

## CHARACTERISTICS OF ATMOSPHERIC WAVES OBSERVED FROM AIRGLOW MEASUREMENTS IN THE NORTHERN HIGH-LATITUDE

Young-In Won<sup>1†</sup>, Bang-Yong Lee<sup>1</sup>, and Soon-Chul Kwon<sup>2</sup>

<sup>1</sup>Polar Research Institute, Korea Ocean R&D Institute, 425-170 Ansan, Korea

<sup>2</sup>MIS Team, Korea Ocean R&D Institute, 425-170 Ansan, Korea

E-mail: yiwon@kordi.re.kr

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### ABSTRACT

The terrestrial nightglow emission in near infrared region were obtained using a Fourier Transform Spectrometer (FTS) at Esrange, Sweden (67.90°N, 21.10°E) and the OH(4-2) bands were used to derive temperature and airglow emission rate of the upper mesosphere. For this study, we analyzed data taken during winter of 2001/2002 and performed spectral analysis to retrieve wave information. From the Lomb-Scargle spectral analysis to the measured temperatures, dominant oscillations at various periods near tidal frequency are found. Most commonly observed waves are 4, 6, and 8 hour oscillations. Because of periods and persistence, the observed oscillations are most likely of tidal origin, i.e. zonally symmetric tides which are known to have their maximum amplitudes at the pole.

*Keywords:* 94.10.Rk Aurora and airglow, 94.80.+g Instrumentation for aeronomy and magnetospheric studies, 94.10.Jd Tides, waves

### 1. INTRODUCTION

The principal dynamic features of the lower thermosphere and upper mesosphere regions (called MLT) are the tidal structures. These oscillations, excited primarily by insolation absorption of H<sub>2</sub>O in the troposphere and O<sub>3</sub> in the stratosphere and lower mesosphere, propagate upwards and their amplitudes grow exponentially until they reach an altitude where molecular dissipation starts to play a dominant role. Even though the solar forcing is diurnal, the semidiurnal tide (12 hour oscillation) excites efficiently because of its large vertical wavelength and becomes a dominant oscillation in the upper mesosphere and lower thermosphere. On the other hand, the diurnal tide (24 hour oscillation) is trapped and cannot propagate upward except near equatorial latitudes. Because of its deep penetration into the thermosphere, the semidiurnal tide has been received more attention than the diurnal tide in scientific studies. Theoretical studies of tides have been triggered by the work of Chapman & Lindzen (1970) and the solar tidal structures were investigated in detail by Forbes & Vial (1989).

The intensity and temperature fluctuations related to the tides and gravity waves have been the subject of numerous theoretical and experimental investigations (Viereck & Deehr 1989, Walterscheid & Schubert 1995). Several results from airglow observations report intensity and temperature fluctuations near tidal periods. These oscillations at upper mesospheric altitudes at high-latitudes

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<sup>†</sup>corresponding author

cannot be ascribed to a classical migrating tide because the predicted forcing is very weak and tends to vanish at the poles. Pseudo-tides, generated by gravity wave momentum fluxes modulated by the solar driven tide were proposed to interpret the large 12 hour mesopause temperature variation at 78°N (Walterscheid et al. 1986). Sivjee & Walterscheid (1994) concluded that the measured 6 hour quasi-monochromatic variation of the winter mesopause represented the effect of a zonally symmetric non-migrating tidal oscillation, though the source of the excitation remained in question. On the other hand, Oznovich et al. (1995) proposed an inertio-gravity wave as an explanation of the large amplitude oscillation of temperature and airglow brightness in the polar mesosphere based on the facts that temperature variations lead OH airglow brightness variations and the appearance is relatively infrequent. Observations of more persistent and dominant 8 hour period oscillations were reported by Oznovich & McEwen (1997) and the preference was given to a tide as an explanation of the origin. However, the interpretation of measurements with theory often brings conflict and this suggests a need for further exploration of the model in relation to various aspects of the measurements.

Recently, there has been a remarkable improvement in the techniques for measuring upper mesospheric temperatures by observing a number of OH vibration-rotation bands (Meinel bands). Since the identification of the hydroxyl (OH) emissions by Meinel (1950), many researchers have made ground-based, and rocket-borne observations of individual OH vibrational-rotational bands and identified their peak altitude at 87 km with a half width of  $\sim 8$  km (Baker & Stair 1988). Because rotational relaxation is sufficiently rapid in this region, the distribution of rotational lines within a band is expected to represent the kinetic temperature of the gas (Turnbull & Lowe 1983). Ground-based measurements of the OH rotational lines therefore provide the atmospheric temperature at this height.

As a part of upper atmospheric research program, the Polar Research Institute, Korea Ocean Research & Development Institute (KORDI) has used a Fourier Transform Spectrometer to study the atmospheric waves in the high-latitude thermosphere and upper mesosphere region. In this report, we present our preliminary results taken at Esrange, Sweden during the winter of 2001, with emphasis on the characteristics of the observed oscillations.

## 2. MEASUREMENTS

The Polar Research Institute of KORDI has been involved in performing ground-based optical observations of terrestrial nightglow emission using a FTS (Won et al. 2001). The instrument employs a thermoelectrically cooled InGaAs detector with maximum sensitivity in the wavelength region 1.0 to 1.7  $\mu\text{m}$ . The system provides 5 choices of spectral resolution that can be selected manually. Increasing the spectral resolution compromises temporal resolution: for the current study, we chose 4  $\text{cm}^{-1}$  as the unapodized spectral resolution, sufficient to resolve individual rotational lines. Co-addition of interferograms up to  $\sim 5$  minutes was used to increase the signal-to-noise ratio. The spectral response of the detector is determined by calibration with a low brightness source that is integrated with the experiment. This source has been calibrated against an intensity standard permitting absolute intensity determinations of atmospheric emissions and details of these spectral and wavelength calibrations are described in Espy et al. (1995).

Rotational temperature was retrieved from a least squares fit to the calibrated intensity distribution of the OH(4-2) Meinel band. The rotational lines were assumed to have intensities that conform to a Boltzmann distribution of excited OH amongst the rotational levels of a vibrational state. The analysis also provides the intensity of the vibrational level. The detailed procedure for the analysis of OH rotational temperature and band intensity is described in Won et al. (1999).

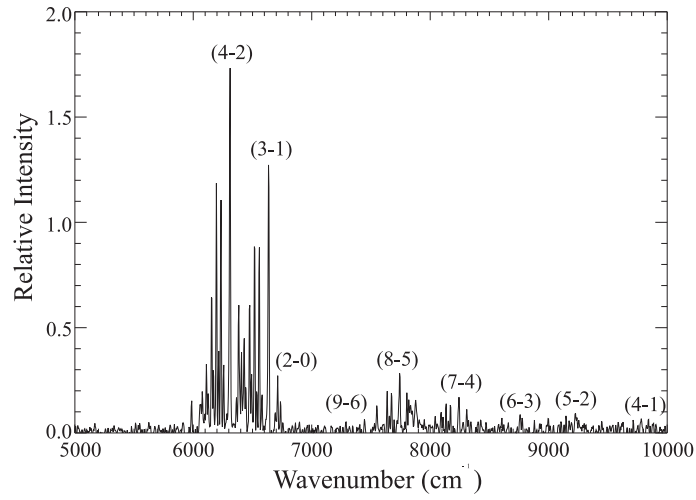


Figure 1. A sample of nighttime OH spectrum recorded at Esrange. Interferograms over about a 5-minute period (50 interferograms) were co-added to get this spectrum.

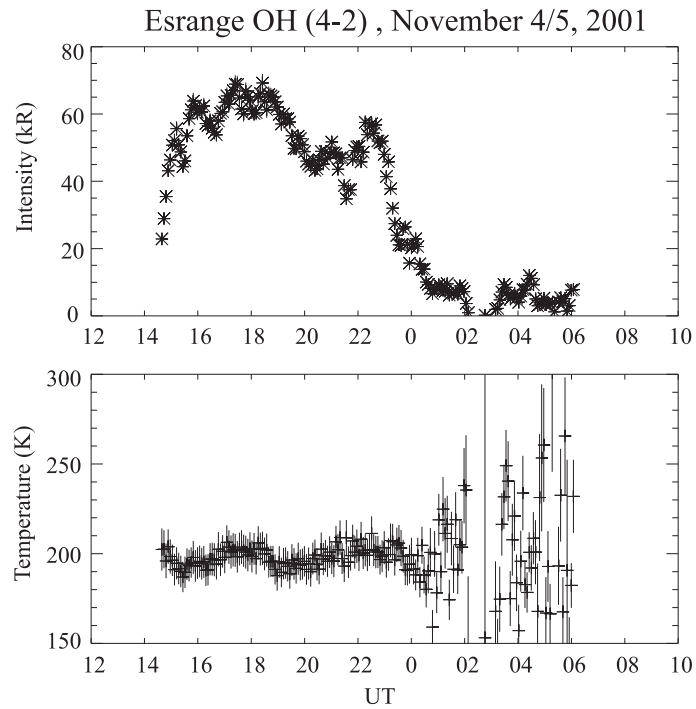


Figure 2. A composite plot of OH(4-2) emission rate and rotational temperature measured on the night of November 4, 2001 with error bars (statistical uncertainties) superimposed.

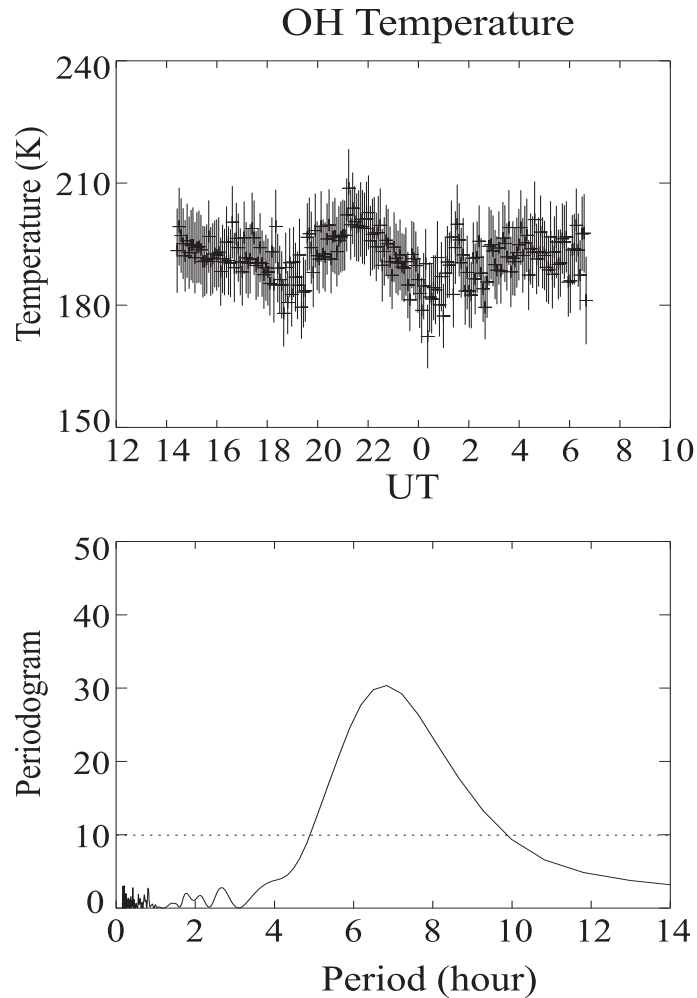


Figure 3. The OH rotational temperature variation measured on November 15, 2001 at Esrange and the corresponding Lomb-Scargle periodograms.

The FTS is housed in a hut on KEOPS (Kiruna Esrange Optical Platform System), located on top of a hill in Esrange (European Sounding Rocket Launching Range) near Kiruna, Sweden. The system is fully automated and has been in continuous operation since its installation in late October 2001. It measures terrestrial nightglow from OH molecules whenever the solar depression angle is 4 degree below the horizon. The observing time covers approximately between August 5 to next May 8 at Esrange. Because of the short span of available nighttime, it is not easy to derive meaningful information on the wave characteristic during equinox period. For this reason, six months of observations from October until March are used in this study, excluding data obtained beyond April. Cloud condition is another factor limiting the amount of useful data. An example of the acquired spectrum of the OH nightglow at Esrange is displayed in Figure 1, from which the

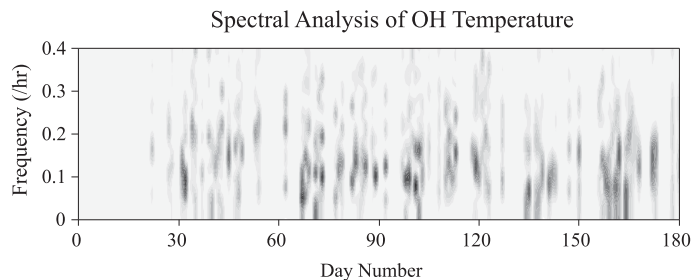


Figure 4. Gray-scale filled contour plots of the Lomb Scargle spectral analysis of OH rotational temperature results for the six month period starting from October 1, 2001. The highest contour range is dark-filled.

rotational temperature and the emission intensity are derived such as shown in Figure 2 for the night of November 4, 2001. The increase in error bars and noisy fluctuation in the temperature variation coincides with the sharp decrease in the emission intensities, indicating that the cloudy condition starts from  $\sim 0$  UT. It is not difficult to filter out data during cloudy condition by using the criteria of error bars and emission intensity. Power shut-down also limits the observation sometimes, but very rarely.

To search for wave-caused oscillations, we used a Lomb-Scargle spectral analysis for unevenly sampled data (Press & Rybicki 1989) and applied to each measurement. Figure 3 shows an example of measured OH temperature variation with the corresponding Lomb-Scargle periodogram during the night of November 15. The horizontal dashed line in periodogram indicates a power level corresponding to a significance level of  $P = 0.01$  (99.9 % confidence level). The periodogram clearly shows a dominant peak near 6 hour in this result, which is far above the significant level. It is found that strong peaks are commonly observed from the spectral analysis of the measured temperature variation for the whole data set, but not confined in just one period. The similar analysis can be done using the intensity result and in fact, the intensity variation also reveals a peak similar to that of temperature result. However, as was pointed out by Takahashi et al. (1990), the airglow emission may respond to atmospheric wave propagation with different time scale due to the different responses in the variations of minor constituents in the emission layers and the observed temperature variation can be regarded to be more representative of dynamical features. For this reason, we only used temperature results in our statistical analysis.

### 3. RESULTS AND DISCUSSION

Figure 4 shows a spectral density contour of the individual Lomb-Scargle analysis results against the day and frequency for the six month period from October 1st, 2001. A significant gap in the early October is caused by the fact that the observation started in October 23; other gaps are caused mostly by cloudy condition and sometimes by instrumental failure. Strong spectral peaks are frequently observed near  $0.17 \text{ hr}^{-1}$  (6 hour) and  $0.125 \text{ hr}^{-1}$  (8 hour), but broadly located in between. Islands of spectral peaks in much lower frequencies (less than  $\sim 0.08 \text{ hr}^{-1}$ ) are also seen, but may be the results of imperfect detrending in the spectral analysis or leakage from the large amplitude. Also, the length of the daily data sets is inadequate to determine the relative power unambiguously below certain value, i.e. limiting frequency, which is about  $0.05 \text{ hr}^{-1}$  in the December solstice and gets

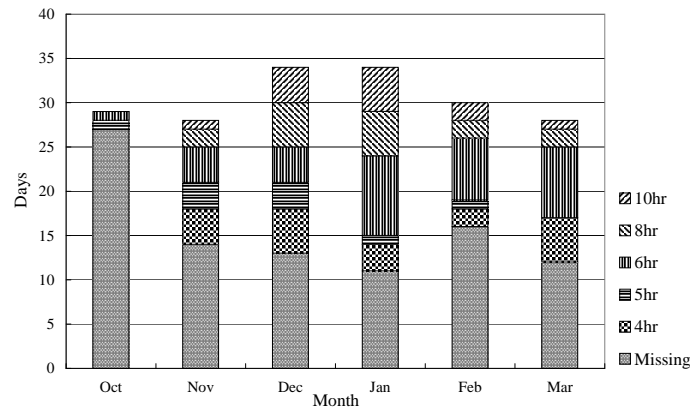


Figure 5. Histogram of observed waves sorted by period and month.

larger as approaching to equinox. Therefore, it is not meaningful to discuss spectral results below  $\sim 0.08 \text{ hr}^{-1}$ . The spectral peaks do not show a biased feature toward a certain month, but are rather evenly distributed, implying the persistent nature of the observed atmospheric waves. It is noted that there is a feature which appears to be well defined; the dominant period seems to shift from low frequency ( $\sim 10$  hour period) near the beginning of the November to near high frequency ( $\sim 4$  hour period) at the end of the month and then back to low frequency at the early December. This cyclic variation of spectral peaks from low frequency to higher one has an interval of slightly more than a month. This might be related to source transience or interactions that transfer energy from one wave to another.

Once observing the results of the spectral analysis, we chose peaks with their values greater than the significance level and counted them according to their periods. Peaks are rounded to nearby integer periods and recorded as a function of month as seen in Figure 5. Here, we limit the peaks below the 10 hour period; above which the length of the night may not be sufficient to confirm the occurrence of power as described previously, and the spectral peaks in longer periods could be biased toward the mid winter. The number of missing day, caused either by cloudy condition or by instrumental failure, is less than half for most cases. From the histogram, the 6 hour oscillations are found to be most commonly observed over Esrange. Other waves with periods of 8, 4 hours are also frequently observed. These periods correspond to higher tidal frequencies, but this does not necessarily mean that observed waves are tides. Numerous results have been reported regarding the existence of large amplitude variations in the MLT temperature in tidal periods. More specifically, there have been number of reports on high-latitude tides between 12 and 6 hr periods (Walterscheid et al. 1986, Sivjee & Walterscheid 1994). The classical migrating tide is not appropriate in explaining the observed oscillations because its amplitude should be very small in the polar region (Forbes 1982a,b). Rather, they associated the measured oscillation to the zonally symmetric tide. Zonally symmetric tides are standing oscillations and have the same UT variation at every location around a circle of latitude, i.e. zonal wave number zero. The latitudinal variation of Hough functions for zonally symmetric tides shows a maximum amplitude at the pole (see Figure 3 of Walterscheid & Sivjee 1996), and favoured for the interpretation of the measured oscillation at tidal periods. More recently, Walterscheid & Sivjee (1996) reported very high frequency oscillation with periods near

3 and 4 hours, which have not been reported previously. Based on the calculated Hough function behavior for the 3 and 4 hour zonally symmetric tides (largest amplitude at the pole), the observed oscillation was regarded as zonally symmetric tide. Won et al. (2003), using multi-station data sets, revealed the dominant and coherent 4 hour oscillations in both the O<sub>2</sub> and OH airglow brightness and rotational temperatures and ascribed it to a zonally symmetric tide because of no phase difference between the two locations.

On the other hand, Oznovich et al. (1995) proposed an inertio-gravity wave for the explanation of observed temperature and intensity oscillations near 8 hour period based on the comparison with theoretical values. Later, however, Oznovich & McEwen (1997) raised a question on the gravity wave explanation because of the persistence of the observed 8 hour oscillations. The frequently observed nature of the 8 hour oscillation, and the consistent negative phases for Krassovsky's ratio, resulted in a conflict for the explanation of the origin of the fluctuations and they suggested a further detailed inspection of the model with respect to various parameters such as lapse rate and minor constituent concentrations.

Other oscillations at 10 and 5 hour periods are also seen, but not as frequently as above mentioned oscillations. Peaks near 10 hour period have been reported and associated with either Lamb wave (Hernandez et al. 1992, Forbes et al. 1999), or modulation of the 12 hour semidiurnal tide by the quasi two day wave. As was mentioned by Meyer & Forbes (1997), the observed waves also may be a gravitational normal mode with period between 5 and 10 hours in the lower thermosphere and upper mesosphere region. Given the short span of data, errors involved, and the transient behaviour, it is not easy to interpret the source of the observed variation.

#### 4. SUMMARY

Lower thermospheric and upper mesospheric temperatures have been measured from ground-based observations of near IR airglow emissions from OH over Esrang (67.90°N, 21.10°E), Sweden. The instrument has been in routine operation since its installation in October, 2001. During the observation period in the winter of 2001/2002, oscillations with various periods were observed in OH airglow brightnesses and rotational temperatures. These results provide a good opportunity for us to characterize the high latitude waves by spectral analysis. A brief summary can be made as follows. We performed the Lomb-Scargle spectral analysis to the measured temperatures and found dominant oscillations at various periods near tidal frequency; most commonly observed waves being 4, 6, and 8 hour oscillations in Esrang. The high frequency wave such as the 4 hour wave has hardly been reported previously. Considering the consistency of the occurrence and the fact that the classical migrating tides have nearly zero amplitude at the pole, the observed oscillations are interpreted as zonally symmetric tides because only these are likely to generate significant fluctuation at high latitudes. The excitation source for these zonally symmetric tides is known to be the same as for the migrating tides, i.e. solar forcing. However, electro-dynamical sources over the polar cap, aurora, and nonlinear forcing by lower harmonics (24, 12, 8, 6 hours) are also possible source for the observed oscillations at tidal periods since the high frequency zonally symmetric tides are only reported in high latitude. Another possibility for the observed waves may be various natural oscillations between 7 and 10 hours in the lower thermosphere and upper mesosphere region, responding to the forces over a range of periods.

A continuous monitoring of OH airglow is planned for further investigation and understanding of the temporal distribution and the sources of observed waves, and its possible influence to the thermodynamics of upper atmosphere. We also plan for a comparison with other measurements such as from radar or observations from other locations for verification.

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