High-Detection-Sensitivity Doppler and Boltzmann Lidars for First Measurements of Vertical Fluxes of Sensible Heat and Meteoric Na and Fe in Antarctica

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Abstract: McMurdo lidar observations have turned out to be an extraordinary science-discovery journey in Antarctica, owing to advancement in resonance-fluorescence Doppler and Boltzmann lidars. This report presents the high-detection-sensitivity lidars that have enabled the first measurements of heat, Na, and Fe fluxes in Antarctica, allowing the inference of cosmic dust influxes and metal species lifetimes.

1. Introduction

Observing the space-atmosphere interaction region (SAIR) represents a singular challenge, as it is too high for balloon but too low for satellite observations. SAIR is a crucial part of the Sun-Earth system because it creates the environment that allows human life to thrive by protecting the Earth's surface from the harsh space environment. SAIR is also a complex region where transformation of energy and momentum happens frequently among different sources like the Sun, the Earth's magnetic field, the ionosphere, and the neutral atmosphere. Vertical transport in SAIR involves energy from below, in the form of atmospheric waves of different periods (like gravity & tidal waves), and from above, in the form of solar radiation, auroral precipitation, and Joule heating, etc.

Lidar provides a unique tool to make direct measurements in SAIR, especially when using metal atoms/ions as tracers to study the physics, dynamics, & chemistry of ion-neutral coupling and cosmic dust as well as transport of energy and constituents. Lidar measurements of SAIR in Antarctica where significant solar wind energy reaches SAIR via particle precipitation and Joule heating, represent grand challenges but also utmost rewards to the lidar research.

Since Dec 2010, the University of Colorado lidar group has been making lidar observations to explore SAIR at McMurdo, Antarctica for over a decade. Numerous eye-opening science discoveries have emerged from the lidar data, pushing the envelope of space-atmosphere sciences. The Antarctica lidars also reflect the significant progress in lidar technologies and campaign explorations, which has recently led to high-resolution measurements of vertical winds, temperatures, and species, enabling the profiling of vertical fluxes of energy and metal species (such as Na and Fe) as well as studies of cosmic dust influxes and metal lifetimes.

The main goal of this report is to delineate the advanced lidar technologies and precious engineering experiences gained over the last decades in Antarctica. The lessons we learned will propel future lidar expeditions.

2. Na Doppler and Fe Boltzmann Lidars at McMurdo, Antarctica

The Fe Boltzmann lidar running at McMurdo owns a legendary history—it made the airborne observations of 1998 Leonids meteor shower over the Pacific Ocean [1] and the Pole-to-Pole measurements from the North Pole (90ºN) to the South Pole (90ºS) in 1999 [2]. The Fe Boltzmann factor concept was proposed by Gelbwachs [3], and the Fe Boltzmann lidar was developed by Chu, Papen, Gardner, and co-workers with its principles and instrumentation described in [4]. After making observations at Rothera Station in 2002-2005, the lidar system was refurbished and upgraded at the University of Colorado [5]. Then it was deployed by our team to McMurdo in late 2010 [6, 7] and has been running there for over a decade.

This Fe lidar employs two injection-seeded, frequency-doubled, Pulsed Alexandrite Lasers

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(PALs) in a linear configuration running at 372 and 374 nm. Two PALs were developed by Walling, Heller, and co-workers of Light Age, Inc. (LAI). An initial technical issue was the mode hops of two seed lasers caused by optical feedback from powerful PAL pulses. We resolved the issue by adding Glan-laser polarizers to the optical isolators used inside the PALs' injection seeding boxes as the original polarizers could not afford the laser pulses.

Over the years at McMurdo, the original seed lasers were replaced with two robust Toptica external cavity diode lasers (ECDLs) running at 744 and 748 nm in a well-insulated climate chamber; the original plastic pump chambers were replaced with stainless-steel pump chambers with their reflector qualities largely improved; the original injection seeding plates were replaced with thin-film polarizers (TFPs) arranged at the Brewster angles with high damage thresholds; and the LBO housings for second harmonic generation were extended for improved frequency-doubling efficiencies but reduced risks of optical damages by UV laser light. The lidar team has also developed the yearly refurbishment of PAL pump chambers (e.g., reflectors, laser rods, & quick connectors) and components in PAL power consoles. This is why the Fe lidar is still running strong for discovery sciences in Antarctica even after a quarter of a century since its birth.

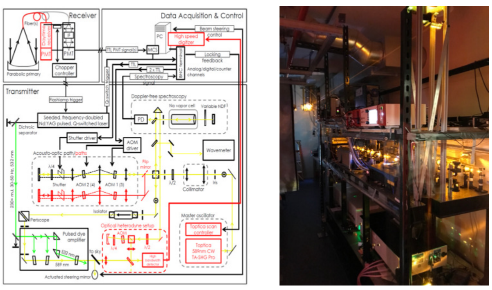

Figure 1. High-detection-sensitivity STAR Na Doppler lidar with a special double-level structure at McMurdo, Antarctica.

Adding a Na Doppler lidar, which employs a 3-frequency ratio technique [8] to probe vertical wind, temperature, & Na density, next to the Fe Boltzmann lidar in Jan 2018 had elevated the McMurdo lidar campaigns to unprecedented highs for science discoveries and engineering explorations in the unique and harsh conditions. The first issue was the limited lab space with heating in Antarctica. In response to it, we came out an innovative design of a double-level Na Doppler lidar transmitter as illustrated in Fig 1.

This transmitter design fit the Na lidar with the Fe lidar in Arrival Heights Lidar Observatory hosted by Antarctica New Zealand, enabling the first simultaneous and common-volume Na/Fe lidar observations in Antarctica [9].

This Na Doppler lidar was named STAR (Student Training and Atmospheric Research) as it was initially developed in Boulder by graduate students under the supervision of the lead author using a refurbished ring dye laser (RDL), a repaired Nd:YAG laser, and a home-assembled pulsed dye amplifier (PDA). The innovative design and implementation of receivers at very high efficiencies made this STAR lidar with an 81-cm aperture to achieve very high signal levels/resolutions [10].

Significant upgrades were made to the lidar transmitter before its deployment to Antarctica, e.g., RDL and YAG were replaced with a solid-state 589-nm CW laser source (TA-SHG Pro) made by Toptica and a new 50-Hz YAG laser made by Spectra-Physics, respectively.

Crucial additions made at McMurdo include three robust periscopes to 1) elevate the cw laser beam height for the AOM path, Na saturation-absorption spectroscopy, & wavelength meter measurements, 2) shoot the 589-nm CW beam from the upper optical table to the lower table for injection into the PDA, and 3) direct the outgoing PDA laser pulses to be close to the STAR telescope mirror for overlapping with the receiver field of view.

Implementation of the STAR Na Doppler lidar in Antarctica represented another significant progress in lidar engineering. Despite being student products initially in Boulder suffering various issues, the STAR lidar implementation and upgrades in Antarctica were conducted by the experienced lead author, which pushed the STAR lidar to a new level – accurate, stable, robust, and reliable. Her rebuilt of the PDA and entire AOM path, coupled with the robust TA-SHG Pro laser, made this Na lidar way more stable and easier operation than the Fe lidar.

Major issues dealt with include YAG pump chamber, flashlamp simmer, internal cooling water system, and high-voltage power supplies as well as PDA dye circulator hoses plus optical damages to dye cell 3 (DC3). Replacing dye cells and Na cells for Doppler-free spectroscopy and Faraday filter setups are refurbishment tasks for long-term observations.

3. Simultaneous Observations of Temperatures, Vertical Winds, & Na and Fe Densities in Antarctica

Very-high-resolution measurements by the Na Doppler lidar were demonstrated in Figure 2. The raw data were collected at $\Delta t = 4.5\ s$ and $\Delta z = 24\ m$. Temperature, vertical wind, and Na density (TWD) were retrieved at resolutions of 2.5 min and 0.96 km, enabling the coverage of full temporal spectrum of gravity waves from the buoyancy period (~5 min) to inertial period (~12.3 hr) at McMurdo [11].

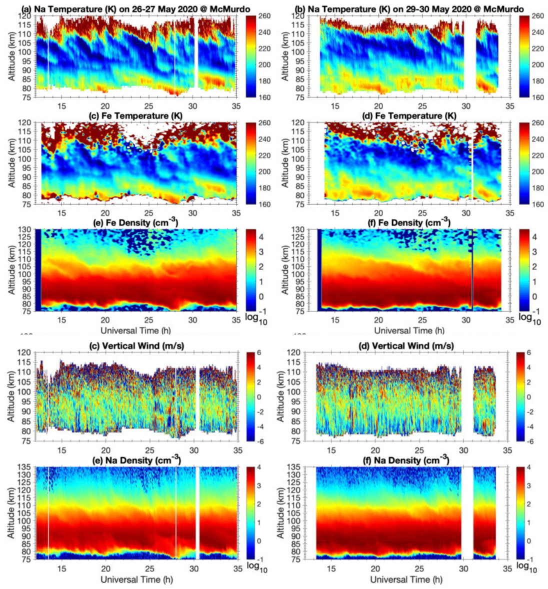

Figure 2. Simultaneous lidar observations of Na temperatures, vertical winds, and Na densities [11], along with Fe temperatures and Fe densities at McMurdo in late May 2020.

The unique vertical wind and temperature measurements show high-frequency and long-period gravity waves at the same time, which were the first-ever vertical wind measurements in Antarctica. The simultaneous measurements of Fe temperature and Fe density are also shown in Figure 2, where Fe T resemble Na T features very well but at lower resolutions (15 min and 0.5 km). Both Fe and Na layers exhibit similar altitude shifts and density changes between the two lidar runs in late May 2020.

4. First Measurements of Vertical Fluxes of Sensible Heat, Meteoric Na and Fe in Antarctica

The initial derivation of sensible heat and meteoric Na fluxes using an interleaved data processing technique [12] has led to the discoveries of upward sensible heat flux in the lower thermosphere (97–106 km) and large downward Na fluxes peaking at ~84 km [11].

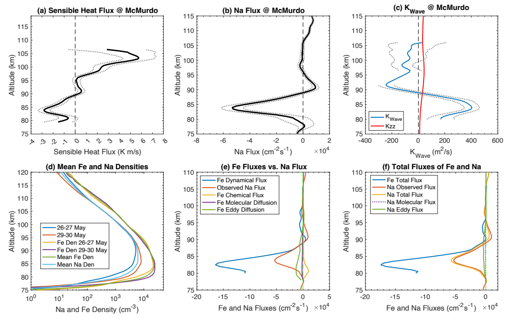

Figure 3. (a-c) Sensible heat and Na fluxes and K_{Wave} [11], (d) Fe and Na density profiles, and (e-f) Fe fluxes and Na fluxes at McMurdo.

Wave-induced effective diffusivity K_{Wave} was derived from Na lidar data but can be applied to Fe and other species, so we derive the wave-induced Fe flux by using K_{Wave} and measured Fe density plus estimating Fe chemical flux:

$$\overline{w'\rho'_{Fe}} \simeq -\bar{\rho}_{Fe} K_{Wave} \left(\frac{g}{R\bar{T}} - \frac{g}{C_p\bar{T}} + \frac{1}{\bar{\rho}_{Fe}} \frac{\partial \bar{\rho}_{Fe}}{\partial z} \right) + \overline{w'\rho'_{Fe}}_{Chemical}. \quad (1)$$

We also estimate Fe eddy and molecular fluxes. Figure 3 shows the preliminary results of Fe dynamical, chemical, eddy, & molecular fluxes. The dynamical flux apparently dominates the downward Fe flux. The chemical flux is positive and only important at lower altitudes, while the eddy and molecular fluxes are much smaller than the dynamical flux. Adding the four fluxes together, we obtain the total Fe flux.

Non-breaking gravity waves play major roles in mixing and transporting constituents in the upper atmosphere by inducing Stokes drift, mixing of constituents, and chemical flux. Such mixing and transport by non-breaking waves are fundamentally different than mixing by the random turbulence and molecular thermal motions. This is because each wave imparts an organized motion to the atmosphere, although the cumulative effects of many waves appear random. Consequently, non-breaking waves can transport species against the gradients of their densities and mixing ratios [11].

5. Cosmic Dust Influxes and Fe/Na Lifetimes Inferred from Data

For meteoric species like Fe and Na, their density changing rates are determined by meteoric input as the source, by chemical production and loss, and by transport:

$$\frac{\partial N_M}{\partial t} = S_M + P_M - L_M - \nabla \cdot (N_M \vec{V}_M). \quad (2)$$

To maintain stable abundances of metal layers, the meteoric influxes must be balanced by downward transport; therefore, the measured Na and Fe fluxes can be used to infer meteoric influxes. Moreover, because Fe and Na species have very different volatile characteristics, their vertical flux ratios can be used to infer cosmic dust entry velocities. It is worth noting that the dynamical transport inferred from Fe and Na fluxes can be applied to all major and minor species which play important roles in global atmospheric and climate models. These points provide strong motivations for measurements of vertical fluxes of Fe and Na atoms.

The peak Fe and Na flux ratio is ~3, which is some-degree larger than our Boulder Fe/Na flux ratio of ~2.14. Such small flux ratios indicate slow entry velocities of cosmic dust, because fast meteors would cause the flux ratios to be close to 15 that is the Fe/Na abundance ratio in the primitive CI chondrites.

The fractions of Fe and Na ablated above their peak flux altitudes are computed using the CABMOD injection rates of Fe and Na. Then the total fluxes of atomic Fe and Na are estimated using these fractions. Dividing the lidar-measured Fe and Na column abundances with the peak values of the total Fe and Na fluxes gives the effective lifetimes of Fe and Na atoms in the upper atmosphere. Our preliminary results are ~40-45 hr for Fe and Na.

These preliminary results still have quite some uncertainties, mainly concerning the estimation of Fe chemical flux. We also need meteoric ablation and WACCM chemical model data to estimate the global meteoric influxes. Soon we will reprocess the Fe and Na data, retrieving Fe densities using Na temperatures, and then cross-correlating with Na lidar's vertical winds to derive the Fe flux directly.

6. Conclusions

High-detection-sensitivity Na Doppler and Fe Boltzmann lidars have enabled the first high-resolution profiling of temperatures, vertical winds, and Na and Fe densities in SAIR, leading to the first measurements of vertical fluxes of sensible heat and meteoric Na and Fe in Antarctica. These measurements help further studies of vertical transport and cosmic dust on entry velocities, influxes, and metal lifetimes.

The Antarctica lidar observations over a decade have been a science-discovery journey. The lidar technologies developed and engineering skills gained through the journey are true assets to future lidar explorations.

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