Observational and modeling study of mesospheric bores

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Abstract

In mid-latitude studies of the dynamics of the mesosphere and lower thermosphere, some of the most intriguing phenomena observed high over the Hawaiian night skies are internal bores. These events are documented in monochromatic airglow images taken by high performance all-sky CCD imaging systems operating at the Maui Space Surveillance Site on top of Haleakala Crater. Data continues to be collected as part of the ongoing, collaborative Maui - Mesosphere and Lower Thermosphere (MALT) campaign, jointly sponsored by the National Science Foundation and the Air Force Office of Scientific Research. Bolstered by the Maui-MALT dataset, several theories now exist for mesospheric bores, agreeing in principle that they are likely nonlinear structures spawned by gravity waves and propagating within ducted waveguide regions. We investigate these plausible theories using a multi-instrument approach, looking for correlation between bores and thermal inversion layers or wind shears, both potential guiding structures for bore propagation.

1. Motivation

It was a dark and stormy night.[1] A few hundred kilometers from paradise, out over the Pacific, a storm was brewing in the troposphere. Back over the islands, however, as twilight fell and the splendor of the tropical sunset faded, the stars emerged twinkling and bright on this moonless night. High atop the volcano tiny red lights, commonly used to preserve night vision, flickered on, signaling the start of the work shift. The Menehune[2] and bugs[3] were at bay, and here at the summit of the House of the Sun[4], conditions were prime for nature to reveal her secrets, with *all eyes on the sky... nowhere to hide*[5]. While

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[1] A common narrative cliché made famous by comic strip artist Charles M. Schulz, but originally penned by Victorian novelist Edward Bulwer-Lytton, 1rst Baron Lytton, as the beginning of his 1830 novel *Paul Clifford*.
[2] Also known as Nawao. Menehune are the legendary, mystical, `little people' of Hawaii, similar to pixies or trolls, who roam the forests at night with mischievous intent and industrious, engineering prowess.
[3] Refers to the bug infestation of 2002.
[4] Translation of the Hawaiian name *Haleakalā* for the entire shield of the East Maui volcano. Early Hawaiians applied the name only to the summit area, the site where the demigod Maui snared the Sun and forced it to slow its journey across the sky.
[5] Also in Hawaiian: *Nā maka í ka laní Nā wahí `ole í ka pe'e*. -- the motto of Detachment 15 of the Air Force Research Laboratory's Directed Energy Directorate. Included as a nod to Detachment 15 which conducts the research and development mission on the Maui Space Surveillance System (MSSS) at the Maui Space Surveillance Complex (MSSC).

Pele[6] slept, thunder rumbled in the distance barely disrupting the tranquility of this peaceful night. And yet, inaudibly, a disruption had occurred. Emanating outward from the storm cell, much like a ripple leaving a stone tossed in a pond, a gravity wave had been launched. Immediately it began to climb, leaving the storm clouds of the lower atmosphere far behind as it forged its way out of the cold, upper troposphere and on through the warmer stratosphere. Throwing off phase disturbances orthogonally downward, it continued to propagate upward growing in amplitude as it ascended. No sooner had it burst past the mesopause in the coldest region of Earth's atmosphere near 85 km altitude, than it encountered a formidable barrier at a critical level where the medium was traveling horizontally at the same speed as the wave, halting the wave's journey upward. The intrigue began to escalate. The gravity wave fronts behind it kept coming, piling up in a turbulent jam providing the piston-like forcing which drove the gravity wave down the corridor of an inversion layer until it reached its nonlinear breaking point, and like a sonic boom transformed into a hydraulic jump forming the leading edge of a mesospheric bore. And now close to a hundred kilometers below, the Valley Island was in sight, as this trapped mysterious wavefront surged along making constant progress through the guiding tunnel of the inversion layer. In the pitch black of this moonless night, as the tourists and kamaaina[7] alike slumbered serenely below, the bore found itself in a glowing region of dim light, poised for the cameras below.[6]

This opening narrative illustrates the development of a mesospheric bore originating in a localized region of the lower atmosphere, yet resulting in more global impact as energy and momentum flux are transported across regions both vertically to higher altitudes and horizontally through a wave-guiding structure to distant latitude-longitude locations where the flux is then deposited through dissipative effects. Upward vertical transport of even small amounts of energy and momentum can have disproportionately large effects on the upper-atmospheric global budgets as a result of exponential growth in amplitude due to the decrease in atmospheric density with height. These vertical amplification effects allow energy, momentum, and chemical processes, coupled from the lower atmosphere, to serve as sensitive indicators of small changes. Chemical reactions, occurring at a specific altitude based on the intrinsic constituent profile at that altitude can produce chemiluminescent light which then serves as a dynamical tracer as it is transported by wave disturbances.

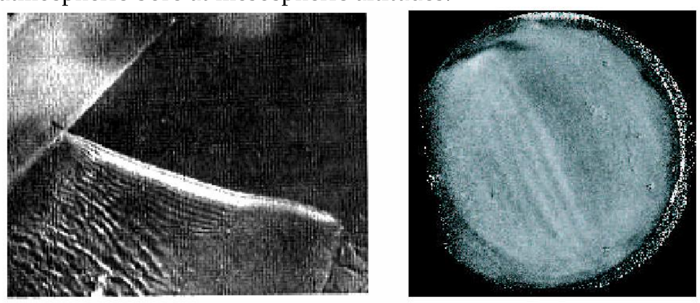
Once discarded as a hard-to-reach quiet area, the mid-latitude mesosphere and lower thermosphere (MLT) region has in recent years been revealed to be an accessible, active, important, and interesting sector of the atmosphere. Spatial irregularities, such as wavelike or undulatory structures created in the atmosphere by events impacting mesospheric dynamics -- while interesting in their own right for the purpose of basic scientific advancement to gain an understanding of the still vast geophysical unknown -- are of particular interest to many in the scientific and military communities who view these structures as either enabling or impeding their own specific goals. Structured small-scale and large-scale plasma disturbances in the ionosphere are known to impact satellite communication and navigation signals. The influence of waves and tides on the structure and brightness of airglow layers, infrared in particular, along with diurnal and seasonal variations in these layers, can all impact the military's efforts in surveillance, imaging, and missile defense. In general, variations from the ambient background, that is structured formations, turbulent regions, and gradients, even in neutral gases, can hinder the efforts of those looking past the MLT region, those maneuvering through the MLT region, and those focusing directed energy within the MLT region. Ecologically speaking, it is imperative to understand the climatology of the region so that secular variations or sudden impacts, arising from possible human influences upon the environment, might be detected, recognized as potential harbingers of global change, and addressed. Anthropogenic CFC gases deteriorating the effectiveness of the stratospheric ozone layer is a well-known illustration of this point. As studies of the upper atmosphere continue, ever more is understood of this highly interconnected system. Each new study provides incremental insight into this important atmospheric region and our environment as a whole.

[6] Hawaiian goddess of volcanoes currently thought to reside in Kilauea on the Big Island. The remnants of Pele still remain on her former residence, the summit of Haleakala, which lies within the Land of Pele as part of Hawaii National Park.

[7] A long-term Hawaiian resident.

2. Introduction

Sighting bores near the mesopause is a relatively new phenomenon -- the first such observation occurred a little over a decade ago, late in 1993, during the Airborne Lidar and Observations of Hawaiian Airglow (ALOHA-93) campaign. One particularly spectacular gravity-wave event from this campaign resembled aerial views of tidal bores in river channels. This striking resemblance, illustrated in Figure 1, inspired *Dewan and Picard* [1] to coin the term "mesospheric bore" when they attempted to explain the ALOHA-93 event and in the process proposed the first basic mathematical model for an atmospheric bore at mesospheric altitudes.



(a) (b)

Fig. 1. (a) Tidal bore on the River Mersey from the air *Dewan and Picard* [1], from *Tricker* [9]). (b) Internal bore in the mesosphere at 96-km altitude over Peru. This 557.7-nm wavelength airglow image was taken by the Cornell All-sky Roving Imager (CARI).

A tidal bore, or hydraulic jump, in an open channel is an abrupt change in the depth of the channel fluid in response to a transition from supercritical (where the flow velocity exceeds the long-wave speed) to subcritical flow. These bores are analogous to the shock that forms in a gas in the transition from supersonic to subsonic flow. The literature also reveals a second class of bores - the stratified, or internal, bore - occurring in stably stratified fluids. While examples of stratified bores have been documented for the troposphere and oceans, none were ascribed to the mesosphere until *Dewan and Picard* [1] advanced their analytic theory attributing the sharp airglow fronts with trailing oscillations to "mesospheric bores". They hypothesized that the spectacular sharp front event of 10 October 1993 could be explained by an internal undular bore. Both channel and internal bores can appear either with or without trailing waves in the wake of their leading edge. Bores with trailing waves are termed ``undular''; those lacking trailing oscillations are ``turbulent'' or foaming bores[5]. The website www.boreriders.com offers an interesting collection of photographs of river bores.

While most mesospheric bore observations confirm the validity of the original symmetric bore theory model of *Dewan and Picard* [1], some events recorded by the Cornell University imagers appear to conflict with it [7]. Most of the previously documented mesospheric bores displayed either a complementary effect, with lower airglow layers appearing to brighten behind the leading edge of the front while corresponding upper layers appeared to darken, or a complete lack of complementarity with regard to the variation in radiance. The conflicting observations demonstrate an "inverse" complementarity, that is, the lower layers appear to be pushed up (becoming darker) while the corresponding upper layers are pushed down (becoming brighter), which appears to be inconsistent with current bore models. In *Loughmiller et al.*, [8], we extend the basic model, proposing one possible explanation for these confounding observations. This extension theorizes that two simultaneous bores exist one above another to allow for the inverted complementarity in the airglow observations. Using vertical temperature profile data from the SABER (**S**ounding of the **A**tmosphere using **B**roadband **E**mission **R**adiometry) instrument on NASA's TIMED (**T**hermosphere, **I**onosphere, **M**esosphere **E**nergetics and **D**ynamics) satellite, we show that multiple guiding structures do exist to support this claim.

This paper is organized as follows. In Section 2, we briefly describe our field site, as well as the basic instrumentation and processing methods used to obtain the airglow images. The basic mesospheric bore theory is given in Section 3, along with the equations for this symmetric analytical model. Standard and new "inverse" bore data is presented in Section 4, along with one proposed theory to address the inverted intensity contrast observations. The resulting bore taxonomy scheme is also shown in this section. In Section 5, satellite data is presented supporting the dual bore theory proposed to explain the inverse bore data. We conclude with a summary in Section 6. Section 7 provides references, and Section 8 offers acknowledgements.

3. Campaign site and instrumentation

The Maui Space Surveillance Complex (MSSC) on top of Haleakala volcano on Maui, HI -- operated by the United States Air Force Research Laboratory (AFRL) -- provides an ideal location to study the mid-latitude mesosphere and lower thermosphere. This Air Force facility has served as our on-going field campaign site since October 2001. The Maui-MALT initiative was a scientific data collection campaign jointly-sponsored by the National Science Foundation (NSF) and the Air Force Office of Scientific Research (AFOSR) to promote upper atmospheric studies of the mesosphere and lower thermosphere (hence, MALT). The program was comprised of scientists from Cornell University, the University of Illinois at Urbana-Champaign, Utah State University, Pennsylvania State University, and the Aerospace Corporation. The program was in operation from the late fall of 2001, initially centered around the use of the giant 3.67-meter Advanced Electro-Optical System (AEOS) telescope as the optics for two different LIDAR (Light Detection and Ranging) systems. Multiple imagers and radar were deployed at the site by Maui-MALT participants to provide coordinated data, as well as coverage when the telescope was not available.

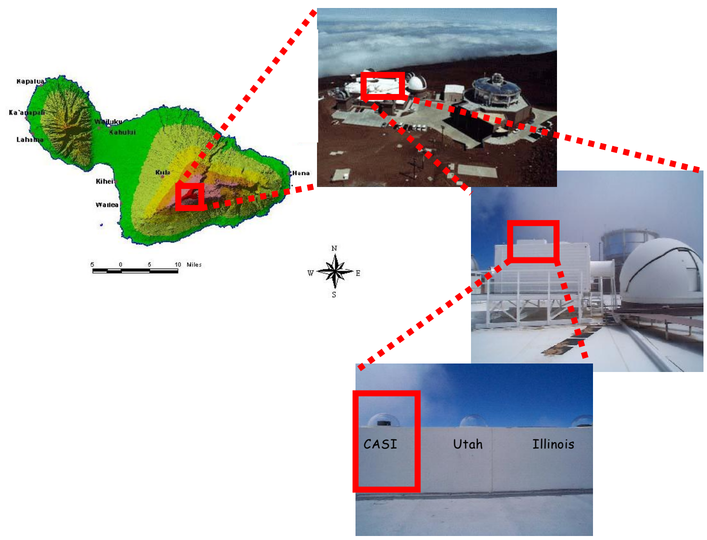


Fig. 2. Field location of CASI installed on roof of MSSS at MSSC as part of Maui-MALT campaign.

For Cornell University's participation, two cameras were fielded at this location. Important to this study on mesospheric bores -- our **C**ornell **A**ll-**S**ky **I**mager (CASI), a “standard” all-sky airglow imager located on the roof of the Maui Space Surveillance Site (MSSS) building as shown in Figure 2. This imager provides a nighttime, horizon-to-horizon snapshot of the state of the ionosphere at different heights, and is useful for observing atmospheric waves, mesospheric bores, meteor trains, and the airglow perturbations associated with equatorial spread-F. CASI, shown in Figure 3 in its “roving” configuration, is a self-contained, monochromatic imaging system. The hardware for this system is comprised of a scientific-grade, charge-coupled device (CCD) fronted by fast (f/4) telecentric optics, a five-position filter wheel, and an all-sky (wide-angle (180^o) fisheye) optics lens. An electronics unit controls the camera, and a liquid circulation unit removes heat from the thermo-electrically cooled CCD chip. To minimize noise, the CCD is cooled to approximately -40^{o}C and pixels are binned on-chip by a factor of 2, producing 512 x 512 images from the 1024 x 1024 CCD. The entire system runs on a PC and is controlled by a Windows-based program that was developed at Cornell University by graduate students.

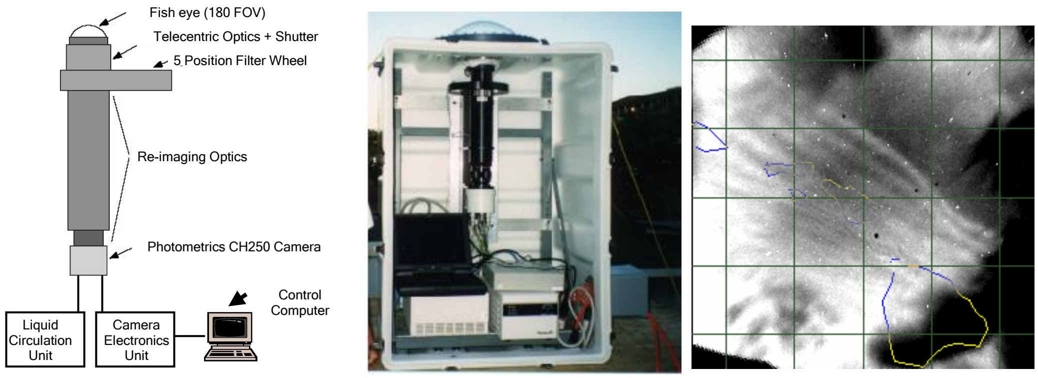


Fig. 3. Self-contained all-sky airglow imager with block diagram of corresponding components shown at left. A geographically projected bore event is shown in the right panel to illustrate the field of view of the imager.

Since chemiluminescent reactions emit radiation of specific wavelengths and these correlate fairly well to specific altitudes (as shown in Figure 4), we choose various narrow-band filters to isolate each wavelength, and hence, its corresponding altitude for study. To inspect mesospheric altitudes, several filters can be employed to isolate a range of airglow emissions. Hydroxyl emissions at 87 km are captured by the 865.0-nm near infrared broadband OH filter using integration times of 8 s. A 589.3-nm wavelength narrow-band filter captures sodium (Na) emissions peaking at 90 km; a 557.7-nm narrow-band filter captures greenline (OI) emissions at 96 km. Exposure times for both narrow-band filters are 90 s. Before examining the airglow emissions as tracers of mesospheric dynamics, the airglow images underwent the following processing:

- spatial calibration to stars
- removal of stars from images
- correction for vignetting by the optical system
- correction for van Rhijn effect, i.e., line-of-sight brightening near the horizon
- unwarping, i.e., geographic projection and interpolation

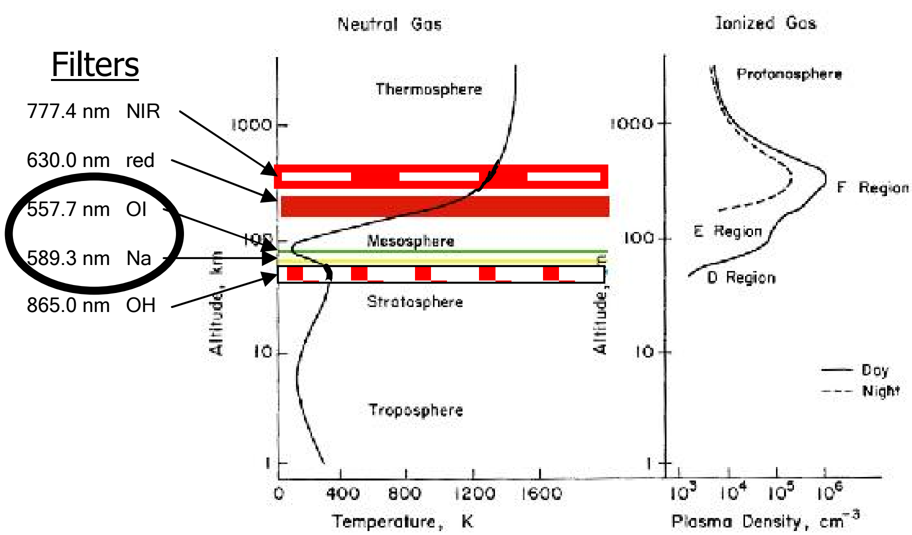


Fig. 4. Temperature and density profile of the atmosphere of the Earth. The airglow filters operated in CASI are identified along with their corresponding altitude layers. The primary filters used for this study are circled above.

4. Basic bore theory

Responding to remarkable mesospheric phenomena captured in airglow images for the first time during the ALOHA-93 campaign, and drawing on similarities to the existing literature on tidal and internal bores, *Dewan and Picard* [1] advanced the first analytic theory attributing the sharp airglow fronts with trailing oscillations to "mesospheric bores". The "channels" in the atmospheric bore cases are hypothesized to be layers of statically stable air surrounded immediately above and below by less stable layers. *Dewan and Picard* [1, 2] proposed that layers of temperature inversion, also called **m**esospheric **i**nversion **l**ayers (MILs), provide the required layer of high stability. In explaining the first documented mesospheric bore observed during the ALOHA-93 campaign, they suggested that a horizontal waveguiding channel existed between two airglow layers, at approximately 90--94 km, in which a bore propagated. As the bore passed overhead, it produced symmetric oscillations about the center of the channel. The upper layer (OI 557.7 nm) was vertically displaced upward, making it cooler, less dense, and presumably less bright. The lower layer (OH) was displaced symmetrically downward, making it warmer, more dense, and brighter. In Figure 5, a schematic of the symmetric bore theory illustrates this vertical displacement.

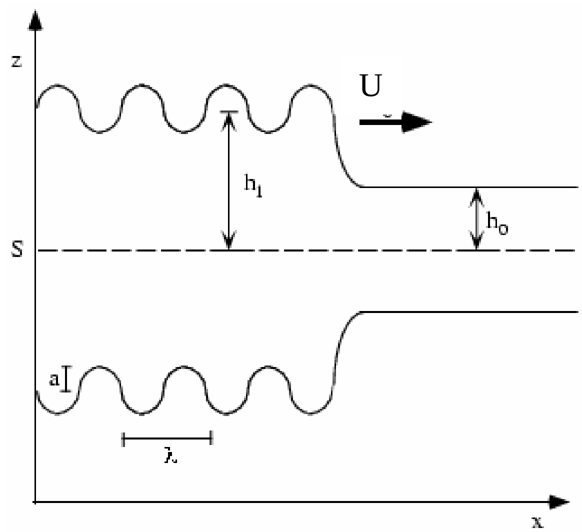


Fig. 5. Illustration of a symmetrical undular bore with symmetry plane S, where the displacement is zero in analogy with the rigid bottom in channel bores. In this schematic, the z axis is altitude and the x axis is horizontal distance. h_0 is the undisturbed height of the fluid; h_1-h_0 is the height of the bore; U is the bore velocity; λ is the wavelength of the trailing oscillations; and a is the bore amplitude. (From *Dewan and Picard* [1].)

A summary of the basic equations of the analytic bore theory postulated by *Dewan and Picard* [1] follows. They state that the equations governing open-channel bores will hold for this basic model if the acceleration due to gravity, *g*, is replaced by the buoyant acceleration, *g'*, defined as:

$$g' = g\frac{\Delta\phi}{\bar{\phi}} \tag{1}$$

where ϕ is the potential temperature. The equation for the bore velocity is then:

$$U^2 = \frac{1}{2}g'(h_0 + h_1)\frac{h_1}{h_0} \tag{2}$$

Lighthill [5] used laboratory experiments to show that, for an undular channel bore, the bore strength, β, defined as the normalized bore amplitude, is bounded above:

$$\beta \equiv \frac{h_1 - h_0}{h_0} \leq 0.3 \quad \text{(approx.)} \tag{3}$$

When this upper bound for the bore strength is exceeded, turbulent bores with no trailing waves result. For weak bores, where $\beta << 1$, the waves behind the discontinuity are sinusoidal, as seen predominantly in the mesospheric bore data. The wavelength of the waves behind the bore is given by:

$$\lambda = \frac{2\pi h_1}{3} \sqrt{\frac{2h_0}{h_1 - h_0}} \tag{4}$$

The amplitude, *a*, of the displacement about the perturbed height, h_1, for the waves behind the bore can be approximated by:

$$a = \frac{1}{\sqrt{3}} \frac{h_1}{h_0} (h_1 - h_0) \tag{5}$$

Dewan and Picard [1] use expressions for the rate of energy dissipation, *D*, and for the amount of energy per wave crest, *E*, to come up with an expression for the rate of wave crest generation, *W*, given by:

$$W = \frac{D}{E} = \frac{U(h_1 - h_0)^3}{2a^2 \lambda h_1} \tag{6}$$

Using this equation for *W*, counting the number of wave crests (*C*) behind the bore, and knowing the velocity of the bore (*U*), one can use the following equation:

$$\chi = U \frac{C}{W} \tag{7}$$

to estimate the distance to the point where the bore originated.

To identify mesospheric undular bores according to the basic bore theory, the distinguishing criteria are as follows:

- A front separating light & dark regions. Phase speed, U = 20-100 m/s.
- Trailing waves "locked" to the movement of the front.
- Presence of a ducting structure, e.g. a mesospheric inversion layer (MIL).
- Layers vary in phase ("correlated") or 180^{o} out of phase ("standard"), depending on the altitudes of the MIL and the airglow layers.
- Number of trailing waves increases by 2-3/hr.
- Close linkage to periods of heightened gravity wave activity.

Motivated further by open-channel bore theory, as well as by inversion layer formation theory [3, 4], *Dewan and Picard* [2] extended their original work to include a possible mechanism for mesospheric bore generation. They showed that when the horizontal phase velocity of a gravity wave and the total background wind (including the mean wind plus the tidal component) are equal (i.e., at a critical layer), the resulting interaction between the wind and wave, combined with nonlinear effects, accelerates the fluid and acts as a piston, driving bore formation. *Dewan and Picard* [2] proposed that mesospheric bores could be formed by the same mechanism initially responsible for producing the inversion layer itself, serving as a waveguide for the bore. This bore generation scheme is the basis for one possible explanation – the dual bore theory (described in detail in *Loughmiller et al.* [8]) – for the inverted contrast airglow observations.

5. Data and analysis

The event depicted in Figure 6 illustrates a standard bore exhibiting the expected anti-correlated intensity pattern whereby a dark front advances in the upper airglow layer while a corresponding bright front propagates below.

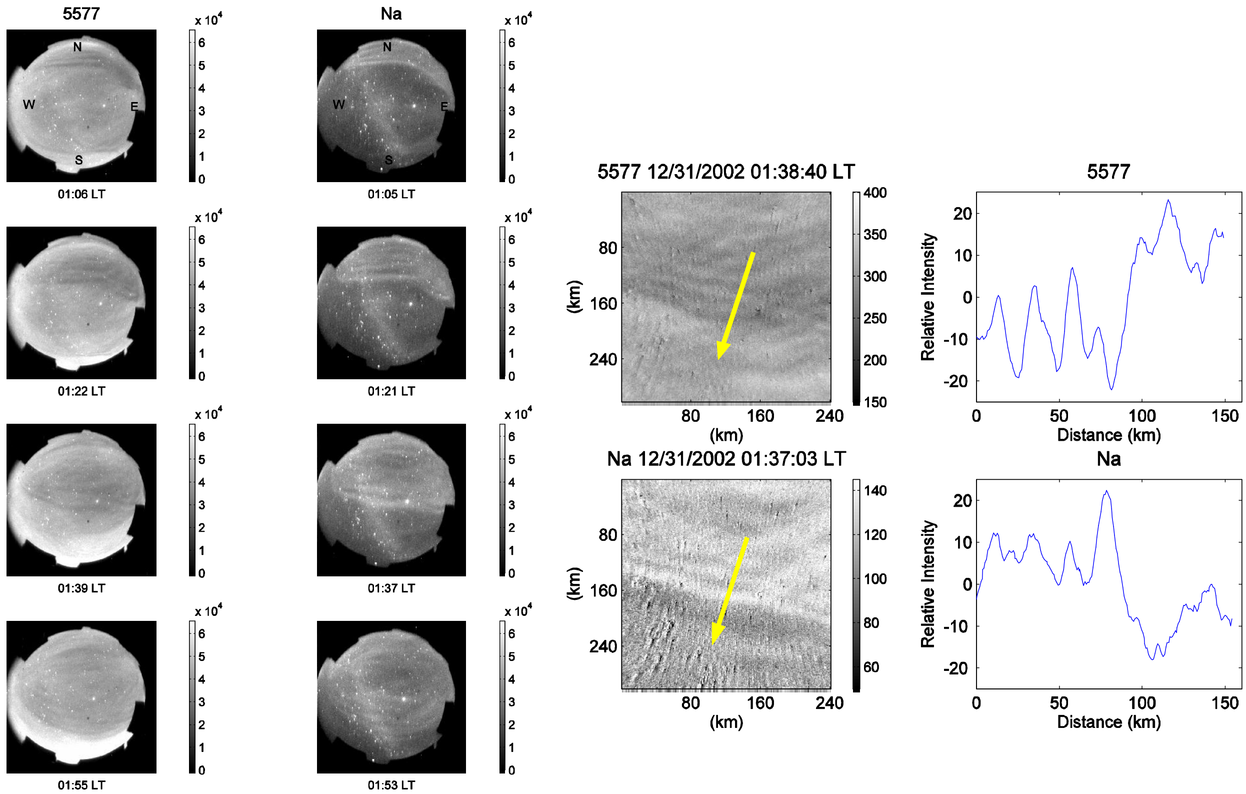


Fig. 6. The 8-plot on the left shows a time series of OI (557.7 nm) and Na (589.3 nm) airglow emission images depicting a front approaching approximately from the north on 31 December 2002. Time increases from top to bottom. The 4-plot on the right shows geographically projected images and cross-sections of both layers at one time. The arrows indicate the direction of propagation of the front. The line-plots show the relative intensity values across the scan lines (indicated by the arrows) in the geographically projected images. 0-km on the scan-line plots corresponds with the base of the arrows.

Contrasting with this standard event, the conflicting observations, as shown in Figure 7, exhibit an “inverse” complementarity. The lower layer (Na 589.3 nm) appears to be pushed up (becoming darker) while the corresponding upper layer (OI 557.7 nm) is pushed down (becoming brighter), which appears to be inconsistent with current bore models. Initially confounding the theory, these observations have now been analyzed and used to extend the theory further. We have proposed that the inverse relationship could be caused by the existence of two bores occurring simultaneously, one above the other.[6] This extension of the original theory also accounts for the apparent horizontal phase shift of 22 km between layers in the observations of Figure 7.

The distinctions in the airglow observations can be summarized by the mesospheric bore taxonomy scheme presented in Figure 8. The mesospheric undular bores imaged over the last decade fall into two basic types – *standard* and *inverse* -- categorized by how the upper and lower airglow emission layers oscillate with respect to each other. As such, note that observing a minimum of two emission heights for an event is necessary in order to distinguish this relationship, and hence, to classify the bore. The “correlated” and “standard” bore types are two similar variations, with the difference depending on which airglow layers are observed and in which region the bore is propagating. For a “correlated” bore, the upper and lower layers vary in phase with the bore either beneath or above both airglow layers; for the “standard” case, the bore drives the airglow layers apart, such that the layers vary 180^{o} out of phase. For the inverse complementarity situation, the upper and lower emission layers appear to be drawn together. The existence of two simultaneous bores nearly vertically aligned would create this observed effect.[8]

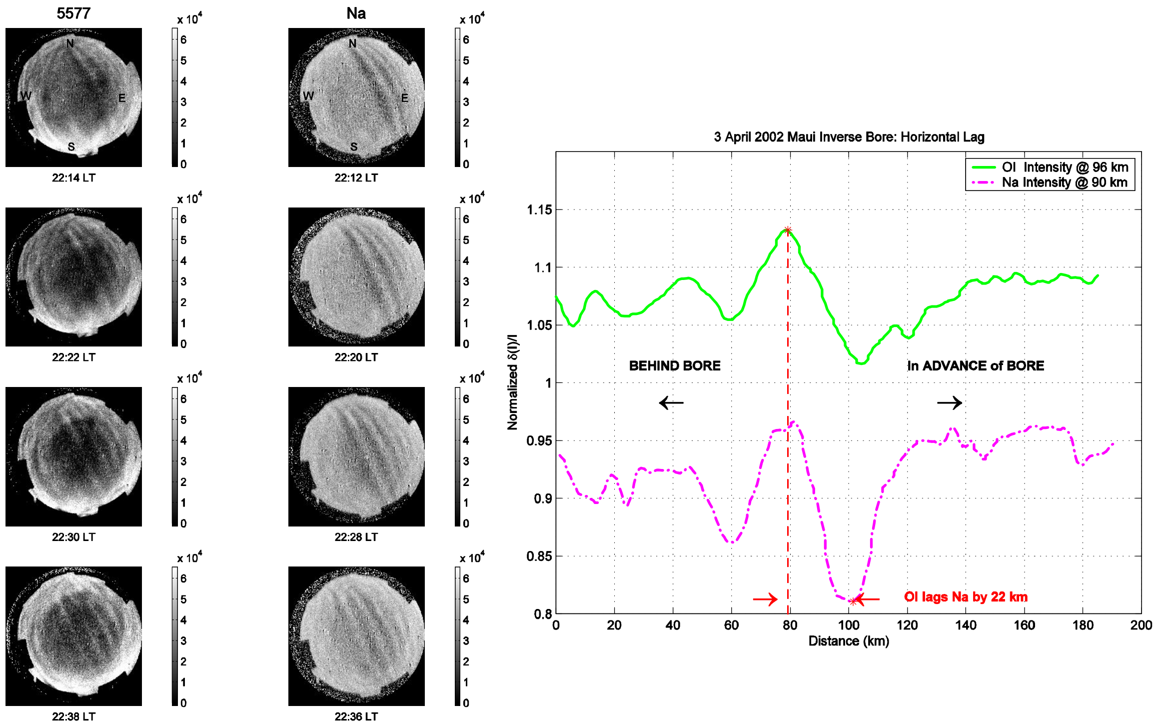


Fig. 7. The 8-plot on the left shows a time series of OI (557.7 nm) and Na (589.3 nm) airglow emission images depicting a front approaching approximately from the northeast on 3 April 2002. Time increases from top to bottom. The plot on the right shows cross-sections of both layers at one time showing the relative intensity values across the scan lines. Note that there is a horizontal lag between the leading edges of the front at the two heights.

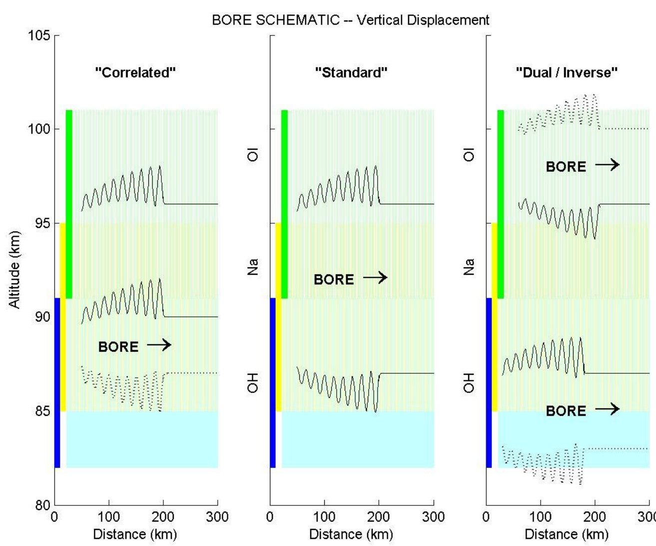


Fig. 8. Schematic depicting basic mesospheric undular bore classifications. Solid lines indicate the vertical displacement (*not* airglow intensity) of observed airglow emission layers. Dashed lines indicate either the assumed vertical displacement of emission layers *not* observed, or regions outside airglow emission layers. (From *Loughmiller et al.* [7])

To demonstrate the possibility that corresponding MILs exist for both the standard and inverse events, and could provide suitable propagation ducts for these bores, we examined coincident vertical temperature profiles from the SABER limb-scanning instrument on TIMED (see Figure 9 and Figure 10). Indeed, we found that MILs did exist, and analysis of the corresponding squared Brunt-Vaisala frequency verifies that the atmospheric temperature structure produced a duct that was sufficient to support bore propagation.

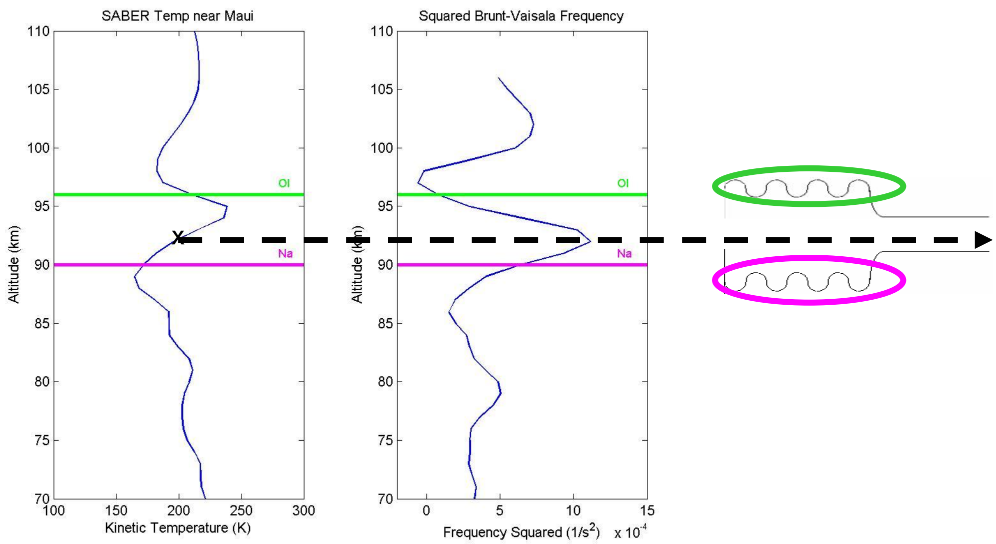


Fig. 9. Temperature and buoyancy frequency profiles over Maui, HI, on 31 December 2002. Temperature data from the SABER instrument on NASA's TIMED satellite is shown in the left panel with the corresponding squared Brunt-Vaisala profile plotted in the panel to the right.

Note that the MIL in the temperature data aligns with a large ducting region centered between the two observed airglow emission heights at 96 km (OI 557.7 nm - green) and 90 km (Na 589.3 nm - magenta). The schematic at the far right illustrates that the waveguide splits the two layers driving them apart as predicted by the basic bore theory.

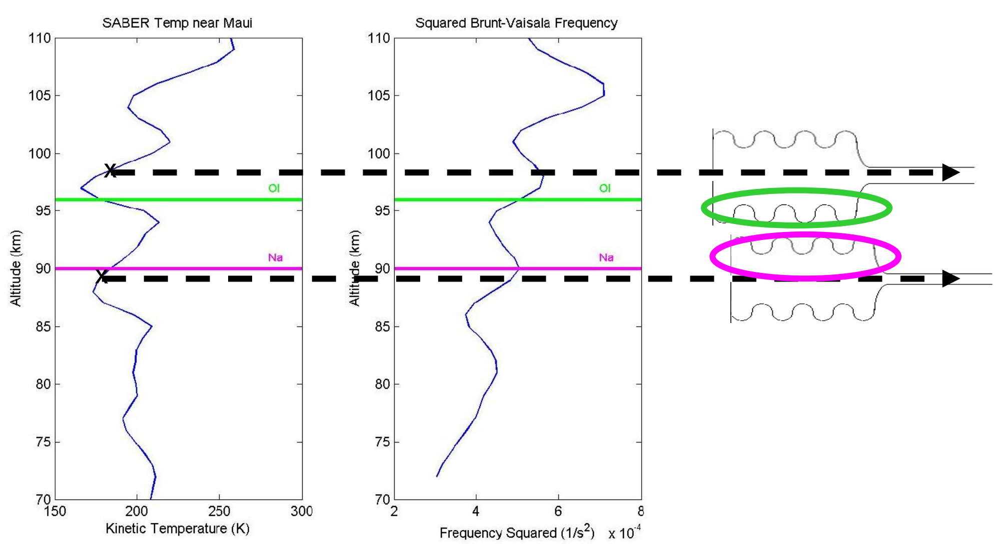


Fig. 10. Temperature and buoyancy frequency profiles over Maui, HI, on 03 April 2002. Temperature data from the SABER instrument on NASA's TIMED satellite is shown in the left panel with the corresponding squared Brunt-Vaisala profile plotted in the panel to the right.

Note that in this case *two* MILs are evident in the temperature data in our airglow observation region, aligning with *two* ducting regions vertically bounding the two observed airglow emission heights at 96 km (OI 557.7 nm indicated in green) and 90 km (Na 589.3 nm indicted in magenta). The schematic at the far right illustrates that the two waveguides could each support a bore, thus driving the two sandwiched airglow height layers together as predicted by the dual bore theory. Additionally, the leading edge of the upper and lower fronts could be offset by a horizontal lag.

6. Conclusion

In this paper, we revisited the basic analytic theory behind mesospheric bores along with motivation for these studies. We discussed three distinctly different taxonomic types of bore data observed to-date, and described the intensity contrast variations present in these airglow images. For the standard and inverse bore types, we presented airglow image data for representative events. One theory (the dual or multiple bore theory) is briefly described as a possible explanation for the inverse data which confounds the symmetry underlying the existing basic theory. A detailed description of the inverse theory explaining the dual bore hypothesis is formulated in *Loughmiller et al.*[8]. We further establish the plausibility of that proposed theory by presenting here coincident temperature profile data from the SABER instrument on NASA's TIMED satellite. This multi-instrument investigation revealed the existence of MILs in accordance with the theoretical expectations. One MIL was evident in the temperature data for the standard bore event, while two MILs were found in the data coincident with the inverse contrast airglow data. Analysis of the associated Brunt-Vaisala profiles revealed ducting structures accurately placed and sufficient in strength to support the observed bore propagation. While alternative explanations have also been proposed, the multi-instrument analysis reported here for the example inverse dataset is found to support the quantitative dual bore concept.

7. References

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8. Acknowledgements

The authors thank the staff at the Maui Space Surveillance Complex for their support in maintaining the instrumentation for the Maui-MALT campaign. The work originating at Cornell University was supported by the National Science Foundation under grant ATM-0000196 and by the Air Force Office of Scientific Research under grant F49620-01-1-0064 and FA9550-05-01600. At Embry-Riddle Aeronautical University, PJL is supported by the NSF CEDAR Postdoc Program under grant ATM-0437247; MPH is supported by NSF grant ATM-0408407. The work at AFRL and Arcon is supported by the Air Force Office of Scientific Research (Dr. Kent Miller, AFOSR/NE) and by NASA under the SABER program.