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Key Points:

- Shock-induced auroral intensification excited large-scale gravity waves
- Waves from the northern and southern auroral regions constructively interfered
- Constructive interference caused 60% nightside equatorial density enhancements

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Constructive interference of large-scale gravity waves excited by interplanetary shock on 29 October 2003: CHAMP observation

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Abstract In this paper we report the detection of full constructive interference between two large-scale gravity waves in the upper thermosphere from the CHAMP accelerometer measurements. The two waves are separately excited in northern and southern auroral regions by the shock-induced auroral intensification on 29 October 2003. They propagate equatorward and encounter near the equator, where constructive interference occurs and causes nightside equatorial neutral density enhancements of ~60%. This result demonstrates that the constructive interference can be a potential mechanism for large density increases in the equatorial region during magnetically active periods.

1. Introduction

Gravity waves are prevalent in the polar region of the thermosphere and can be excited by impulsively enhanced Lorentz force of auroral electrojet currents and heat input due to Joule heating and particle precipitation in the high-latitude thermosphere [e.g., *Yeh and Liu*, 1974; *Richmond*, 1978, 1979; *Mayr et al.*, 1990; *Hocke and Schlegel*, 1996]. The observed gravity waves are generally categorized into two groups according to their horizontal wavelengths, namely, small-to-medium scale (less than 1000 km) and large scale (1000–4000 km). The small-to-medium-scale waves are easily dampened by physical processes including ion drag, molecular viscosity, and thermal conduction and thus are mainly confined to middle to high latitudes [*Richmond*, 1978; *Bruinsma and Forbes*, 2010]. On the other hand, the large-scale waves are weakly dissipated owing to their large wavelengths and thus can propagate to large distances away from the source [*Mayr et al.*, 1990; *Bruinsma and Forbes*, 2010]. This indicates that the large-scale waves represent an important energy transfer mechanism. Together with large-scale circulation, they can transfer momentum and energy from high latitudes to low latitudes during magnetically active periods [*Richmond*, 1979; *Fujiwara et al.*, 1996; *Gardner and Schunk*, 2010; *Qian et al.*, 2012]. For this reason, they have received considerable attention in previous observational and numerical studies [e.g., *Mayr et al.*, 1990; *Forbes et al.*, 1995; *Balthazor and Moffett*, 1999; *Fujiwara and Miyoshi*, 2006; *Bruinsma and Forbes*, 2010].

The large-scale waves propagate quasi-horizontally both toward the poles and toward the equator with a ring-like longitudinal extension [*Bruinsma and Forbes*, 2010]. It is generally believed that the equatorward propagating waves from the northern and southern auroral regions can encounter near the equator and interfere either constructively or destructively, depending on the phase relations between these two sets of waves. In principle, when the phase difference is a multiple of 2π, full constructive interference occurs and the magnitude of the displacement is the sum of the individual magnitudes, whereas when the difference is an odd multiple of π, full destructive interference occurs and the magnitude of the displacement is equal to the difference in the individual magnitudes. If the difference is intermediate between these two extremes, the magnitude of the displacement lies between the minimum and maximum values. Modeling evidence for constructive and destructive interference of large-scale waves in the thermosphere have been provided in many studies [e.g., *Fujiwara et al.*, 1996; *Gardner and Schunk*, 2010]. However, convincing observational evidence has been rarely reported, owing to the limited temporal and/or spatial resolution of ground-based and satellite observations [*Mayr et al.*, 1990; *Forbes et al.*, 1995]. Recently, *Bruinsma and Forbes* [2010] found that wave-like structures or traveling atmospheric disturbances (TADs) as manifestations of

Table 1. The Dates for Large-Scale Gravity Waves Identified in CHAMP Data (1 January 2001 to 31 August 2010) and the Corresponding Local Time of the Orbit Plane

ID	Date	SLT (Dayside)	SLT (Nightside)
1	2001/3/27–28	15.3	3.3
2	2001/4/11–12	13.9	1.9
3	2001/4/13	13.8	1.8
4	2001/4/28	12.5	0.5
5	2001/8/17–18	14.3	2.3
6	2001/9/25–26	10.8	22.8
7	2001/10/21–22	8.4	20.4
8	2001/11/5–6	7.0	19.0
9	2001/11/24	17.3	5.3
10	2001/12/24	14.6	invisible
11	2002/3/30	invisible	5.9
12	2002/4/23	15.7	invisible
13	2002/5/23	12.9	0.9
14	2002/8/19	16.9	4.9
15	2002/9/30	13.0	1.0
16	2002/10/16	11.6	23.6
17	2002/11/19–20	8.4	20.4
18	2003/2/4	invisible	1.5
19	2003/5/29–30	15.0	3.0
20	2003/7/29–30	9.4	21.4
21	2003/8/17–18	7.7	19.7
22	2003/10/29	13.1	1.1
23	2003/10/30	12.9	0.9
24	2003/11/4	12.5	0.5
25	2003/11/6–7	12.3	0.3
26	2003/11/9	12.0	0.0
27	2003/11/11	11.9	23.9
28	2003/11/15	11.5	23.5
29	2003/11/20	11.1	23.1
30	2004/1/22	17.3	5.3
31	2004/3/9–10	12.9	0.9
32	2004/5/20	6.3	18.3
33	2004/6/15	16.0	4.0
34	2004/7/22–23	invisible	0.5
35	2004/9/13–14	7.6	19.6
36	2004/11/7–8	14.6	2.6
37	2005/1/7–8	9.0	21.0
38	2005/1/17–18	8.0	20.0
39	2005/1/21–22	7.7	19.7
40	2005/2/18	invisible	5.1
41	2005/5/15	9.3	21.3
42	2005/6/14	6.4	18.4
43	2005/8/13	13.0	1.0
44	2005/8/24	12.0	0.0
45	2006/7/14	invisible	18.0
46	2006/12/15	15.9	3.9
47	2007/3/11–12	7.9	19.9
48	2007/3/25	invisible	18.7
49	2008/3/26	6.7	20.7
50	2008/5/5–6	invisible	5.0
51	2010/8/24	invisible	2.3

large-scale waves can occasionally be monitored from a space-based platform with orbital period (i.e., temporal resolution) of approximately 80–100 min, although it is very difficult to unambiguously track individual waves over large distances. This implies that it should be possible to find out the evidence of full constructive interference from in situ satellite measurements, such as the CHAMP satellite (with orbital period of 93 min). Motivated by this implication, we examined densities near 400 km derived from accelerometer measurements on CHAMP for the period 1 January 2001 through 31 August 2010 and identified 51 large-scale gravity wave events in which the waves propagated down to the equator or beyond (It should be mentioned that the greater relative density perturbations during the solar minimum period (2006–2010) make it more difficult to identify large-scale gravity waves over large distances, and thus, we might have missed some events.). The 51 events are listed in Table 1, where the four columns present the event reference number, the date when the waves are detected, the corresponding local time of the orbit plane at the equator on the dayside, and that on the nightside. Among the 51 events, we successfully identified one, and only one, full constructive interference event, which is associated with interplanetary shock on 29 October 2003. To our best knowledge, this event provides the first unambiguous evidence of full constructive interference in the upper thermosphere. This paper will give a report of this event.

2. CHAMP Data

The CHAMP satellite was launched into a near-circular orbit with an inclination of 87.3° and an initial altitude of 456 km on 15 July 2000. The high inclination ensures almost complete latitudinal coverage, whereas all local times are sampled approximately every 130 days. The triaxial accelerometer on board provides high-resolution (0.1 Hz sampling rate; 80 km in track) measurements, which yield estimates of thermospheric mass density with accuracy of about 6×10^{-14} kg m^{-3}. Details of the derivation procedure and related errors are given by *Liu et al.* [2005]. In the present study, all density data are normalized to a constant altitude of 400 km as described in *Guo et al.* [2007].

3. Observations

The Halloween storms are a series of three storms occurring between 29 and 31 October 2003, associated with two coronal mass ejections (CMEs), with the first on 28 October and the second on 29 October. This

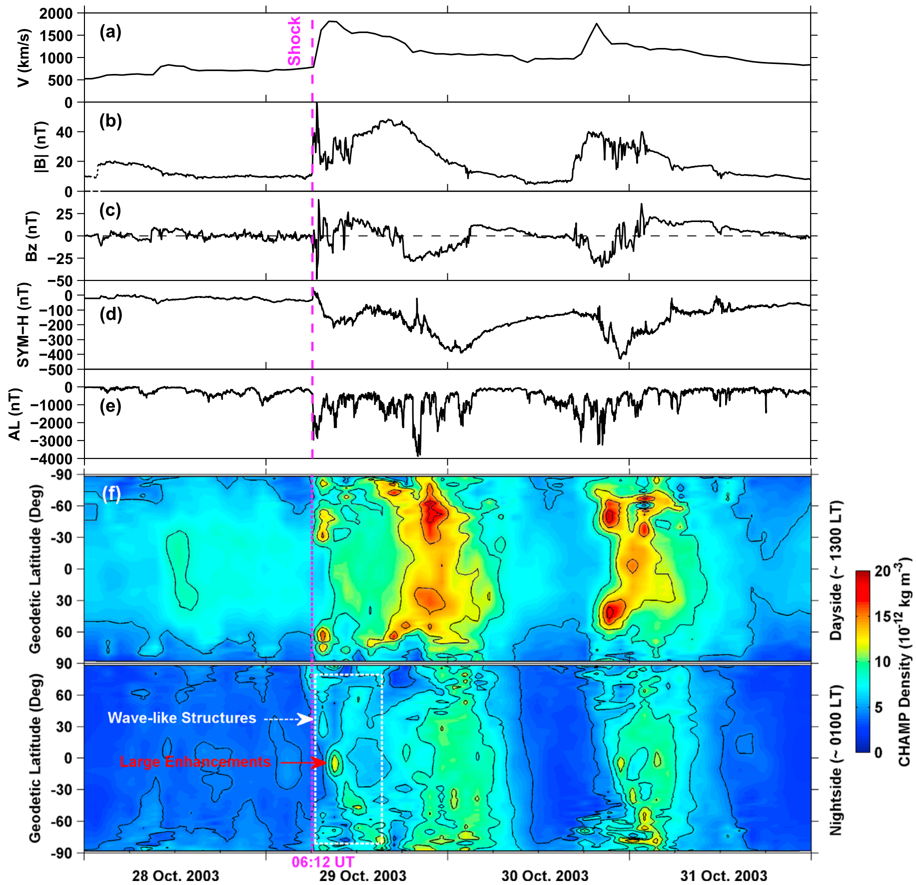

Figure 1. Variations of (a) solar wind velocity *V*, (b) interplanetary magnetic field intensity |*B*|, (c) southward magnetic field *Bz*, (d) *SYM-H* index, (e) *AL* index, and (f) CHAMP neutral density at 400 km and near 1300 LT (top; latitude axes in reversed order) and 0100 LT (bottom) during 28–31 October 2003. The interplanetary parameters are observed by ACE and shifted 15 min. The vertical dashed line indicates the shock of interest, at 0612 UT on 29 October. The white rectangle marks the wave-like structures. The arrow marks the large enhancements exhibited in the wave-like structures.

occurred during a longer period of intense activity on the Sun [*Skoug et al.*, 2004]. Figures 1a–1e show the time series of the solar wind speed *V*, the magnitude of interplanetary magnetic field |*B*|, and its north-south component *Bz* measured from the ACE spacecraft (time shifted), as well as the symmetric current index *SYM-H* and the westward auroral electrojet index *AL* during 28–31 October 2003. The shock induced by the first CME is of interest in this paper. It occurred at 0612 UT on 29 October, as indicated by the vertical dashed line. When it encountered the Earth, the geomagnetic field was strongly compressed producing a sudden storm commencement (SSC), which can be clearly seen in the *SYM-H* index. Shortly after the SSC, the westward electrojet increased significantly ($AL < -2000$ nT) due to shock-induced aurora intensification [*Yamauchi et al.*, 2006]. The shock-induced aurora activity (often termed as *shock auroral* [*Zhou et al.*, 2003]) was observed by the IMAGE satellite (not shown here). Sudden increases in Lorentz force of auroral electrojet currents and energy deposition (mostly in the form of Joule heating) due to aurora intensification have the potential to excite gravity waves. Indeed, large-scale traveling ionospheric disturbances, as manifestations of large-scale gravity waves, were detected in different longitude sectors [*Ding et al.*, 2007; *Afraimovich et al.*, 2008]. Herein we further examine the CHAMP density for the propagation features of large-scale gravity waves in the thermosphere.

Figure 1f illustrates the measured densities on the dayside (~1300 LT) and nightside (~0100 LT) during 28–31 October 2003. Obviously, thermospheric densities at high latitudes were significantly enhanced in response to the shock-induced auroral intensification on 29 October, particularly on the dayside, as reported in [*Liu and Lühr*, 2005]. Then wave-like structures appeared as expected. These structures are very evident on the nightside, but not clearly visible on the dayside, which might be due to the elevated effects of ion

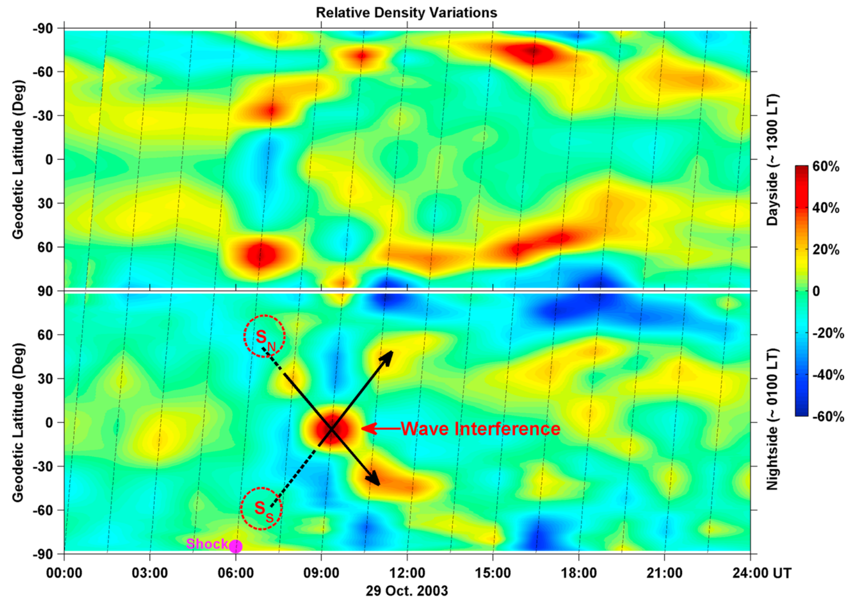

Figure 2. Latitude versus time variations of the filtered relative density at 400 km and near 1300 LT (top; latitude axes in reversed order) and 0100 LT (bottom) on 29 October 2003. The parallel dashed lines represent the orbital track of the CHAMP satellite. The measurements are confined to the orbital tracks, and the interorbital density structures arise from linear interpolation. The magenta dot marks shock arrival time. The black arrows show a pair of large-scale waves propagating from the northern and southern auroral sources (S_N and S_S) to the equator and into the opposite hemisphere on the nightside (see the details in the text).

drag [*Richmond*, 1979; *Balthazor and Moffett*, 1999; *Bruinsma and Forbes*, 2010]. It is interesting to note that at around 0940 UT, nearly 3.5 h after the shock arrival, the nightside wave-like structures exhibit unusual large enhancements in the equatorial region, which are even larger than the nightside equatorial density enhancements during the following two superstorms. As discussed later, they are a direct consequence of constructive interference between two large-scale waves.

4. Analysis and Discussion

In order to elucidate the characteristics of large-scale TADs observed on 29 October 2003, we adopt the method given in *Bruinsma and Forbes* [2007] to compute 25- and 151-point (250 and 1510 s, corresponding to scales of approximately 2000 and 11900 km, respectively) running means along the orbit and then subtract these two trends. This processing effectively extracts scales from 1000 through 5900 km. Then we calculate the relative density variation as the residual-to-(151-point) trend ratio. The results are displayed in Figure 2. Note that the CHAMP measurements are confined to the orbital tracks that represented by the parallel dashed lines. The interorbital density structures are a result of linear interpolation, which will help us on the identification of gravity wave propagation.

By following maxima from high to low latitudes and further to the opposite hemisphere, we identify a pair of propagating large-scale waves on the nightside, which are indicated by the arrows. *Perevalova et al.* [2008] showed that the waves were generated in the auroral zone. Therefore, it is reasonable to assume that the two waves were separately launched out of the northern and southern auroral sources (S_N and S_S) and excited by the shock-induced auroral intensification on 29 October. The wave fronts were not detected by CHAMP in the source regions of both hemispheres (hence represented by the dashed lines), owing to its limited temporal sampling. The two waves propagated equatorward and encountered near the equator, where wave interference occurred, resulting in ∼60% nightside equatorial density enhancements. The magnitudes of these enhancements are almost the sum of the amplitudes of the individual waves that are on the order of 20–30% (observed at midlatitudes), considering that the maximum amplitudes might be undetected by CHAMP. This strongly suggests that the two waves constructively interfered near the equator. After the constructive interference, they passed through each other and penetrated into the opposite hemisphere. The possible scenario for the two gravity waves generation, propagation, and interference in the

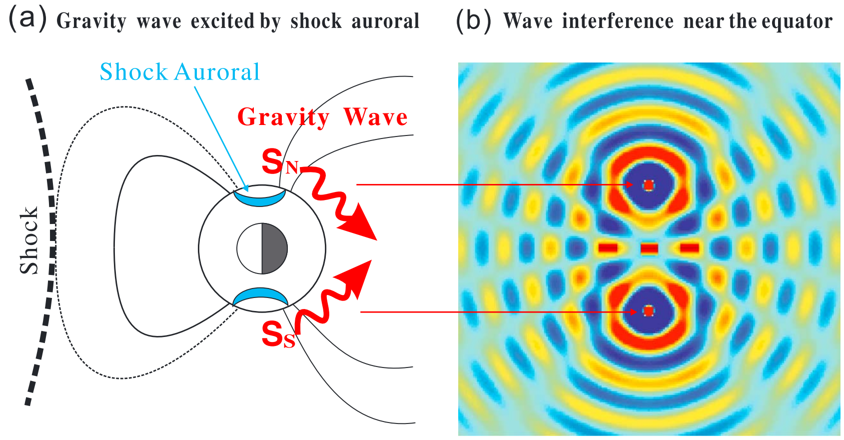

Figure 3. Schematic diagram showing (a) thermospheric gravity waves excited by shock-induced aurora intensification; (b) large-scale waves propagating away from auroral sources in the horizontal directions and constructively interfering near the equator.

upper thermosphere is illustrated in Figure 3. It should be noted that this figure describes only the ideal propagation of gravity waves without dissipation. In reality, there is significantly larger dissipation on the dayside than on the nightside, due to larger ion drag and poleward meridional wind.

This full constructive interference event demonstrates that (1) the constructive interference between waves could be an important mechanism to explain the observed large density increases in the equatorial region during magnetically active periods [*Prölss*, 1982; *Burns and Killeen*, 1992] and that (2) the observed magnitudes of the wave amplitudes might not be directly related to the power of wave excitation because of wave interference. This is important for our understanding of gravity wave amplitudes that are often poorly correlated with the geomagnetic index as reported in the prior studies [e.g., *Mayr et al.*, 1990; *Bruinsma and Forbes*, 2010].

5. Conclusion

We have presented observational evidence for full constructive interference between two large-scale gravity waves in the upper thermosphere from the CHAMP accelerometer measurements. The two waves are separately excited in northern and southern auroral regions by the shock-induced auroral intensification on 29 October 2003. They propagate equatorward and constructively interfere near the equator, resulting in ∼60% nightside equatorial neutral density enhancements. This work confirms that the full constructive interference between gravity waves can be a potential mechanism to explain large density enhancements in the equatorial region during magnetically active periods. Consequently, it poses a challenge to thermospheric density modeling and satellite drag predictions.

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