FROM ANTARCTICA LIDAR DISCOVERIES TO OASIS EXPLORATION

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ABSTRACT

Stunning new science discoveries including neutral thermospheric metal layers in the 100–200 km altitude from McMurdo lidar campaign and other world lidar observations have led to a new initiative in the middle and upper atmosphere science community—the very large-aperture lidar Observatory for Atmosphere Space Interaction Studies (OASIS). These discoveries and the recent technology breakthroughs in Fe and Na Doppler lidars are presented to illustrate the science drivers and technology foundations forming the basis for OASIS.

1. INTRODUCTION

Can lidar observations and resulting discoveries help advance humanity's exploration of the universe, especially in the search for exoplanets? This is a question to which all lidar researchers wish to answer a big "YES" but wondered "how" in the past. In this paper we present a pathway, enabled by the new lidar discoveries from Antarctica and then from the rest of the world, which can make good contributions to this question through exploring the Earth's Space-Atmosphere Interaction Region (SAIR) with lidar.

The pathway starts at understanding the Earth—our home in the universe. Earth has remained habitable during the last 3.5 billion years because of the effects of a set of key universal processes that govern the evolution of planetary atmospheres everywhere. For example, the Earth's magnetic field shields our atmosphere from the energetic particles in the solar wind that are partially responsible for stripping Mars of its primordial atmosphere. The Earth's carbonate-silicate cycle provides a feedback mechanism that controls atmospheric CO_2 levels and climate over long time scales, preventing the runaway greenhouse effect that is responsible for the high temperatures on Venus today. Many coupled feedback processes are at play in a planetary atmosphere system. But most of these are unknown and cannot be addressed without a complete description of the atmosphere, from lower interaction with land/ocean to upper interaction with space [1].

The natural upward extension of a planet's atmosphere ultimately leads to its interaction with space, where atmospheric neutral gases entwine with the dynamic plasma of space. This SAIR is common to all planetary systems, yet its properties, and the processes that govern them, are not described sufficiently to fully understand its role in an atmosphere's development and evolution. However, the SAIR is known to be essential for sustaining life on Earth by absorbing extreme solar radiation, ablating meteoric materials, regulating gaseous escape, dissipating energetic particles and fields from space, while balancing influences from the planet itself in the form of wave energy and momentum originating from the lower atmosphere.

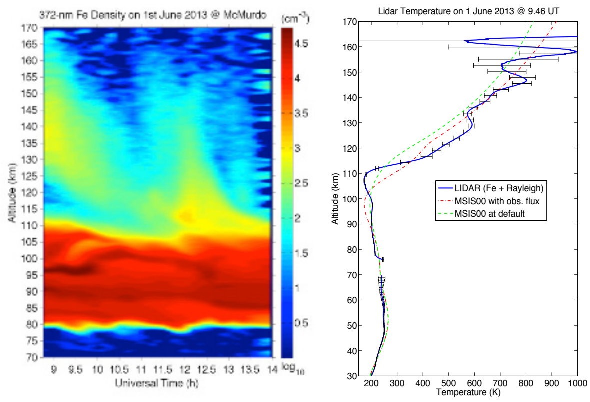

Fig. 1. Neutral Fe layers and temperatures observed by Fe lidar reaching 170 km at McMurdo, Antarctica.

The overarching goal of the pathway is to significantly advance our understanding of the fundamental, universal processes in the Earth's SAIR and how they shape the atmospheres of Earth-like planets throughout our galaxy. By doing so with advanced lidars and cluster instruments, the world's lidar researchers provide spectroscopic signatures for Earth-like planets!

This pathway remained a dream in the past, because no lidars could detect the atmosphere or space above ~110 km, until the discoveries of neutral metal layers in the altitude range of 100–200 km made by an Fe Boltzmann lidar at McMurdo, Antarctica [2] and then followed by other lidar measurements in the rest of the world. Such neutral metal layers with an example shown in Figure 1a provide excellent tracers for lidar to observe the neutral atmosphere into the thermosphere and their interaction with the ionosphere. This stunning lidar observation at McMurdo was made with a telescope of 40-cm diameter. To turn the dream into reality, scientists from the atmosphere and space science community began to consider 100 m^2 telescopes with advanced next-generation lidars. We name this pathway OASIS—The Observatory for Atmosphere Space Interaction Studies [1].

In this paper several new science discoveries during the McMurdo lidar campaign from 2011 to 2015, along with the most recent lidar technology breakthroughs, are presented to illustrate the science drivers and technology foundations forming the basis for OASIS.

2. MCMURDO LIDAR CAMPAIGN

The McMurdo lidar campaign started in Dec 2010 when an Fe Boltzmann temperature lidar was installed at the Arrival Heights observatory (77.8ºS, 166.7ºE) by the University of Colorado via collaboration between United States Antarctic Program and Antarctica New Zealand [3]. The lidar has been operated there ever since. The lidar observations are all year round and cover full diurnal cycle, weather permitting. Four graduate students (Zhibin Yu, Brendan Roberts, Weichun Fong, and Cao Chen) have braved through the harsh Antarctic winters of 2011–2014, and the 5th winter-over student (Jian Zhao) is operating the lidar to collect data in 2015. The rich lidar data from McMurdo cover from ~10 km all the way to over 170 km.

McMurdo lidar data have enabled many new science studies, in combination with co-located radar and satellite observations as well as numerical modeling, e.g., the discoveries of thermospheric Fe layers, fast gravity waves and elevated temperatures under geomagnetic storms [2], polar mesospheric clouds at 78ºS [3], diurnal variations of Fe layers and solar effects on the layer bottomside [4], two simultaneous inertia-gravity waves in Antarctica [5], large eastward planetary waves in the stratosphere [6], temperature tides from 30–110 km [7], and vertical evolution of potential energy density and vertical wavenumber spectrum of Antarctic gravity waves from 35 to 105 km [8]. The lidar temperature data led to a discovery of fast amplitude growth with altitude of diurnal temperature tides in the winter lower thermosphere and dependence on geomagnetic activity, which was then studied with CTIPe model and attributed to the Hall-ion-drag induced adiabatic cooling and heating [9].

These discoveries and observations provide unique opportunities to study the complex physical, chemical, dynamical, energetic and electro-dynamical processes in the Earth's atmosphere and space environment. Here we choose a few new studies to present.

3. THERMOSPHERIC METAL LAYERS OPEN A NEW DOOR TO EXPLORE SAIR

The most intriguing discovery is perhaps the neutral Fe layers with clear gravity wave signatures observed well into the thermosphere of 100–200 km altitude. Such discovery challenges the current understandings of the upper atmosphere composition, chemistry, dynamics and energetics, while the neutral metal layers open the door for lidars to measure neutral temperatures and winds in the thermosphere directly. Measurements of the neutral thermosphere are woefully incomplete and in critical need to advance our understanding of and ability to predict the SAIR. Figure 1b demonstrates one of the first lidar measurements of neutral temperatures from 30 to 170 km on 1 June 2013 at McMurdo. Modern Fe Doppler lidars can certainly use such metal layers to measure the neutral winds directly.

An earlier example on 28 May 2011 exhibits clear gravity wave features from 35 to 155 km with periods of 1.5–2 h (see Figure 2a) [2]. *Chu et al.* [2] hypothesize that the thermospheric Fe layers are formed through the neutralization of vertically converged Fe^+ layers that descend in height following the gravity wave downward phase progression. Conversion from Fe^+ to Fe in the thermosphere is most likely through the direct recombination of Fe^+ with electron: $Fe^+ + e^- \rightarrow Fe + h\nu$. Except for this qualitative explanation, we know very little about these layers, e.g., why, when, and where these thermospheric layers occur, how they vary, and to what altitude range they extend. Although the main metal layers between ~75 and ~105 km come from cosmic dust entering the Earth's atmosphere, it is puzzling how these heavy neutral metals are transported to such high altitudes.

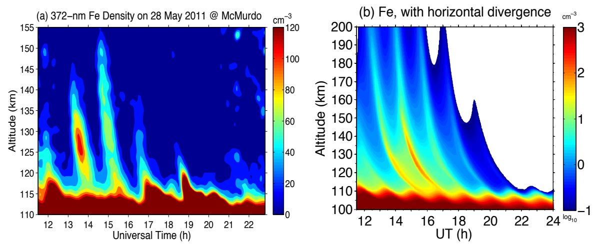

Fig. 2. (a) Thermospheric Fe layers with 1.5-h gravity waves up to 155 km observed by lidar on 28 May 2011 at McMurdo [2]. (b) Numerical simulation of Fe layers by the University of Colorado Fe/Fe^+ model.

To quantitatively explain the observations and advance the understanding, we have developed a thermospheric Fe/Fe^+ model for the polar region. Details of this model can be found in *Yu and Chu* [10] and in a PhD dissertation of Dr. Zhibin Yu. Here we illustrate one of the model results in Figure 2b and briefly introduce some important model findings. Figure 2b represents a nice reproduction of the Fe layer observations, except the modeled contrast is not as high as the observations.

Numerical simulations confirm the hypothesis by *Chu et al.* [2] that the thermospheric Fe layers are produced through the neutralization of vertically converged Fe^+

layers. The Fe/Fe^+ model quantitatively demonstrates that the conversion from Fe^+ to Fe above 120 km is mainly through the direct electron-Fe^+ recombination. While the meteor injection rate of iron species is negligible above 120 km, we find that the polar electric field is sufficient in transporting Fe^+ ions from their main deposition region (~80–110 km) to the E–F regions, therefore supplying the source for Fe atoms in the thermosphere (see Figure 3).

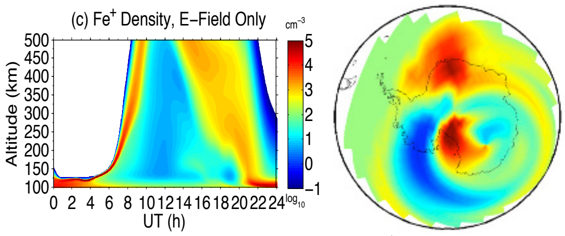

Fig. 3. (a) Vertical transport of Fe^+ ions by the polar electric field on 28 May 2011 at McMurdo. (b) A map of vertical ion drift velocity at 117 km: Ion upward transport (red) patch is over McMurdo for many hours.

Furthermore, the model predicts that diurnal variations of the convection electric field (Figure 3b) should lead to diurnal occurrence of thermospheric Fe layers. This has been proven by the 50 hours of continuous Fe observations taken by Mr. Cao Chen in June 2014 at McMurdo (see Figure 4). Fe layers occurred three times with the layer height peaking around 8 UT.

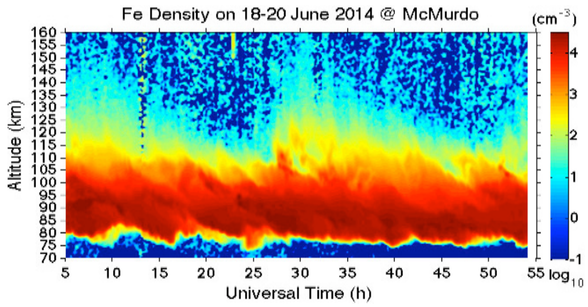

Fig. 4. Continuous 50 h of lidar observations show a diurnal period occurrence of thermospheric Fe layers.

The thermospheric metal layers are not limited to McMurdo but appear to be a global phenomenon. Indeed, similar layers have been observed at other Antarctic stations, e.g., Fe layers at Davis [11] and Na layers at Syowa. Similar metal layers have also been observed at mid- and low-latitudes following the McMurdo discoveries, e.g., K layers up to 155 km at Arecibo, Puerto Richo, and Na layers up to 170 km at Lijiang, China and Cerro Pachon, Chile [12]. In principle, as long as metal ions like Fe^+, Na^+ and K^+ can be transported upward, neutral metal atoms can be formed through direct recombination so they are detectable by lidars with sufficient detection sensitivity. These metals provide tracers for the world's lidar researchers to measure the SAIR worldwide!

4. POLAR WAVES SHAPING THE SAIR

The recent McMurdo lidar data in March 2015 indicate the Fe layers reaching 180 km with ~1–3 h wave period. Such waves frequently occur and survive into the thermosphere as shown in Figures 1, 2 and 4. They have gravity wave nature. However, the 4–9 h waves demonstrated in Figure 5 are so persistent that they have been observed lasting throughout 3 days in winter and even 7 days of a lidar marathon in summer. Are they relatively localized inertia-gravity waves or planetary-scale inertia gravity waves (forced Class I gravity mode)? This remains a mystery–for details see *Chen et al.* [13]. Considering such waves easily cause ±30 K temperature perturbations near 100 km, it is important to identify its nature, sources and impacts.

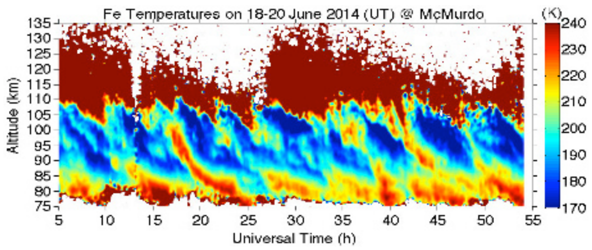

Fig. 5. Continuous 50-h temperature measurements show persistent 4–9 h waves on 18–20 June 2014.

In addition to the several studies on gravity, tidal and planetary waves mentioned earlier, the extensive datasets collected in May 2014 show the long-period temperature variations over 5–6 days (Figure 6), indicating planetary wave influences in the mesopause region. Atmospheric waves across various spatial and temporal scales transport energy, momentum and constituents among different atmospheric regions, so shape the SAIR significantly.

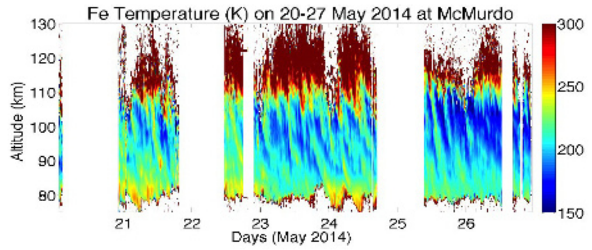

Fig. 6. Temperatures measured over 6 days in May 2014 indicate planetary wave influences.

5. RECENT LIDAR BREAKTHROUGHS

Several new powerful Fe and Na Doppler lidars with simultaneous wind, temperature & density capabilities have been developed recently. They represent some significant advancement in lidar technologies. One is high-efficiency lidar receiver architecture developed at the University of Colorado Boulder that allows the Na Doppler lidars to achieve very high resolutions with ~80-cm diameter telescopes, enabling new science inquiries from turbulence to the middle thermosphere [12]. Another is the Major Research Instrumentation (MRI) Fe/Rayleigh/Mie Doppler lidar that has revolutionized the resonance lidar transmitter and receiver technologies. The advanced concepts of modular resonance Doppler lidar are integrated with a unique Pulsed Alexandrite Ring Laser (PARL) and a new acousto-optic modulator (AOM) path design, along with absolute frequency stabilization of laser pulses using Doppler-free Fe spectroscopy and optical heterodyne detection (OHD) techniques. Combined with high-efficiency receiver and data acquisition system, the MRI Fe Doppler lidar has achieved superb Fe signal levels at Table Mountain in 2014, making this lidar a new workhorse for SAIR exploration. Details will be given in the full paper.

6. CONCLUSIONS

Three basic questions have commanded the attention of atmosphere and space scientists for generations [1] –
1) What are the fundamental processes that shape the Earth's upper atmosphere and govern its evolution?
2) How do these processes affect weather and climate?
3) What roles do they play on other planets?
These questions are especially relevant today as rising concentrations of greenhouse gases are changing Earth's climate and increasing numbers of extra-solar planets are being discovered in our galaxy.

Using the recently discovered neutral metal layers in the thermosphere, the modern Doppler lidars can directly measure the neutral winds and temperatures along with metal species densities to address key SAIR science issues. Because the densities of thermospheric metal layers are usually 50–1000 times lower than the main layer peak at ~90 km, the very large-aperture and high-power lidars as envisioned by the OASIS are required to realize the world lidar researchers' dreams to answer these key questions.

The OASIS pathway will enable lidar researchers to explore the plasma-neutral atmosphere coupling in SAIR, investigate transport and turbulence processes, and study influences of space processes (e.g., cosmic dust, energetic particle precipitation, and radiation) and planetary processes (e.g., compositions and waves). Understanding these universal processes will certainly help advance the exploration of the universe.

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