High-Resolution Lidar Observations of Mesospheric Sodium and Implications for Adaptive Optics

Paul Hickson and Thomas Pfrommer

Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T1Z1, Canada.
hickson@physics.ubc.ca, pfrommer@phas.ubc.ca, Tel. 604-822-3853, Fax. 604-822-5324.

Abstract: We describe new observations of sodium density variability obtained with a high-resolution lidar system. These show significant mean altitude variations extending to frequencies above 1 Hz with a near-Kolmogorov spectrum.

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OCIS Codes: (010.3640) Lidar, (010.1285) Atmospheric correction

1. Introduction

The Earth’s mesosphere and lower thermosphere contains a region of atomic metals deposited by meteoric ablation [1]. Laser adaptive optics systems commonly create artificial “laser guide stars” (LGS) in this layer by resonant excitation of sodium atoms [2]. The sodium region has a typical vertical extent on the order of 10 km and a mean altitude of roughly 90 km. LGS so produced are cylindrical in shape and appear star-like only when viewed exactly end-on. The finite thickness of the region becomes an important factor for very large telescopes because the LGS appear significantly elongated when seen from the edge of the telescope entrance pupil. Also, variations in the mean altitude of the sodium region translate into variations in focus of the LGS. These variations cannot be distinguished from focus variations that arise from optical turbulence. This results in a loss of AO performance that increases with aperture size [3]. Natural guide stars can in principle provide the needed focus information, but as these are generally quite faint, photon noise limits the bandwidth of the resulting signal. Therefore, it is of critical importance to know the temporal behavior of the sodium density structure on the short timescales relevant for AO.

Our knowledge of the dynamics of the sodium region comes largely from atmospheric lidar studies. However, no previous studies have had sufficient spatial or temporal resolution to directly investigate the AO regime. Performance estimates for AO systems for extremely-large telescopes have thus relied on uncertain extrapolation of low-frequency measurements over four decades in frequency [4]. This has motivated us to develop a lidar system capable of direct measurements of the sodium density with high spatial and temporal resolution. Initial measurements of mesospheric sodium dynamics are reported elsewhere [5]. Here we present a brief summary of results of most relevance for AO.

2. Sodium density structure

The sodium lidar system of the University of British Columbia employs a pulsed frequency-doubled Nd:YAG laser pumping a dye laser tuned to the sodium D2 resonance transition at a wavelength of 589.1 nm [6]. The pulse repetition rate is 50 Hz and the pulse length is 7 ns. The typical transmitted pulse energy is 100 mJ, giving a mean output power of 5 W. The beam is colimated, with a half-power width of 10 cm, and projected vertically. Returned photons from the sodium region are collected by the Large Zenith Telescope - a zenith-pointing astronomical telescope employing a 6-meter f/1.5 parabolic rotating liquid primary mirror [7]. The lidar detector, located at the telescope’s prime focus, employs a segmented collimator to divide the beam to feed four identical detectors in order to reduce counter coincidence losses. Each channel includes pupil imaging optics, a narrow-band sodium-wavelength filter, and a high-speed high-efficiency photomultiplier. The present system provides vertical profiles of sodium density with a spatial sampling of 4.8 m and a temporal sampling of 20 ms. Typically ~ 1500 sodium photons are detected from each laser shot. An upgrade to the counting electronics is currently in progress that is expected to increase the number of detected photons by about an order of magnitude.

An example of the sodium density profiles is shown in Fig. 1. Here we see that the sodium density exhibits multiple clouds whose structure evolves with time. The lifetime of an individual cloud is typically a few hours. Some clouds appear rapidly and can reach densities that are an order of magnitude greater than the mean sodium background. These sporadic sodium layers can cause shifts in the mean sodium altitude of several km in just a few minutes. There is evidence for a general downward drift of the layers with time. We often see turbulent structure such as Kelvin Helmholtz instabilities [5]. Also apparent in the figure are coherent oscillations that sometimes extend throughout the sodium region. These have a period of several minutes and can be attributed to gravity (buoyancy) waves propagating upward through the region.
3. The fluctuation power spectrum

Variation of the mean sodium altitude translates directly to focus errors for any sodium AO system employing continuous-wave lasers. For a telescope of diameter $D$, and sodium mean height $h$ (above the telescope) the piston-removed rms wavefront error resulting from a height variation $\Delta h$ is $\sigma = \Delta h \frac{D^2}{16\sqrt{3}h^2}$, at the zenith. For a thirty-meter telescope, this corresponds to a wavefront error of ~ 4 nm per meter of height variation.

Fortunately, sodium mean height is a robust parameter that is readily measured and does not require knowledge of the absolute sensitivity or efficiency of the lidar system. A typical power spectrum, derived from one night of continuous data acquisition, is shown in Fig. 2. These data are well fit by the power law $P_\nu \approx 35 \nu^{-1.8} \text{m}^2\text{Hz}^{-1}$, where $\nu$ is the fluctuation frequency in Hz. The slope of this power law is close to the value of -5/3 expected for Kolmogorov turbulence. System noise, from laser mode instability and vibrations, becomes dominant at frequencies above a few Hz. However there are plausible physical reasons to expect that the power law continues to ~ 150 Hz. This frequency corresponds to the advection of spatial scales of ~ 1 m, the mean free path at the sodium altitude. Molecular viscosity will attenuate fluctuations on smaller scales.

Fig. 2. Temporal power spectral density of sodium mean altitude. The spectrum is fit well by a power law (dotted line) having a near-Kolmogorov slope that extends over at least five orders of magnitude in frequency. The flattening above a few Hz and the resonances seen at 5 and 10 Hz are believed to arise from instrumental effects. Superimposed is a low-frequency spectrum derived using data from the Colorado State University lidar [4].
4. Spatial variations

Under the assumption of frozen flow, we can draw conclusions about the transverse spatial structure of the sodium mean height. The temporal power spectrum can be converted to a spatial power spectrum by assuming a constant wind speed. In fact it is known that there are substantial variations in wind speed with altitude in the mesosphere [8], however, this assumption will provide at least a first-order estimate of the spatial power spectrum. We adopt a horizontal wind speed of $v = 15 \text{ ms}^{-1}$, which is typical at this altitude at the time of year that our data were obtained. Making the substitution $\nu = \nu k/2\pi$, where $k$ is the spatial wave number, we obtain $P_k \approx 7.3 k^{-1.8}$ m.

5. Meteor trails

Transient spikes seen in the sodium density, as shown in Fig. 3. These arise from meteor ablation trails that are carried across the lidar beam by the mesospheric wind [9]. We typically detect several per night, mostly near the bottom of the sodium region. These trails are highly localized, typically a few tens of meters across, and last for a fraction of a second. The density in these trails can be more than an order of magnitude higher than the background.

Fig. 3. Meteor trails. Spikes in the sodium density occur when meteor ablation trails drift across the laser beam.

6. Implications for adaptive optics

A detailed discussion of the impact of these variations on AO is beyond the scope of this paper, but a few remarks are in order. Focus errors arising from sodium altitude variations couple into AO performance in several ways. In addition to the direct impact of uncorrected focus wavefront error, misfocussing of the LGS results in higher-order radially-symmetric terms that arise from spherical aberration in the LGS optical train.

The spatial variations discussed in Section 4 are very large. The rms focus wavefront error for two LGS in an asterism, separated by 30 m, is predicted to be of order 120 nm. The impact on advanced AO systems such as multi-object AO may be substantial.

Finally, sodium AO system must be designed to tolerate the rapid transients caused by meteor trails.

7. References