

Spectrometric and imaging measurements of a spectacular gravity wave event observed during the ALOHA-93 campaign

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Abstract. During the ALOHA-93 campaign coincident imaging and interferometric measurements of the near infrared and visible wavelength nightglow emissions were made from Haleakala Crater, Maui. On 10 October, 1993 a most unusual wave event was observed. This disturbance appeared as a sharp "front" followed by several conspicuous wave crests which progressed rapidly through the imager's field of view (180°). As the front passed overhead the interferometer detected a sudden jump in both the OH intensity (>50%) and its rotational temperature ($\sim 20\text{K}$) with the temperature increase leading the intensity by almost 15 min. At the same time the imager registered a sharp decrease in the OI(557.7 nm) emission intensity. A description of this remarkable event follows.

Introduction

Observations of gravity waves in the near infrared (NIR) and visible wavelength nightglow emissions (altitude $\sim 80\text{-}100\text{ km}$) have been reported by a number of researchers over the past two decades. The measurements have primarily been made using instruments such as photometers and spectrometers (aimed at the zenith) [eg. Takahashi et al., 1985; Lowe et al., 1991] and by narrow field imagers (usually aimed at low elevations to enhance the line of sight signal) [eg. Armstrong, 1982; Taylor et al., 1987]. Both techniques have revealed independently a wealth of short period (<1 hour) wave structure in the mid- and low latitude mesosphere and lower thermosphere. However, coincident imaging and spectrometric observations of a common emission volume are relatively rare [Taylor et al., 1991]. Such measurements are highly complementary and permit the investigation of gravity wave events in considerable detail. In particular the relationship between the temperature and intensity perturbations induced by the passage of these waves is of considerable interest. During the ALOHA-93 campaign a suite of instruments was operated from Haleakala Crater, Maui, to investigate the dynamics of short period gravity waves in unprecedented detail. These included the University of Western Ontario infrared Michelson Interferometer (UWOMI-3) and the multi-wavelength, all-sky CCD imager of Utah State University. Coincident data were obtained on several nights and a variety of wave displays were observed. In this paper we present measurements of the transit of one spectacular event as recorded by these instruments and discuss its remarkable properties.

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Observations

During the period 6-23 October, 1993, joint imaging and spectrometric observations were made from the DOE Safeguard Facility, Haleakala Crater, Maui (20.8°N , 156.2°W , 2970m). Brief descriptions of these two instruments and their operational details are given in Taylor et al., [1995] and Lowe and Turnbull [1995]. The spectrometer (field of view 10°) measured the zenith intensity of several OH Meinel bands in the wavelength range 1000-1650 nm, using a scan time of 23s. The all-sky imager recorded structure sequentially in the NIR OH(715-930 nm) bands, the OI(557.7 nm) and Na(589.2 nm) lines and the O₂(0,1) Atmospheric band. The NIR OH filter incorporated a notch at $\sim 865\text{ nm}$ to limit contributions from the O₂(0,1) band. Measurements were made using a repetition rate of 3 and 5 min for the OI emission and ~ 9 min for the other emissions.

10 October Wave Event

The night of 10 October was characterized initially by a faint, but persistent, short horizontal wavelength ($\sim 15\text{ km}$) gravity wave propagating towards the NE in the OI emission layer (altitude $\sim 96\text{ km}$). Occasional small-scale, short-lived "ripple" waves were also observed in isolation at OH, Na and OI wavelengths. However, around 09:30 UT an unusual disturbance was detected in the northwestern sky near the limit of the camera's field of view ($\sim 450\text{ km}$) in all four emissions. This disturbance appeared bright in the OH and Na emissions but dark in the OI and O₂ emissions. By 10:30 UT the disturbance was resolved clearly as a series of elongated wave crests characterized by a leading sharp "front" propagating towards the SE. During the next hour the front moved rapidly over the Hawaiian Islands passing over the optical site and through the interferometer's field of view at $\sim 10:50\text{ UT}$. Sequential images showed similar wave structure in each emission indicating that the disturbance extended throughout the upper mesosphere and lower thermosphere ($\sim 80\text{-}100\text{ km}$) region. Figure 1 shows this event as imaged in the NIR OH and the OI(557.7 nm) nightglow emissions (the first two images are separated by 18 min, while the second and third are separated by 9 min). The data illustrate the spatial extent and temporal coherence of the wave packet and its rapid motion across the sky. By 11:30 UT the disturbance had progressed well to the SE of Maui and only faint evidence of its passage remained in the overhead sky.

At OH wavelengths this event appeared as a series of bright wave crests propagating through a "dark" almost structureless sky. However, in the OI emission it was manifested as a wave propagating into a "bright" nightglow region leaving an apparently depleted emission in its wake. The net effect was quite extraordinary with a marked reversal in contrast between the wave patterns as recorded at OH and OI wavelengths. Figure 1

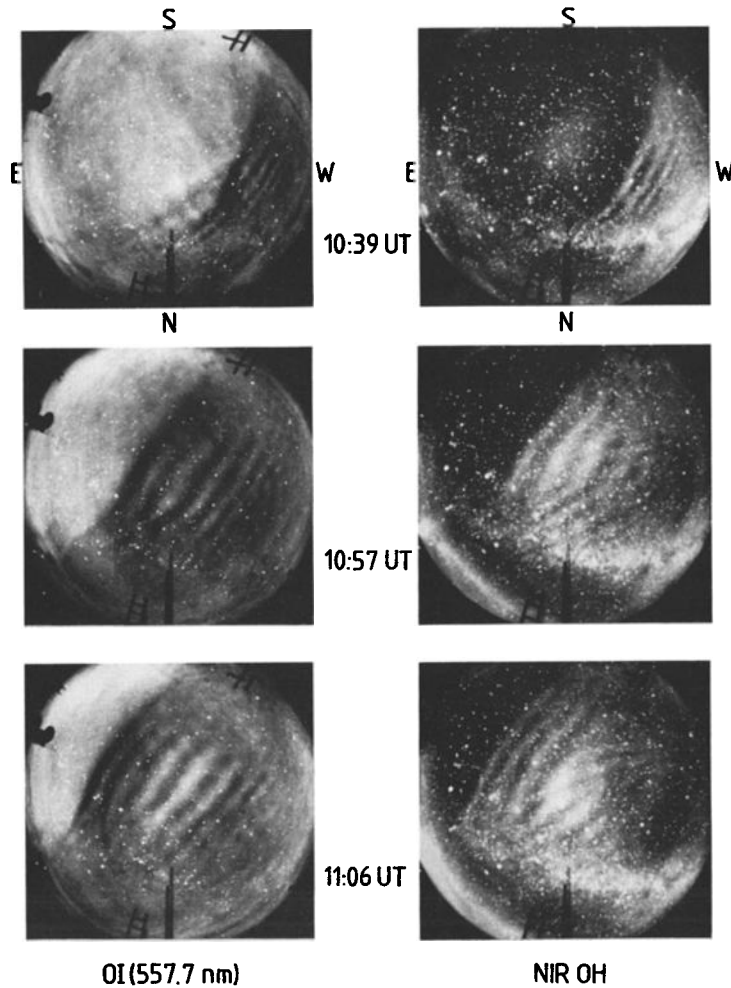


Figure 1. Sequence of all-sky CCD images showing the rapid transit of the wave event at NIR OH and OI(557.7 nm) wavelengths (integration time for OH = 20s and OI = 90s). Note the reversal in contrast of the wave pattern and the presence of the second, fainter wave motion ($\lambda_h = 15$ km) in the OI images.

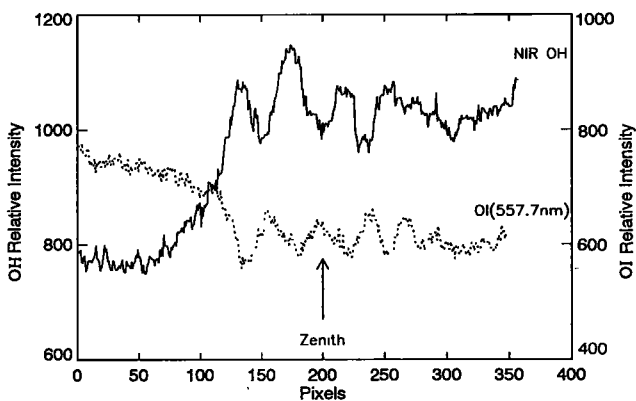


Figure 2. Relative intensity scan across the camera field normal to the wave crests for the OH and OI data at ~10:57 UT when the front passed overhead. Both images have been flat-fielded to remove contributions due to line of sight integration through the nightglow layers and lens vignetting. The OI scan has been shifted horizontally by 8 pixels to compensate for the mean time interval (~1 min) between the two images. Note the alignment of the peaks in OH with troughs in OI and vice versa.

depicts this effect well but the magnitude of the contrast is somewhat exaggerated due to the limited dynamic range of the photographic reproduction. Intensity measurements across the camera field in a direction normal to wave crests (Figure 2) quantify the impact of the front on these two emissions. A significant increase in the broad band OH signal (~33%), in the wake of the front, and a corresponding decrease (~24%) in OI signal intensity was found. In both cases the amplitudes of the coherent waves trailing the front were considerably less (~8-

Table 1. Horizontal wave parameters derived from the image data for each of the four nightglow emissions.

Emission	Assumed Height (km)	λ_h (km)	v_h (ms ⁻¹)	T_{obs} (min)
OH	87	19.3 ± 0.7	75 ± 2	4.3 ± 0.2
Na	90	18.8 ± 0.7	77 ± 2	4.1 ± 0.2
O ₂	94	18.8 ± 0.9	76 ± 3	4.1 ± 0.3
OI	96	20.1 ± 0.7	77 ± 2	4.4 ± 0.2
Average		19.3 ± 0.7	76 ± 2	4.2 ± 0.2

16%) than that of the front. A similar, but less contrasted effect was also observed in the Na and O₂ emissions with the Na images mimicking the OH data and the O₂ images the OI data. The disturbance was observed for over 3 hours as it progressed from the horizon to horizon and showed no signs of dissipating.

Results and Discussion

Table 1 lists the horizontal wave parameters derived from the image data. Within the limits of the measurements the wave motion exhibited the same horizontal wavelength at each emission altitude, $\lambda_h = 19.3$ km, and the same apparent phase speed, $v_h = 76$ ms⁻¹, giving an average observed period, T_{obs} of only 4.2 min. Simultaneous measurements using the MF radar located on Kauai (range ~375 km) indicate that when this event passed over the Hawaiian Islands (09:30-11:30 UT) the average hourly winds in the direction of the wave motion (azimuth ~126°N) were relatively small throughout the 80-100 km region at ~17 ms⁻¹ at OH heights and <10 ms⁻¹ in the higher altitude emissions (J.R. Isler, private communication). The intrinsic period of the wave motion (i.e. its period measured in a frame of reference moving with the wind) was therefore between 4.6 and 5.5 min. This is close to the local Brunt-Väisälä period, estimated at ~4.8 min using a mean OH temperature of 205K from the interferometer data and raises several questions concerning the nature and origin of this disturbance.

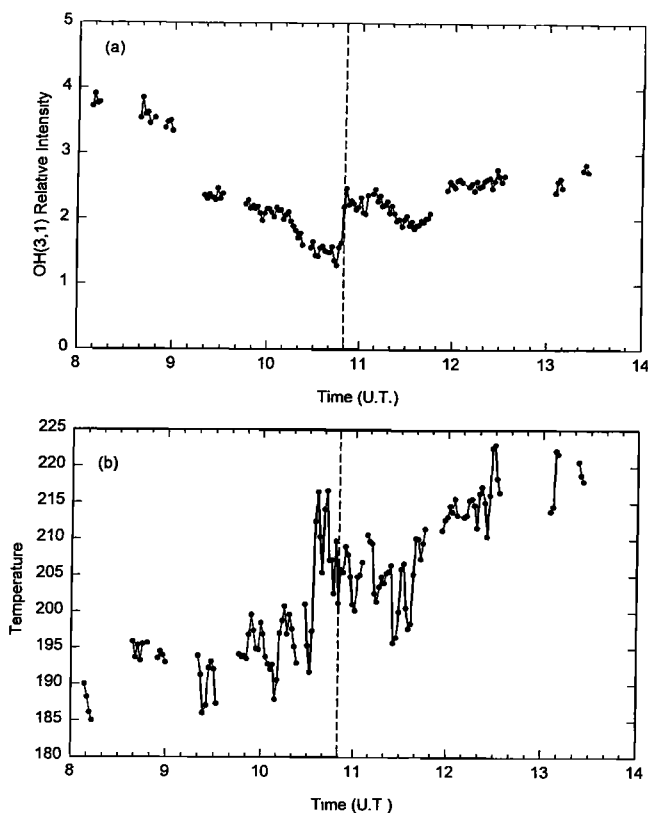


Figure 3. Plots of (a) relative intensity and (b) rotational temperature of the OH(3,1) band. The data have been averaged and are plotted at 1.5 min resolution (the temperature data have been further three point smoothed due to noise). Note the sharp transition induced by the passage of the front and the large (~15 min) time lag between temperature and intensity.

Extensive wave patterns with apparent periods <20 min were observed on many occasions during this campaign. However, only on one previous occasion (during the ALOHA-90 campaign) has such a short apparent wave period been reported [Taylor and Edwards, 1991]. On that occasion (25 March 1990) the display was observed to last for several hours and consisted of a succession of many faint wave crests. The data reported here are quite dissimilar in appearance, consisting of a well defined front and a limited number of wave crests (6-10) progressing behind it. This wave motion stands out in our image data as exceptional in its morphology, clarity and speed of propagation all of which add up to make it a spectacular event. The interferometer data recorded during the transit of this event also point to it being most unusual but for different reasons. Figure 3a shows the intensity of the OH(3,1) band as measured by the interferometer on this night. The data have been averaged and are plotted at 1.5 min resolution. Prior to the event (08:00-10:50 UT) the OH intensity dropped steadily by over a factor of two. A decrease of this magnitude during the pre-midnight hours was usual for this campaign, though it normally took place over a five hour period [Lowe and Turnbull, 1995]. However, at 10:50 UT a sudden jump in intensity was detected commensurate with the passage of the front overhead, as determined from the image data. Figure 4 shows an expanded plot of the interferometer data at 23s temporal resolution (with three point smoothing) for this interval. In less than four minutes the OH intensity increased by over 50%. After this the emission was characterized by several small amplitude variations (12-18%) associated with the passage of the waves. The average period of this oscillation was found to be ~4.4 min in good agreement with the image data. Although an intensity change of 50% is not by itself exceptional the abruptness of the transition (occurring within one cycle of the wave motion) is unprecedented in our data sets. This jump appears more like a discontinuity and is a clear feature of the front-like nature of the disturbance.

The OH rotational temperature data derived from these measurements is shown in Figure 3b. The normal nightly temperature variation during the campaign was an increase from a minimum value of around 195K at ~06:00 UT to about 208K by ~15:00 UT. Prior to the passage of the front the temperature was relatively steady around 195K. However, at 10:31 UT an abrupt increase of ~20K (25K peak to trough) occurred within a short time interval (<4 min) in clear association with the transit of the front. Remarkably this transition in temperature preceded the intensity jump by almost 15 minutes suggesting that the thermal disturbance associated with this event was over three cycles ahead of the intensity disturbance as determined from both the interferometer and image data. This result was confirmed by simultaneous temperature measurements using the OH (4,2) band (data not shown) which are essentially independent from the (3,1) band measurements. Numerous theoretical studies indicate that long period (several hour) gravity waves should exhibit sizable phase shifts between the induced temperature and intensity waves. However, the signature of the front was clearly not wave-like in character raising further important questions concerning the nature of this disturbance and its interaction with the atmosphere.

It is possible that this event may represent a "step-like" disturbance propagating through the 80-100 km level rather than a discrete wave packet, as there was no obvious phase shift in the geographic position of the leading edge as detected in the

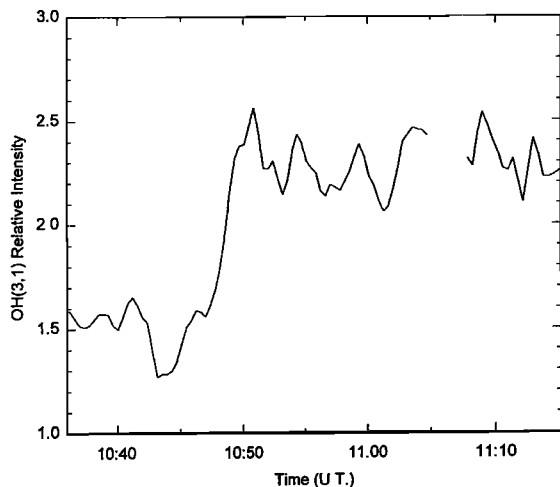


Figure 4. Plot of the OH(3,1) band intensity data at 23s resolution (with three point smoothing) showing the rapid increase in intensity (>50% in less than 4 min) due to the front and the ensuing oscillation induced by the waves.

OH and OI layers (Figure 2). If this were the case then the waves may have been created in-situ in the wake of the passage of a "bore-like" disturbance. Indeed the similarity in morphology of the airglow images to that of a tidal river bore is striking (E.M. Dewan, private communication). Bores and solitons have been observed in the lower atmosphere [Ramamurthy et al., 1990] but not previously in the mesosphere. It is most likely that the waves behind the front are fully ducted waves trapped in the vicinity of the mesopause. The short wave period, close to the Brunt-Väisälä period, and long duration of this event are most consistent with this hypothesis. Freely propagating short period waves of tropospheric origin, on the other hand, would encounter considerable difficulty achieving mesospheric heights.

Another characteristic of this event is the apparent reversal in contrast of the structures as seen in the OH and OI data (Figure 2). As sequential images of these emissions are rare it is not known whether this effect is a common occurrence. However, a similar effect was observed on several other occasions during this campaign but they were far less conspicuous. Recent model calculations by Picard et al. [1995] indicate that the observed contrast reversal and the measured temperature change could be explained by a bore-like intrusion simultaneously raising the OI layer by ~2km and pushing the OH layer down by the same amount. This would also account for the abrupt nature of the intensity change (within an interval of <4 min). As no such rapid change has been reported previously, it remains to be seen whether the observed phenomena can be best accounted for in terms of a ducted bore-like motion.

Summary

Observations of gravity wave events of this starkness and clarity are rare. The "front-like" nature of the disturbance was very distinctive and most unusual. These data offer a unique opportunity to discover important information on the origin and manner of propagation of this new type of disturbance and to investigate its impact on the nightglow emission chemistry. Unfortunately on this night, optical data are available only from the UWO and USU instruments co-located on Haleakala. Nevertheless, these joint observations have revealed the

following remarkable properties:

- unusual "front-like" morphology,
 - sudden large "step" in intensity induced by the front,
 - associated sharp jump in OH rotational temperature,
 - marked time delay between temperature and intensity fronts,
 - companion waves of very short period (<5 min),
 - high apparent phase speed,
 - coherent progression from horizon to horizon with no sign of dissipation,
 - same disturbance seen in all four emissions (80-100 km), and
 - contrast reversal in the OH and OI(557.7 nm) wave structure.
- In total over 100 images of this remarkable event were recorded from which a detailed description of its vertical and horizontal form will be built in due course.

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