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F2-region atmospheric gravity waves due to high-power HF heating and subauroral polarization streams

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[1] We report the first evidence of atmospheric gravity waves (AGWs) generated in the F2 region by high-power HF heating and subauroral polarization streams. Data come from the CHAMP and GRACE spacecraft overflying the High-frequency Active Auroral Research Program (HAARP) heating facility. These observations facilitate a new method of studying the ionosphere-thermosphere coupling in a controlled fashion by using various HF-heating regimes. They also reveal the subauroral F2 region to be a significant source of substorm AGWs, in addition to the well-known auroral E region. Citation: Mishin, E., E. Sutton, G. Milikh, I. Galkin, C. Roth, and M. Förster (2012), F2-region atmospheric gravity waves due to high-power HF heating and subauroral polarization streams, Geophys. Res. Lett., 39, L11101, doi:10.1029/2012GL052004.

1. Introduction

[2] The energy released during geomagnetic (sub)storms is ultimately dissipated in the thermosphere. One of the major indicators of the thermospheric response is generation of atmospheric gravity waves. Since the neutral gas density $N$ is much greater than the plasma density $n$, it is conventionally assumed that the thermosphere responds in $\lesssim 30$ min. However, some observations reveal faster response times [e.g., Williams et al., 1993; Aruliah et al., 2005]. Milikh et al.’s [1993] simulations show that a $0.2$-V/m, 10-min saw-tooth electric pulse produces plasma upflows $U_i \approx 100$ m/s and vertical winds $U_w \approx U_i$ near the F2-layer peak at 300 km. In $\approx 5$ min the thermosphere swelled by one atmosphere scale height. Then, the swelling propagated away and ceased, overall resembling substorm AGW surges [e.g., Hocke and Schlegel, 1996].

[3] Subauroral polarization streams (SAPS), i.e., structured flows of enhanced plasma convection equatorward of the auroral boundary, quickly develop during substorms [e.g., Mishin and Burke, 2005]. Wang et al. [2011] found that the mass density at altitudes $h \approx 400$ km enhances within SAPS on average by $\approx 10\%$ with respect to that without SAPS. This indicates efficient thermospheric heating by ion neutral friction in the F2 region within SAPS. Understanding the development of the thermospheric response in space and time requires coordinated observations of neutral gas, ionospheric plasma, electromagnetic fields, and particle precipitations. This is a formidable task for dynamic localized natural phenomena.

[4] On the other hand, plasma upflows $U_i \approx 100$–300 m/s are routinely produced by high-power high frequency (HF) radio waves injected into the F2-region ionosphere [e.g., Rietveld et al., 2003; Milikh et al., 2008, 2010; Kosch et al., 2010]. Given strong F2-region ionosphere perturbations, it seems worthwhile to explore the thermosphere’s response to high-power HF injections. The objectives of this paper are twofold. First, we report on novel observations of HF-induced AGWs in the F2-region during the October 2008 and August 2011 heating campaigns at the High-frequency Active Auroral Research Program (HAARP) facility (http://www.haarp.alaska.edu/gen.html). We also found substorm SAPS-generated AGWs, in addition to the auroral source. Data come from the CHAllenging Minisatellite Payload (CHAMP) [Reigber et al., 2002] and twin Gravity Recovery And Climate Experiment (GRACE) [Tapley et al., 2004] satellites.

2. Observations

[5] During the campaigns, $O$-mode waves were transmitted toward the HAARP magnetic zenith (MZ) at full power 3.6 MW (the effective radiative power ERP = 450–650 MW) with either 0.5 Hz or 5 Hz 50% square modulation. The F2-peak plasma frequency exceeded the heating frequency $f_0$ by $\geq 0.5$ MHz, ensuring HF beam-ionosphere interaction near 220–240 km [e.g., Mishin et al., 2005]. There have been two CHAMP/HAARP (CH1 and CH2) and two GRACE/HAARP (GH1 and GH2) experiments in October 2008 and August 2011, respectively. Table 1 lists their dates, $f_0$(MHz)/ERP (in MW), heater-on periods, UT-time $T_{mz}$ of the satellite closest approach to MZ at the geographic longitude $\approx 214.1^\circ$E and latitude $\text{Lat}_{mz}$ (see Table 1), and geomagnetic activity. The latter was checked using data from the WDC for Geomagnetism, Kyoto and the University of Alaska GIMA magnetometer array. We note exceptionally quiet conditions prior to and during the CH1 and GH2 experiments. To compare with CH1 and GH2, we selected overflights close in $T_{mz}$ and distance from Lat$_{mz}$ without HF heating during quiet ($q$) and disturbed ($d$) times. They are listed in Table 1 as $Xq$ and $Xd$, where $X$ stands for CHAMP or GRACE and $i = 1, 2, 3$. 

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Thermospheric mass densities $\rho = M \cdot N$ ($M$ is the average mass of neutral constituents) at CHAMP altitudes $h \approx 330$ were inferred from the STAR accelerometer data obtained at 0.1-Hz sampling rate (the Nyquist frequency $f_N = 0.05$ Hz) [e.g., Sutton et al., 2005; Sutton, 2009]. Figure 1 shows mass densities $\rho$, their trends $\rho_{tr}$, and relative residuals $\rho_{tr} - 1$ vs. UT-$T_{mz}$ during the CHAMP overflights $CH1$, $Cq1$, and $CH2$. Here $\rho_{tr}$ is obtained by a simple polynomial fit within $\pm 180$ s about $T_{mz}$. Figure 2 shows filtered mass densities $\rho_{\lambda}$ vs. UT-$T_{mz}$, power spectral densities (PSD) of $\rho_{tr}$ in the interval $57^\circ \leq GLat \leq 67^\circ$, and GLat-$\lambda$ color spectrograms. The auroral boundaries are found by inspecting the AFRL/DMSP database.

It is assumed that the satellite is sampling the spatial, rather than the temporal variations of the neutral density, so $\lambda = \nu_{sat}/f$ ($\nu_{sat} = 8$ km/s) are wavelengths along the satellite track and $f$ are apparent frequencies. This requires the actual wave period $T_{\lambda} \gg 1/f$, which holds for $\lambda < 2000$ km at $T_{\lambda} \sim T_{BV}$. Here $T_{BV} \approx 13$ (18) min at $h = 350$ (500) km is the Brunt-Väisälä (BV) cutoff (the waves at $T_{\lambda} \leq T_{BV}$ are buoyancy waves). To obtain $\rho_{N}$, we applied a passband filter preserving oscillations in the range $200 \leq \lambda < 2000$ km. PSD and spectrograms are obtained by using a standard FFT of $\rho_{tr}$ and complex morlet wavelet decomposition of the measured time series of $\rho_{tr}$, respectively.

The twin satellites GRACE $A$ and $B$ with the SuperSTAR accelerometer, which is an order of magnitude more precise than CHAMP/STAR, flew approximately 25 s apart in a near-circular orbit at $h \approx 470$ km. To maintain the line-of-sight between the satellites, hundreds of micro-thrusts per day are performed. Fortunately, during all listed overflights maneuvers had occurred either well before or after $T_{mz}$ and thus not affected the results. We explore neutral mass densities $\rho$ inferred from 1-Hz accelerometer measurements and sampled at a frequency of 0.2-Hz ($f_N = 0.1$ Hz) corresponding to the available satellite attitude data. We present only data from GRACE $A$, for GRACE $B$ gives virtually identical results after accounting for the time delay. Figure 3 shows neutral mass densities $\rho_{tr}$ and relative residuals $\rho_{tr}$ vs. UT-$T_{mz}$, and PSD of $\rho_{tr}$ at $57^\circ \leq GLat \leq 67^\circ$ for all listed UT-morning overflights. GLat-$\lambda$ color spectrograms are shown for the $GH2$, $Gq3$, and $Gd1$.
overflights. These results have been obtained by the same methods as above. Note that the characteristic spatial scales for CHAMP are smaller than those for GRACE.

3. Discussion and Conclusions

\[9\] The spectrograms indicate waves in and equatorward of the auroral region. We specify their source using the fact that short-scale AGWs decay faster than long-scale waves [e.g., Hocke and Schlegel, 1996]. This comes with the corollary that near \( \text{Lat}_{mz} \) long scales dominate the wave spectrum arriving from the (distant) auroral source, while the short scales originate from a local source. First, we discuss the heating experiments. As SAPS are often observed near HAARP fairly long after substorms [e.g., Pedersen et al., 2007], we checked the AFRL/DMSP database. No SAPS-like flows have been found in the subauroral region near/during all quiet-time overflights, including \( CH1 \) and \( GH2 \) (Figures 2d, 3d, and 3e). This fact allows us to explore the heating effect by comparing the quite-time wave distributions with and without HF heating.

\[10\] GLat-\( \lambda \) spectrograms help visualizing the wave spatial distribution. Note that CHAMP (GRACE) was moving southward (northward). Apparently, only the long waves \( \lambda \geq 500 \text{ km} \) (\( CH1 \)) and \( \geq 1500 \text{ km} \) (\( GH2 \) and \( Gq3 \)) are seen continuous between the auroral zone and \( \leq 65^\circ \) GLat. This agrees with PSD for \( Gq1 \) (Figure 2c) and \( Gq1-3 \) (Figure 3c) comprising mainly of the long waves. Quite the contrary, during the heating experiments the short waves \( \lambda \approx 350 \text{ km} \) (\( CH1 \)) and 1000 km (\( GH2 \)) dominate near \( \text{Lat}_{mz} \) (these regions are encircled by black dashed lines in Figures 2d and 3d). Therefore, we attribute them to the heating effect.

\[11\] A comprehensive model of HF-induced thermospheric perturbations has not yet been developed. High-power radio waves transfer energy to the ionospheric plasma via excited plasma waves [e.g., Fejer, 1979]. Resulting enhanced plasma temperature and ion upflows streaming from the HF-heated spot are regularly observed. During the \( CH1-2 \) experiments, the HAARP digisonde was monitoring plasma below and above the heated layer using three probing frequencies \( f_p \), one below and two above \( f_0 \). Reflections (echoes) of probing signals are placed on the skymap plane using their zenith and azimuth angles of arrival [e.g., Reinisch et al., 1998]. Inspection of the skymaps for \( CH1 \) shows that a minute after the heater was turned on, a tight cluster of echoes appeared in the \( F2 \) layer within \(-3^\circ/+8^\circ \) about MZ and remained during the heating.

\[12\] Figure 4 shows a Doppler skymap taken 30 s before \( T_{mz} \) for \( CH1 \) and raw spectra of the signal Doppler shift \( \Delta f_D \approx f_0 \langle v_{\text{los}} \rangle / 2c \) measured at \( h = 220 \) to 255 km in one
antenna channel. Here \( f_p \approx 3 \text{ MHz} \) and \( \langle v_{obs} \rangle \) is the average line-of-sight speed. The spectra indicate irregular plasma upflows at speeds \( U_i \approx 80 \sim 100 \text{ m/s} \) slightly increasing with \( h \), as indicated by the dashed line [cf. Milikh et al., 2010, Figures 2 and 3]. As both the ion outflow and AGWs, coincident with the \( \delta p/\rho \)-swelling (Figure 1d), are observed near \( L_{\text{min}} \), it seems reasonable to assume that the plasma and neutral perturbations are interrelated.

[13] The collisional heating of the neutral gas (mainly atomic oxygen) by \( O^+ \) ions can be estimated as 
\[
\Delta T_n / \Delta t \approx \frac{3}{4} \nu_{in} (\Delta T_i + M U_i^2). 
\]
Here \( \Delta T_i \) is the increase in the ion temperature and \( \nu_{in} \approx 1.8 \times 10^{-9} \text{ N s}^{-1} \) is the bulk \( O^-O \) collision frequency [cf. Rees, 1989]. There are no means of measuring the ion temperature at HAARP. Therefore, we use the values of \( \Delta T_i \leq 300 \text{ K} \) that have been revealed by the EISCAT UHF radar during the \( U_i \geq 100 \text{ m/s} \) events caused by HF heating in the conditions close to that at HAARP [Rietveld et al., 2003; Kosch et al., 2010]. Taking \( n \approx 3 \times 10^5 \text{ cm}^{-3} \) near the \( F_2 \) peak at \( h \approx 300 \text{ km} \), we roughly estimate the neutral temperature gain from the collisional energy exchange between \( O^+ \) ions and atomic oxygen as \( \approx 3 \text{ K/min} \). This gives \( \Delta T_n \approx 30 \text{ K} \) in a 10-min heating time or \( \Delta T_i/T_n \approx 3\% \). Thus, the local swelling is anticipated to be \( \leq 3\% \). This is consistent with the observed \( \delta p/\rho \) and with Millward et al.’s [1993] \( \delta p/\rho \sim 1 \), which was calculated at the neutral heating rate \( \Delta T_p/\Delta t \approx 100 \text{ K/min} \).

[14] Finally, the above corollary is used to explore the disturbed-time AGWs. From the DMSP data close to the disturbed overflights, we found enhanced SAPS-like flows disturbed overflights, we found enhanced SAPS-like flows. From the DMSP data close to the disturbed overflights, we found enhanced SAPS-like flows.

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