetic storms.

A good correlation between thermospheric densities and CHAMP orbit decay rates can be seen from the results in the three cases (Figure 4). The linear correlation coefficients reached 0.96, 0.95 and 0.94, respectively. ODPR had good
correlations with AP, AE and HP. But the variations of ODPR lagged behind AE and HP. In the three cases, the correlation coefficients between HP and ODPR were about 0.70, 0.70 and 0.68 (c.f. Figure 4), respectively, with a time delay of 3–6 h.

Table 1 gives a summary of the parameters examined in this paper during these storms. For the four CME-storms, two were strong geomagnetic storms (Storms 1 and 4), one was moderate (Storm 7), and the other one was weak (Storm 3). For the three CIR-storms, one was moderate (Storm 2) and two were weak (Storms 5 and 6). The geomagnetic storms caused by the CMEs were, in general, stronger than those caused by the CIRs in this study. The peaks of hemispheric auroral power (HP) during the four CME-storms were 90.9 GW, 49.6 GW, 70.5 GW and 121.0 GW respectively. The maximum of MDPR during these storms were $7.77 \times 10^{-12}$ kg m$^{-3}$, $7.48 \times 10^{-12}$ kg m$^{-3}$, $8.19 \times 10^{-12}$ kg m$^{-3}$ and $3.65 \times 10^{-12}$ kg m$^{-3}$, respectively. The maximum of satellite orbit decay rates were 148 m/day, 145 m/day, 167 m/day and 79 m/day. The peaks of HP during the three CIR-storms were 58.0 GW, 53.8 GW, and 62.1 GW, respectively. The maximum of MDPR during the CIR-storms were $6.61 \times 10^{-12}$ kg m$^{-3}$, $7.02 \times 10^{-12}$ kg m$^{-3}$ and $2.80 \times 10^{-12}$ kg cm$^{-3}$. Correspondingly, the maximum of ODPR were 129 m/day, 134 m/day and 51 m/day, respectively.

Thus, peak auroral energy inputs, thermospheric density changes and satellite orbit decay rates during CME-storms, with the exception of the weak Storm 3, were all larger than those during CIR-storms in each case. However, the total storm effects on thermospheric density and satellite orbit depend not only on the strength of a particular storm, but also on its duration. During the four CME-storms studied, the durations of Storms 1, 3, 4 and 7 were 1.32, 1.64, 2.52 and 2.48 days, respectively. These durations were much shorter than the CIR-storms in each case, which were 4.77, 6.13 and 5.65 days for Storms 2, 5 and 6, respectively. The total variations of orbit altitude in response to the four CME-storms were 32.6 m, 26.5 m, 70.5 m and 36.7 m, whereas the total variations of orbit altitudes caused by the three CIR-storms were 96.5 m, 80.7 m and 38.0 m, respectively. The integrated effect on thermospheric density and satellite orbit decay rates during the CME-storms were thus stronger than those of CME-storms in each case, even though the peak changes in thermospheric density and orbit decay rates during the CME-storms were larger.

Now we examine the correlation between total orbit decay and total auroral energy deposition into the upper atmosphere, $\int (\Delta HP) dt$, where $\Delta HP$ is the difference between HP during the disturbed period and the mean value for the pre- and post-storm periods. During the four CME-storm events, $\int (\Delta HP) dt$ in Storms 1, 3, 4 and 7 were $1.42 \times 10^{15}$ J, $1.61 \times 10^{15}$ J, $4.25 \times 10^{15}$ J and $4.07 \times 10^{15}$ J, respectively. During the three CIR-storms, $\int (\Delta HP) dt$ were $4.34 \times 10^{15}$ J, $7.34 \times 10^{15}$ J and $8.37 \times 10^{15}$ J for Storms 2, 5, and 6, respectively. Thus total hemispheric auroral energies induced by the CIR-storms were larger than those induced by the CME-storms in each case, even though the latter geomagnetic storms were stronger. From the total variations of orbit altitudes and the auroral energies in the three cases above, it can be seen that the total orbit decay effects were related to the total auroral energies during the geomagnetic storms. This is understandable since thermospheric density variations are the result of energy deposition into the upper atmosphere, thus total satellite orbit decay is related to the total energy deposited into the thermosphere/ionosphere system during a storm. Note that the total auroral energy deposition is only an approximation to the total energy deposited by precipitating electrons, in which the global Poynting flux is not included. Since Joule heating and auroral energy is closely correlated [Weimer et al., 2011, and references therein], although there is not a fixed relationship between them, auroral energy inputs can be used as a proxy for total magnetospheric energy inputs to the thermosphere and ionosphere system, as global Joule heating is still difficult to measure.

Figure 4. Correlation coefficients between (left) MDPR and ODPR and (right) HP and ODPR.
thermospheric density and satellite orbit of geomagnetic disturbances are determined by not only the storm strength, but also by the storm duration. During low solar activity condition, there are less CME events, but very frequent and periodic CIR/high speed stream events. Thus the effects of CIR storms are relatively more important under these conditions.

[41] We also found that the total orbital decays during a geomagnetic storm were correlated with the total auroral energy input, which is an indicator of the total energy that is deposited into the thermosphere/ionosphere during the entire period of a storm.

Appendix A

[42] For a two-body motion problem, the semi-major axis $a$ of the satellite orbit is defined as

$$a = -\frac{\mu}{2E_T} \tag{A1}$$

where $\mu$ is a gravitational parameter, and $E_T$ is the specific mechanical energy which is the sum of kinetic energy $E_k$ and central potential energy of the Earth ($U_{cf}$) as a mass point [Battin, 1999]. For a two-body problem, $E_T$ is

$$E_T = E_k + U_{cf} = \frac{v^2}{2} - \frac{\mu}{r} \tag{A2}$$

where $v$ is the velocity of the satellite, and $r$ is the distance between the satellite orbit and the earth center. For a two-body problem, $a$ changes only with the specific mechanical energy, thus it is extensively used in the satellite orbit determination, instead of the real distance $r$ between the satellite orbit and the earth center. In this study, we use the semi-major axis $a$ to study the storm induced effect on the orbit.

[43] Since $E_T$ is not the actual total mechanical energy of the satellite, the value of the semi-major axis $a$ calculated by equation (A1) changes also with location. To study the storm induced effect on the orbit, this fluctuation of $a$ (see dashed line in Figure A1) has to be removed. Considering that the Earth non-spherical potential and centrifugal potential, the total specific mechanical energy of CHAMP is calculated by

$$E' = E_T + U_n + U_{cf} - C \tag{A3}$$

Where $U_n$ is the disturbed potential caused by the non-spherical shape of the Earth, which varies with latitude and longitude [see Battin, 1999]. $U_{cf}$ is the centrifugal potential, which changes also associated with latitude and longitude. $C$ is the mean of $U_n + U_{cf}$ between 2002 and 2006. $U_n$ is calculated according to the EIGEN-3p gravity field model [Reigber et al., 2005], and $U_{cf}$ is given by Jekeli [1999].

[44] Here we define the mean value of $a$

$$\bar{a} = -\frac{\mu}{2E'} = -\frac{\mu}{2(E_T + U_n + U_{cf} - C)} \tag{A4}$$

Thus most of the fluctuations caused by non-spherical gravity and centrifugal potential are removed in $\bar{a}$ (see solid line in Figure A1).
Acknowledgments. This work is supported by the Chinese Academy of Sciences (KZZD-EW-01-2), the National Natural Science Foundation of China (41104098, 41004062, 40921065, 41174139), China Postdoctoral Science foundation (20100481450, 201104790X, the National Important basic Research Project of China (2011CB811405), and the Specialized Research Fund for State Key Key Laboratory. This research is also supported in part by the Center for Integrated Space Weather Modeling (CISM), which is funded by the STC program under agreement ATM-0120950. National Center for Atmospheric Research is sponsored by the National Science Foundation. J. Lei was supported by National Natural Science Foundation of China 41174139 and Thousand Young Talents Program of China. The atmospheric densities data of CHAMP used in this study were obtained from http://sise.colorado.edu/sutton/data.html. The CHAMP orbit data were obtained from GeoForschungsZentrum Informations Systems and Data Center. We also acknowledge the CEDAR data based at the National Center for Atmospheric Research (NCAR) for providing the auroral hemispheric power data used in this study.

Philippa Browning thanks the reviewers for their assistance in evaluating this paper.

References


