MCMURDO LIDAR CAMPAIGN: A NEW LOOK INTO POLAR UPPER ATMOSPHERE

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ABSTRACT

A new lidar campaign is ongoing at McMurdo (77.8°S, 166.7°E), Antarctica with an Fe Boltzmann lidar since December 2010. The data have extended resonance fluorescence lidar measurements into the thermosphere up to 155 km, leading to several intriguing science discoveries in the polar upper atmosphere. This is the first ever lidar detection of neutral species deep into the thermosphere, providing a new look in the thermosphere composition, temperature and dynamics. Furthermore, the large temperature coverage from 30 to 150 km of the lidar allows us to trace gravity waves from 30 to 150 km, providing crucial information to wave coupling and dynamics at this wave "hot spot". The high-resolution lidar data reveal rich spectra of gravity waves. The full diurnal coverage of the lidar enables us to characterize mesospheric clouds and many summer phenomena, leading to a better understanding of polar space science.

1. INTRODUCTION

Polar upper atmosphere provides a unique natural laboratory for studying the complex physical, chemical and dynamical processes in the Earth's atmosphere and space environment. However, it remains as one of the most difficult regions to observe. The McMurdo lidar campaign is aiming to address this issue with high-quality observations for new science discoveries. McMurdo Station (77.83°S, 166.66°E) located on the Ross Island, is half way between the South Pole and the Antarctic Circle. The McMurdo lidar campaign is completing an observational chain in combination with previous lidar measurements made at the South Pole (90°S) and Rothera (67.5°S) [1, 2].

With the support and collaboration of the United States Antarctic Program (USAP) and the Antarctic New Zealand (AntNZ), the University of Colorado lidar group installed an Fe Boltzmann temperature lidar into the AntNZ facility at Arrival Heights, McMurdo in Dec. 2010. This lidar was originally developed at the University of Illinois by Chu, Gardner and co-workers [3] and deployed to the North Pole (1999), the South Pole (1999–2001) and Rothera (2002–2005). Recently it was refurbished and upgraded at the University of Colorado. A schematic of the lidar system is illustrated in Figure 1, and *Chu et al.* [2002] elaborated its principles and technologies in [3].

The main lasers operating at 372 and 374 nm of two Fe absorption lines are the injection-seeded and frequency-doubled pulsed alexandrite lasers produced by Light Age, Inc. The seed lasers are external cavity diode lasers provided by Toptica Photonics. A well-calibrated Bristol wavelength meter (621A) provides the absolute frequency calibration to both lidar channels.

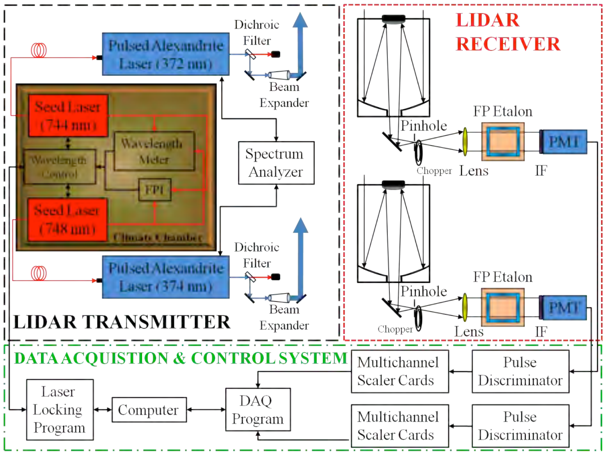

Figure 1. Architecture of the Fe Boltzmann temperature lidar deployed at McMurdo, Antarctica. Details of the lidar system can be found in *Chu et al.* [2002].

This lidar has full diurnal coverage and is capable of detecting polar mesospheric clouds (PMCs), meteoric Fe layers, and temperatures from the stratosphere to the thermosphere by combining the Fe Boltzmann technique (above 70 km) with the Rayleigh integration technique (below 70 km). Gravity and tidal waves can be inferred from temperature or density perturbations. A large amount of lidar data has been collected since December 2010, covering all months from January through December and the full diurnal cycle. This paper highlights several interesting results that have significant implications to the resonance fluorescence lidar technologies and atmosphere and space sciences.

2. FE LIDAR MEASUREMENTS FROM STRATOSPHERE TO THERMOSPHERE (30–155 KM)

The tracers for resonance fluorescence lidars are the meteoric metal species such as Fe, Na, K, Ca, etc. [4]. It was believed that these metal atoms are confined in the mesosphere and lower thermosphere (MLT) from 75 to 115 km. Although the 'topside layer' was reported up to

130 km [5], lidar observations had shown neither the neutral layers above 130 km nor the gravity waves above 110 km. Therefore, the 110–200 km range remains one of the least studied regions. Such a point of view has now radically changed because of the Fe lidar observations made at McMurdo, which show the neutral Fe layers extended well into the thermosphere up to 155 km with clear gravity wave signatures [2].

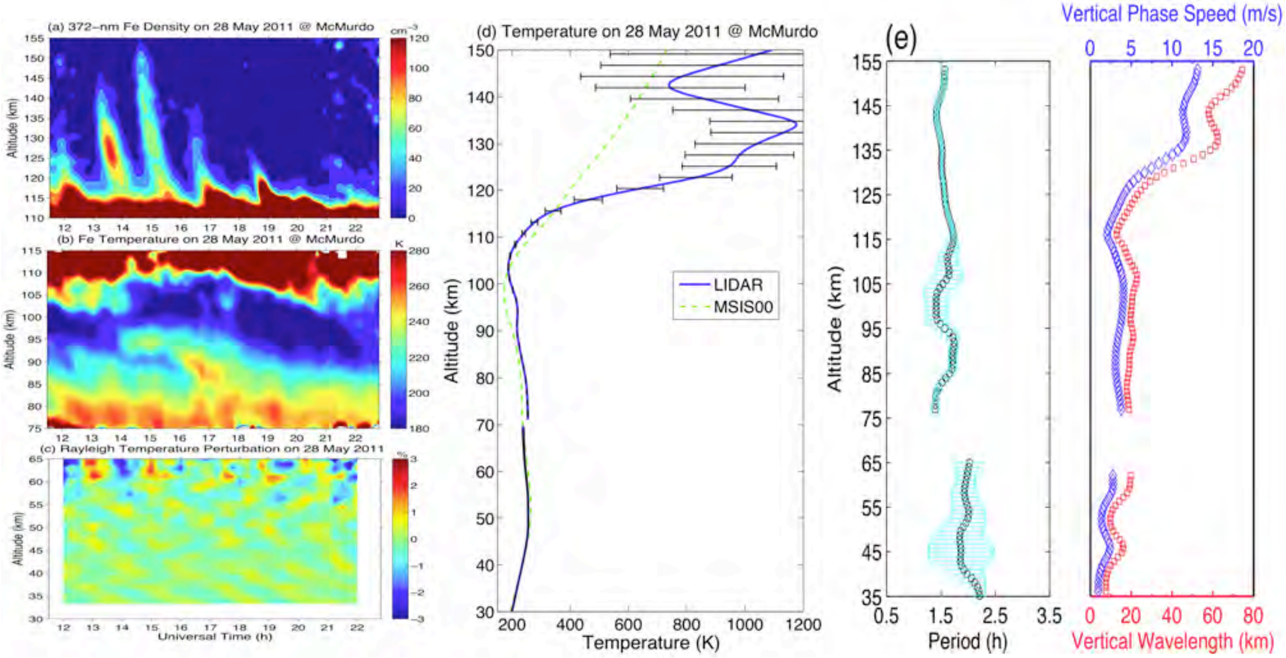

Figure 2. Fe lidar measurements on 28 May 2011 at McMurdo, Antarctica. (a) Thermospheric Fe density contour, (b) MLT temperature contour, and (d) temperature from 30 to 150 km were taken from [*Chu et al.,* 2011b]. (c) Relative perturbations of Rayleigh temperature are new results. (e) The period and vertical wavelength/phase speed are taken from [*Chu et al.,* 2011b], but extended from 75 km to 35 km via incorporating the newly obtained wave analysis results. The errors for vertical phase speed are 0.2–0.8 m/s, and the errors for the vertical wavelength is about 3–5 km.

Illustrated in Figure 2a is one of the examples for the thermospheric Fe layers detected by the Fe lidar at McMurdo [2]. This event occurred on 28 May 2011. The Fe layers between 110 and 155 km are distinct and show apparent wave features. The highest Fe layer occurring around 14.7 UT reaches 155 km, and then descends with time. The profiles of the highest Fe layer exhibit appreciable Fe densities above 115 km in both 372 and 374 nm channels. The number densities in the 372-nm Fe layer vary from ~65 cm^{-3} at 130 km to ~20 cm^{-3} at 150 km, which are small when compared to the main layer peak density of ~20,000 cm^{-3}. Overall the Fe density above 120 km is rather low, with a maximum close to 110 cm^{-3} around 125 km at 13.5 UT. Another event on 2 May 2011 exhibits the maximum Fe density of ~200 cm^{-3} at 120 km in the thermosphere [2].

The occurrence of the thermospheric Fe layers is periodic. Both lidar channels (372 and 374 nm) show the same wave features from 110 to 155 km. The wave has a downward phase progression. The vertical phase speed is largest at the highest altitude but around 125 km the phase speed decreases quickly with decreasing altitude. The vertical wavelength is shortest at 115 km and increases significantly with increasing altitude. Spectral analysis of the Fe layers using wavelet shows that the period of the wave (~1.5 h) is nearly constant through the 115–155 km range. Such wave is also visible from the MLT temperature contour (Figure 2b) derived from the main Fe layers. The MLT temperature variations are dominated by a wave of ~8 h with a vertical phase velocity of -0.7 m/s. Shorter-period waves of ~1.5 h are clearly visible below 90 km. Below the MLT, the short-period waves are visible in the Rayleigh temperature perturbations after the dominant waves of ~8 and 5 h are extracted (Figure 2c). Applying the spectral analysis approach outlined in [2], we derive the apparent wave period, vertical phase speed, and vertical wavelength. The results are illustrated in Figure 2e. The wave period in the Rayleigh region is ~2 h, slightly longer than that in the regions above. Note that the observed wave period can change in time if the background wind changes rapidly. It is clear from Figure 2e that the vertical phase speed and wavelength increase from the stratosphere to the MLT and then to the thermosphere. The waves in the MLT and Rayleigh regions are in general consistent with the thermospheric gravity waves, supporting the hypothesis that the waves originated from the lower atmosphere.

Although the thermospheric Fe densities are low, they are sufficient for deriving the Fe temperatures using the Boltzmann technique [3]. Taking the highest Fe layer that goes to 155 km, we derive the Fe temperatures from 75 to 150 km using the Boltzmann technique. Combining with the Rayleigh integration technique, the Fe lidar is able to measure temperatures from 30 to 150 km as shown in Figure 2d. Also plotted are the MSISE-00 temperatures for McMurdo location on 28 May 2011. The MSIS temperatures are close to the lidar data below 110 km. Above 115 km and below 135 km, the Fe temperatures are much warmer than MSIS. As discussed in [2], the elevated temperatures appear to be linked to Joule heating enhanced by aurora.

As discussed in [2], the observed thermospheric Fe layers are most likely linked to the layered Fe^+ ions that are neutralized to produce Fe. Vertically converged Fe^+ ion layers descend in height with time, following the gravity wave downward phase progression, which forms the observed layer shape. It is likely that the direct recombination with electron converts Fe^+ to Fe during the dark polar night [2]. Our further analysis indicates that the thermospheric Fe layers correspond to the cold phase when descending into the MLT region (not shown). This result makes sense, as the recombination rate is higher at lower temperatures. Certainly, the quantitative explanations of these events require detailed modeling studies considering all possible chemical reactions related to Fe^+, Fe, the compounds, sources and sinks and all possible paths to convert between Fe^+ and Fe. Information on Fe^+ and other background species and wind is also necessary to the quantitative modeling. To figure out the wave sources, it is necessary to make gravity wave modeling and ray-tracing studies. Overall these resonance lidar observations are challenging our understanding of polar upper atmosphere.

3. WAVE DYNAMICS AT MCMURDO, ANTARCTICA

The lidar measurements in the last 15 months have revealed very active wave activities at McMurdo. The example in Figure 2 illustrates the wave influence in a very large range from the lower to upper atmosphere. Here we present another case where the high-resolution MLT temperature measurements reveal both long- and short-period waves in Figure 3.

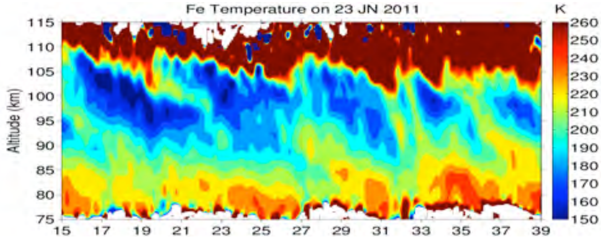

Figure 3. Fe temperatures vs. UT and altitude in the MLT region measured on 23-24 June 2011 at McMurdo.

Strong wave activities like Figure 3 are common at McMurdo. Nearly every observational day shows strong waves, especially from May through August. To further analyze the wave spectrum, we plot a time series of temperature at 100 km in Figure 4, which shows a large amplitude wave with a period of ~5–6 h, a short-period wave of ~2–3 h, and an even higher frequency wave with a period of ~30–50 min. A wavelet analysis confirms the existence of these waves.

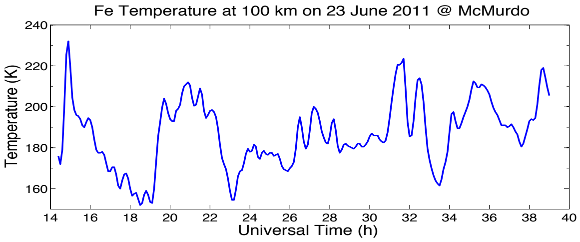

Figure 4. Time series of temperature at 100 km. The temperature errors are less than 3 K.

More comprehensive studies of gravity waves can be found in a companion paper [6], in which the wave intrinsic properties are derived. Furthermore, by taking monthly composite, we are also able to characterize tides at this high southern latitude. It is noteworthy that the tidal amplitudes are relatively small at McMurdo.

4. SUMMER POLAR REGION UNDER SUNLIGHT

Summer polar region is under sunlight through the full diurnal cycle, thus demanding the lidar to have full-diurnal capability as demonstrated by the McMurdo Fe lidar. Figure 5 illustrates the detection of PMC in a lidar run over 30 hours. PMCs show up near 85 km through the entire period, with variations in the brightness and altitude likely modulated by various waves.

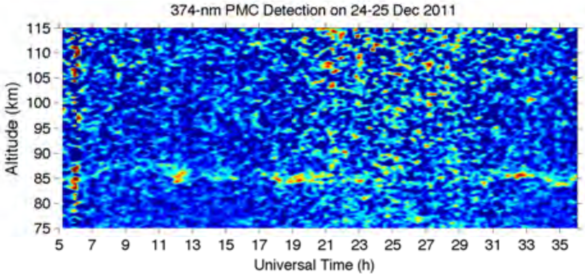

Figure 5. PMC layers detected by the 374-nm channel continuously for over 30 hours on 24-25 Dec 2011.

The McMurdo Fe layers are observed to be very dynamical, not only showing the thermospheric Fe layers as in Figure 2, but also exhibiting dramatic changes in the MLT region, especially during summer season. Such an example is plotted in Figure 6. Through the 32-h observations, the peak Fe density varies from a typical summer value of about several thousands cm^{-3} to an extremely high density of $\sim 2\times10^5$ cm^{-3}. Fe column abundance increases over 10 times around 25 UT.

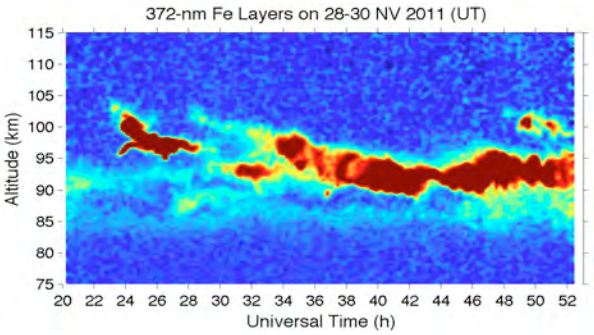

Figure 6. Fe layers detected in the 372-nm channel on 28-30 November 2011.

Such high density is comparable to Leonid meteor trails; however, the high density occurs in an altitude range much wider than a meteor trail of a few 10s or 100s meters. The extreme growth of Fe layers is certainly sporadic, but the large width of such layers from 34 to 50 UT calls for a revision to the definition of sporadic layers, challenging our understanding of the formation mechanisms of these layers.

5. CONCLUSIONS AND OUTLOOK

The McMurdo campaign with an upgraded Fe Boltzmann temperature lidar has made several new science discoveries in the polar upper atmosphere studies. An intriguing discovery is the neutral Fe layers with clear gravity wave signatures extended well into the thermosphere (110–155 km), which provides new insight of the thermosphere composition, thermal structure and wave dynamics. The Fe lidar operating at UV 372 and 374 nm wavelengths is also very powerful in resolving gravity waves from ~30 km all the way to 155 km or higher. The simultaneous detection of PMC, Fe layer and temperature enables comprehensive studies of polar middle and upper atmosphere. It is fair to say that the McMurdo lidar observations are transforming our understanding of the thermosphere and mesosphere.

Such a discovery of thermosphere Fe layers with gravity wave signatures has significantly extended the detection range of resonance fluorescence lidars from the lower to upper thermosphere (above 150 km). It is worth to note that such a discovery was made with a decade-old Fe Boltzmann lidar that has only 40-cm receiver apertures. Several steps may be taken in the future to do exciting science out of these new discoveries. First, a large aperture optical facility will dramatically improve the signal strength and resolution, potentially pushing the detection range further upward to above 160 km. Second, the new-generation Fe lidar, like the Major Research Instrumentation (MRI) Fe Doppler lidar based on a pulsed alexandrite ring laser, will provide both temperature and wind measurements that will significantly help the science studies of the observed thermosphere Fe layers. Third, operating the Fe Doppler lidar along with an incoherent scatter radar will bring the needed information of both the neutral and ion layers as well as the background temperature, wind and density. Adding further collaboration with atmospheric modeling, we believe this is the way to bring a closure to understanding the thermosphere Fe layers, and to make really comprehensive studies of the thermosphere, ionosphere, and their interactions and impacts.

The McMurdo lidar campaign has opened a door to new science discoveries and breakthroughs. We intend to continue the McMurdo observations for the next 5–10 years, covering at least a solar cycle. The data will be invaluable to the upper atmosphere and space science research, and will provide crucial information to climate models and space weather forecast models.

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