SHORT TIMESCALE VARIABILITY OF THE MESOSPHERIC SODIUM LAYER

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Abstract. In this article we investigate the short-term characteristics of the sodium layer and their implications for laser guide star systems. We report measurements of sodium density and centroid-height variations on timescales of 100 ms upwards. Significant centroid-height variations on short timescales may necessitate frequent refocussing of the beam and wavefront sensor system. We present results from observations of the mesospheric sodium layer taken at the Max Planck observatory in Calar Alto, Spain in September 1997 and August 1998. We describe our experiment which uses the resonant optical backscatter of 589.2 nm laser light from the upper atmosphere as a measure of sodium abundance. Short-term variations are dominated by the formation of dense sporadic layers in the normal sodium layer. Measurements were made on 3 nights in 1997 and on 2 nights in 1998. Somewhat unexpectedly for a mid-latitude site, sporadic sodium layers were seen on 4 of these 5 nights. One of the sporadic layers was observed for its duration. The 2 km wide layer reached a maximum intensity of approximately two and a half times that of the background layer and could be distinguished from the background for over five hours. Centroid height variations of up to 400 m were observed on timescales of 1–2 min. In 1998 we were sensitive to variations of 5% or more in total sodium abundance on timescales of 100 ms upwards. We found no evidence for variations of this level on these short timescales.

Keywords: adaptive optics, laser guide star, mesospheric sodium layer

Abbreviations: AO, adaptive optics; LGS, laser guide star; Na_s, sporadic sodium

1. Introduction

Like many others, the AO system at the Calar Alto observatory makes use of a sodium laser guide star (LGS) (Davies et al., 1998). The short- and long-term characteristics of the sodium layer have important implications for the design of such an LGS system. In this article we investigate short-timescale variations which, if present, may necessitate frequent refocusing of the beam and wavefront sensor system.

Short-term variations are dominated by the formation of sporadic mesospheric sodium (Na_s) layers (see for a review Clemesha, 1995). Na_s layers are superimposed on the ever-present background and are characterised by a rapid increase (on

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the order of a few minutes upwards) in sodium density over a narrow (∼1–2 km) altitude range. The appearance of a sporadic layer can cause the total abundance to increase by a factor of two or more. There appears to be no significant seasonal difference in occurrence frequency or maximum sodium concentration. The formation mechanisms of these Na_s layers are not yet well-understood but they have always appeared to be a strongly latitude-dependent phenomenon, having been regularly observed at both low and high latitudes but not at mid-latitude sites. Na_s layers have been observed at Sao Paulo, Brazil (23°S) (Clemesha et al., 1980), Andoya, Norway (69°N) (von Zahn et al., 1987; von Zahn and Hansen, 1988) Longyearbyen, Svalbard (78°N) (Gardner et al., 1988) and Mauna Kea, Hawaii (19°50′N) (Kwon et al., 1988). Up until recently, despite frequent observations by many groups, only a small number of sporadic sodium events were reported at mid-latitude sites. The first report of a Na_s layer at a mid-latitude site was at Haute Provence, France (44°N) (Megie, 1988). Senft et al. (1989) report the first Na_s layers at Urbana (40°N) after more than 10 yr of LIDAR measurements. It was a surprise, therefore, when Nagasawa and Abo (1995) observed more than 100 Na_s layers in two years at their Tokyo (35.6°N) LIDAR site.

In this article we investigate whether or not sporadic sodium events are observed at the mid-latitude site of Calar Alto. We also investigate whether variations in Na abundance occur on even shorter time-scales.

2. The experiment

We investigate the density variation in the mesospheric sodium layer by observing the resonant optical backscatter from the upper atmosphere when it is excited by a laser tuned to the Na D_2 line. If only a small fraction of the laser power is absorbed (so its intensity is roughly constant throughout the layer) and the laser intensity in the sodium layer is low, the return flux is proportional to the abundance of sodium atoms in the layer. Measurements show this to be the case for our experiment (Rabien et al., 2000). A schematic diagram of the experimental setup is shown in Figure 1.

The laser, part of MPIA/MPE's ALFA adaptive-optics system, was projected from a 0.5-m launch telescope beside the 3.5-m telescope at Calar Alto, Almería, Spain (long = 2.54°W, lat = 37.22°N). The laser system used is described by Rabien et al. (2000). We observed the resulting LGS from an auxiliary telescope approximately 300 m away. In 1997 we used a 1.23-m telescope and in 1998 a 2.2-m telescope. Due to projection effects, the LGS appears as an elongated (∼100″ at zenith) strip in the sky (Figure 2), and the relative brightness along its length can, in principle, be used to find the sodium-layer centroid height, layer thickness and relative sodium column density. Most of our observations were taken with the LGS at, or close to, zenith. The absolute sodium density was not calculated from our

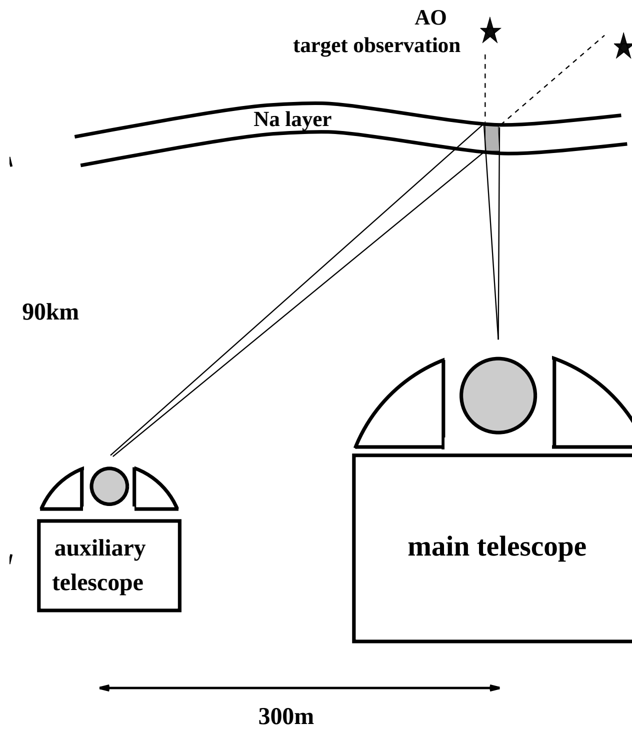

Figure 1. Schematic diagram of the experimental set-up.

photon return measurements as many details of the laser system and its interaction with the atmospheric sodium are still unknown.

3. Observations

Observations were made in September 1997 and August 1998 using the NUI, Galway 'TRIFFID' camera mounted at the cassegrain focus of the Calar Alto 1.23-m and 2.2-m telescopes, respectively. For these observations no re-imaging optics were used. The TRIFFID system consists of a multianode microchannel array (MAMA) 2-dimensional photon-counting detector with a B-extended S-20 photocathode (Timothy and Bybee, 1985) and a fast data-collection system (Redfern et al., 1993). The position and time-of arrival of each photon were recorded to a precision of 25 μm and 1 μs respectively. On the 1.23-m telescope the 1024$\times$256-pixel array had an equivalent spatial resolution of 0.5$''$ pixel^{-1}, corresponding to approximately 70 pixel^{-1} vertically along the sodium plume. On the 2.2-m telescope we had an equivalent spatial resolution of 0.3$''$ pixel^{-1}, corresponding to approximately 40 m pixel^{-1} along the plume. Timing was achieved using a GPS receiver and an ovened 10-MHz crystal. The observations were made using a sodium (590 nm) filter with a bandwidth of 10 nm.

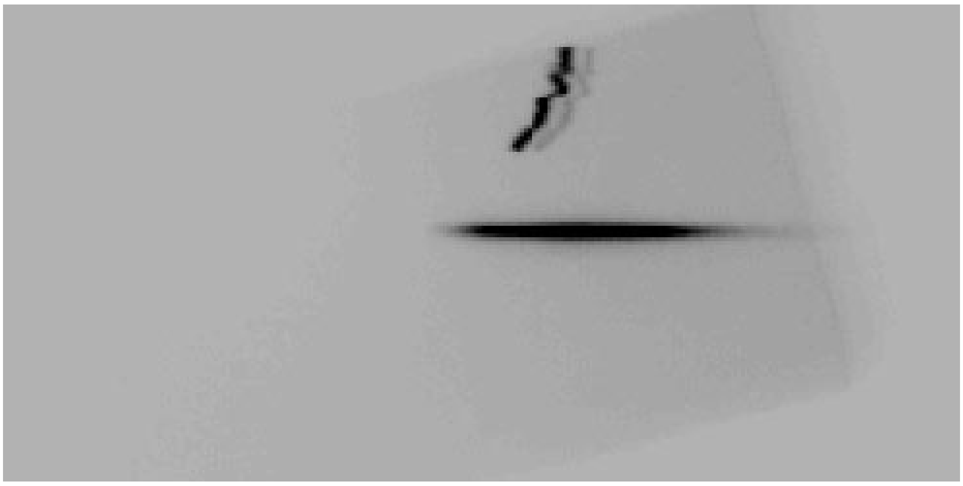

Figure 2. Elongated sodium guide star (25-minute integration). Two background stars, moving relative to the artificial sodium star, can also be seen. Altitude increases to the right (1 pixel = 0.5″, image is 256×426 pixels).

TABLE I
Summary of observations

Date	Start time (LST)	End time (LST)	Length of observation (min)
1997 September 21	00:10:25	00:40:00	20
1997 September 21	22:33:39	23:29:30	40
1997 September 22	18:52:47	04:36:47	230
1998 August 15	19:25:38	19:51:45	26
1998 August 16	19:02:39	20:06:15	63
1998 August 16	22:11:55	23:03:00	51

In 1997 our observing program was determined primarily by the commissioning tests being carried out on ALFA at the time. There are therefore considerable gaps in the data when the laser was unavailable. The times of all the observations, and the period during which the laser was on, are summarised in Table I.

4. Data reduction

In order to look for sporadic sodium layers, density (relative) profiles of the sodium layer were made. The data were first binned into 1-ms frames and divided by a deep flatfield image. A post-exposure shift-and-add sharpening technique Shearer et al., 1996) was used to produce an integrated image. During our observations the LGS was either tracking an astronomical object or stationary, pointing at zenith. In either case the LGS, as seen from the auxiliary telescope, does not move at the sidereal rate so we have used the peak of the LGS strip itself as a reference, rather than bright, nearby stars as is generally the case with observations of astronomical objects. The image of two natural stars can be seen in Figure 2, showing the drift of the LGS relative to the sidereal rate. Following the LGS peak in this way corrects for effects such as telescope wobble and allows us to track the LGS when it is itself moving.

An integrated image of each 5 min worth of flat-fielded data was made. The photon counts as a function of height were determined for the full width of the sodium strip, and this was further averaged over 5 pixels (equivalent to approximately 350 m in length (1997) or 200 m (1998)). Pixel numbers were converted into distance along the sodium layer by assuming the bottom of the layer to be at an altitude of 85 km. A detailed pointing model for the auxiliary telescope is necessary in order to make this conversion accurately. An error of 5 km in our value for the height of the layer would result in a $\sim$10% error in the distance estimates.

To investigate total density variations on even shorter timescales, photon arrival times from the LGS strip were determined. Photon counts as a function of time and their power spectra were then calculated.

Centroid height variations in the 1998 data were determined by bining the data into 100 ms intervals and determining the centroid of the LGS for each interval. As the LGS was stationary and pointing at zenith for the 1998 observations the LGS centroid variations in the vertical direction could be attributed to changes in the centroid height of the sodium layer.

5. Results

The average sodium density profile for each 5-minute segment of data was calculated as described above. Observations were made on three consecutive nights in 1997, with a significant fraction of the third night being sampled. A sporadic sodium layer was observed on two of those three nights. In 1998 a sporadic sodium layer was observed on both nights.

On 1997 September 22 the Na_s layer began to appear at 19:15 LST and lasted approximately 5 hr. It reached an amplitude about 2.5 times that of the background layer, which appeared to move towards lower heights as the sporadic layer appeared. A sporadic layer was also seen to form at 23:10 LST on 1997 September 21 but we did not have sufficient data to determine its maximum height or its duration. In 1998 the Na_s layers were already formed before we began our observations. Profiles from 1998 August 16 (19:02:39 LST) are shown in Figure 3.

Although in the 1997 observations the LGS was not stationary, some measure of sodium-layer centroid height variation could be obtained when natural stars were

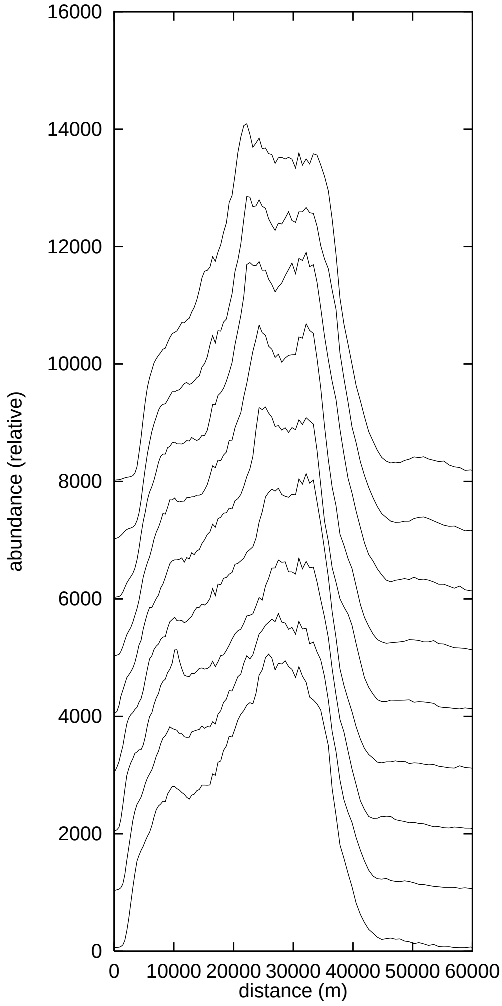

Figure 3. Sodium density profile along the laser guide-star strip on 1998 August 16 (19:02:39 LST). Each profile is an average over 5 min and is smoothed by averaging over 5 pixels. The density profile measurements are relative.

in our field-of-view (e.g. Figure 2). The time resolution of these measurements depends upon the siderial motion and brightness of the stars onto which our tracking technique superimposes the LGS centroid motion. We saw height variations of up to 300 m on timescales of 30 s.

This measurement is much more straightforward for the 1998 data as the sodium layer centroid height can be calculated from the LGS centroid on our detector. In converting from pixels to height, we again took 85 km as the height of the bottom of the normal sodium layer. The centroid height variation was calculated for time intervals of 100 ms and data from August 16 (19:02:39 LST) are plotted in Figure 4.

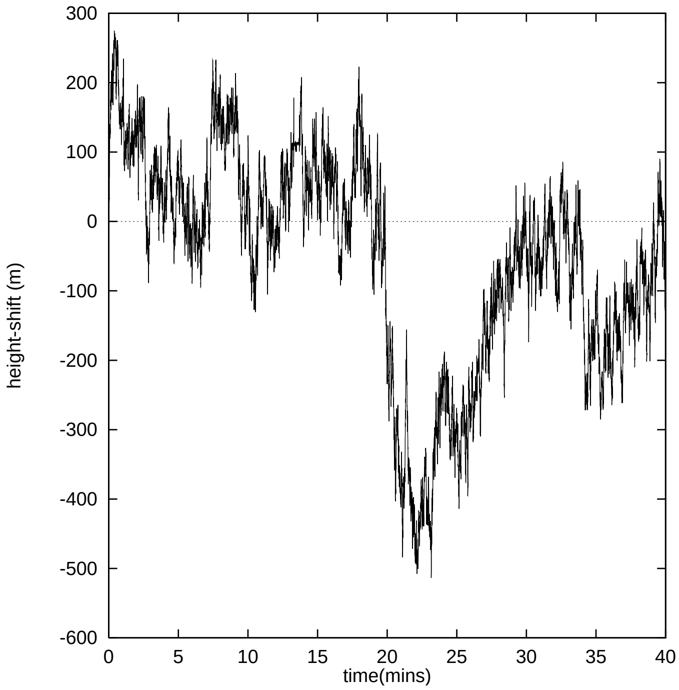

Figure 4. Sodium layer centroid height variations measured on 1998 August 16. Each point is an average over 100 ms.

Our results show layer-height shifts of up to 400 m in a period of 1–2 min. For the 3.5-m telescope in Calar Alto this corresponds to a rms wavefront error of 24.6 nm, and a J-band variance of 0.015 rad s^2. Since the wavefront variance increases as the square of the telescope diameter, the same centroid-height shift would produce much larger wavefront errors for large telescopes and may mean that focal adjustments have to be made on this sort of timescale.

Photon counts from the sodium strip were binned into time intervals from 100 ms upwards. The sensitivity of the experiment was such that a variation of ∼10% (1997) and ∼5% (1998) in the total brightness of the LGS (density of the sodium layer) could be detected in 100 ms. Power spectra of the time series extracted from continuous segments of the data (up to about 60 min in length) were calculated. No evidence for significant abundance fluctuations within the strip, above those expected from photon counting statistics, were found in these data.

6. Discussion

The sporadic sodium layers observed at Calar Alto show characteristics similar to those found at other sites. The ∼2 km-wide sporadic layers formed at the top of the normal sodium layer, whose profile appeared to change with the appearance and growth of the sporadic layer. One of the Na_s layers was observed for its duration and was found to be relatively long lived (events typically last from a few tens of minutes to several hours). We saw no very narrow ($\sim$140 m FWHM), dense, short-lived sporadic layers of the type described by Beatty et al. (1988). This type of layer is generally attributed to meteor trails advected across the observing instrument's field-of-view.

If our observations to date are typical, we can test two possible explanations put forward for the unexpected frequency of occurrence of Na_s layers above the Tokyo mid-latitude site. Nagasawo and Abo (1995) noted a large maximum in the worldwide distribution of sporadic-*E* (Smith, 1978) close to Japan and suggested this as a possible cause for the large number of Na_s layers. Sporadic-*E* layers were found to precede most of the Na_s layers and they may share a common origin. If this is indeed the reason, a large number of sporadic layers should not be observed at Calar Alto, which lies at no such maximum. A second possible explanation, that the occurrence of Na_s layers depends on geomagnetic rather than geographic latitude, was also suggested. Tokyo and Mauna Kea, unlike Urbana and Haute Provence where Na_s layers are rarely observed, lie at low (26° and 20°N, respectively) geomagnetic latitude. Calar Alto, too, has a relatively low geomagnetic latitude (29°N) and so, if this theory is correct, we would indeed expect to see Na_s layers. Senft et al. (1989) noted that when they observed the Na_s layers at mid-latitude, the sodium column abundance was about one-third the value expected at that time of year. They suggest that this may be the reason the sporadic layers were visible above the background sodium layer. We are not in a position at the moment to calibrate our abundance measurements and make a direct comparison with other results.

7. Conclusions

In summary, we set out to investigate three aspects of the mesospheric sodium layer at Calar Alto: (a) whether narrow sporadic layers were seen superimposed on the background layer, despite this being a mid-latitude site, (b) whether there were short timescale variations in the total sodium density (and hence LGS brightness) and (c) whether there were short timescale variations in the centroid height of the sodium layer.

(a) Of the 3 nights in 1997 and 2 nights in 1998 on which we recorded data, Na_s layers were observed on 4 nights. This leads us to believe that they may be common at Calar Alto and that Tokyo is not unusual as a mid-latitude site where many Na_s layers have been observed.

(b) We found no evidence for significant ($>$ 5%) variations of total density on timescales from 100 ms to 30 s.

(c) The sodium layer centroid height was found to vary by up to 400 m in a time period of 1–2 min and this must be taken as a serious consideration when deciding on the maximum time between focal adjustments of a telescope.

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