The Mesospheric Sodium Layer at Calar Alto, Spain

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ABSTRACT

The short- and long-term characteristics of the sodium layer have important implications for laser guide star systems. Short-timescale variations, in particular, may necessitate frequent refocussing of the beam and wavefront sensor system.

In this paper 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, in which we are most interested, 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 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 300m were observed on timescales of 30s. In 1997 we were sensitive to variations of 10% or more in total abundance on timescales of 100ms upwards. We found no evidence for variations of this level on these short timescales.

1. INTRODUCTION

Like many others, the AO system at the Calar Alto observatory makes use of a sodium laser guide star (LGS).[1] The short- and long-term characteristics of the sodium layer have important implications for the design of such an LGS system. In this paper 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 Clemesha, 1995[2] for a review). Na_s layers are superimposed on the ever-present background and are characterised by a rapid increase (on the order of a few minutes upwards) in sodium density over a narrow (~1-2km) 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 layers are not yet well-understood but Na_s layers 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),[3] Andoya, Norway (69°N),[4,5] Longyearbyen, Svalbard (78°N)[6] and Mauna Kea, Hawaii (19°50′N).[7] 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).[8] Senft et al. (1989)[9] report the first Na_s layers at Urbana (40°N) after more than 10 years of LIDAR measurements. It was a surprise, therefore, when Nagasawa & Abo (1995)[10] observed more than 100 Na_s layers in two years at their Tokyo (35.6°N) LIDAR site.

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

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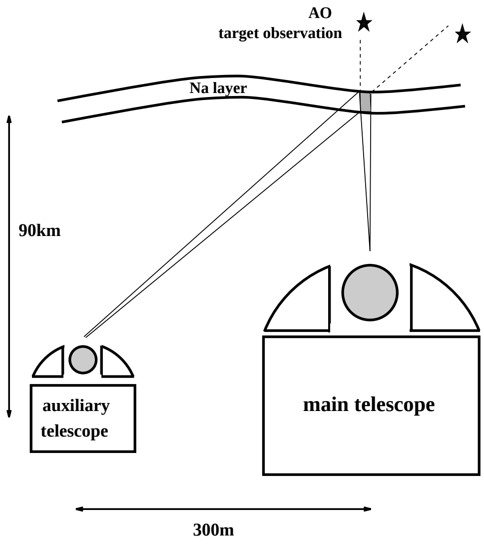

Figure 1. Schematic diagram of the experimental set-up

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. Assuming the sodium layer is essentially unsaturated, the return flux is proportional to the abundance of sodium atoms in the layer. A schematic diagram of the experimental setup is shown in Figure 1.

The laser, part of MPIA'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). We observed the resulting LGS from an auxiliary (1.23m) telescope approximately 300m away. Due to projection effects, the LGS appears as an elongated ($\sim 100''$ 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 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 telescope. 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[11] and a fast data-collection system.[12] The position and time-of arrival of each photon were recorded to a precision of 25μm and 1μs respectively. On the 1.23-m telescope the 1024$\times$256-pixel array had an equivalent spatial resolution of $0.5''$ pixel^{-1} (1997) and $0.3''$ pixel^{-1} (1998), corresponding to approximately 70m pixel^{-1} and 40m pixel^{-1}, respectively, vertically along the sodium plume. Timing was achieved using a GPS receiver and an ovened 10-MHz crystal. The observations were made using a sodium (590nm) filter with a bandwidth of 10nm.

Our observing program in 1997 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 the observations, and the period during which the laser was on are summarised in Table 1.

4. DATA REDUCTION

The data were first binned into 1-ms frames and divided by a deep flatfield image. A post-exposure shift-and-add sharpening technique[13] was used to produce an integrated image. As the LGS does not move at the sidereal rate

Table 1. Summary of observations.

Date	Start Time (LST)	End Time (LST)	Length of Observation (mins.)
1997 Sep 21	00:10:25	00:40:00	20
1997 Sep 21	22:33:39	23:29:30	40
1997 Sep 22	18:52:47	04:36:47	230
1998 Aug 15	19:25:38	19:51:45	26
1998 Aug 16	19:02:39	20:06:15	63
1998 Aug 16	22:11:55	23:03:00	51

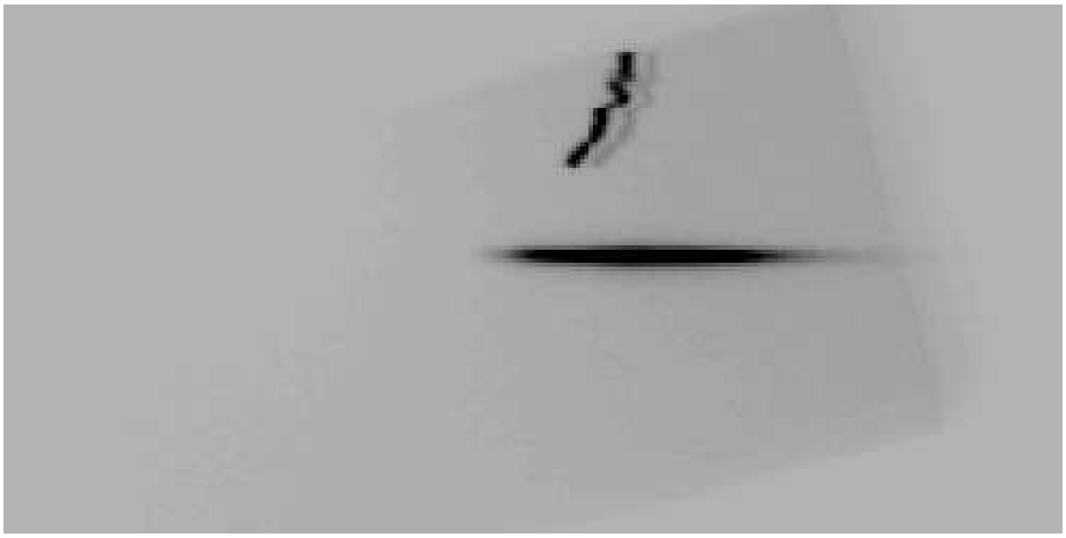

Figure 2. Elongated sodium guide star (25-minute integration). Two background stars, moving relative to the artificial sodium star, can also be seen. Altitude increases to the right. (1 pixel =0.5", image is 256×426 pixels).

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-minutes worth of 1997 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 350m in length). Pixel numbers were converted into distance along the sodium layer by assuming the bottom of the layer to be at an altitude of 85km. A detailed pointing model for the auxiliary telescope is necessary in order to make this conversion accurately. An error of 5km in our value for the height of the layer would result in a ~10% error in the distance estimates.

To investigate 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.

5. RESULTS

Figures 3 and 4 show cuts across the width and along the length of the sodium LGS observed on 1997 September 21. A Na_s layer can clearly be seen in Figure 4. The FWHM of the LGS was $2.5''$ and generally varied between this

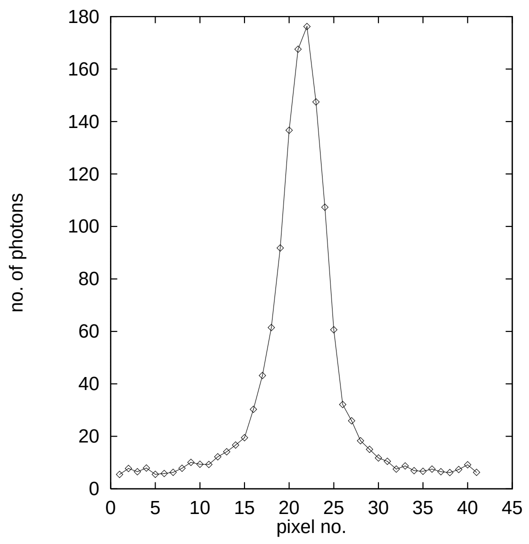

Figure 3. Cut across the width of the elongated sodium LGS. The FWHM corresponds to 2.5″. (5-minute integration from 1997 September 21).

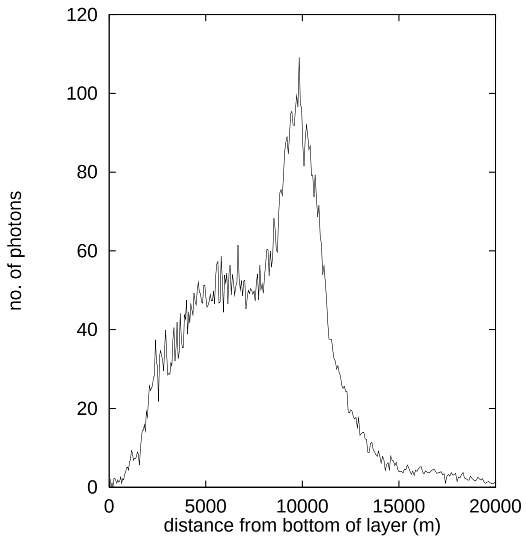

Figure 4. Cut along the length of the elongated sodium LGS. A narrow sporadic layer can clearly be seen towards the top of the layer. (5-minute integration from 1997 September 21).

value and 5″.

The average sodium density profile for each 5-minute segment of data was calculated as described above. In 1997 observations were made on three consecutive nights, with a significant fraction of the third night being sampled. A sporadic sodium layer was observed on two of those three nights. Profiles from 1997 September 22 are shown in Figure 5. The layer began to appear at 19:15 LST and lasted approximately 5 hours. 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 on 21 September but we did not have sufficient data to determine its maximum height or its duration. Data from 1998 has not yet been fully analysed.

Some measure of sodium-layer centroid height variations could be obtained when natural stars were in our field-

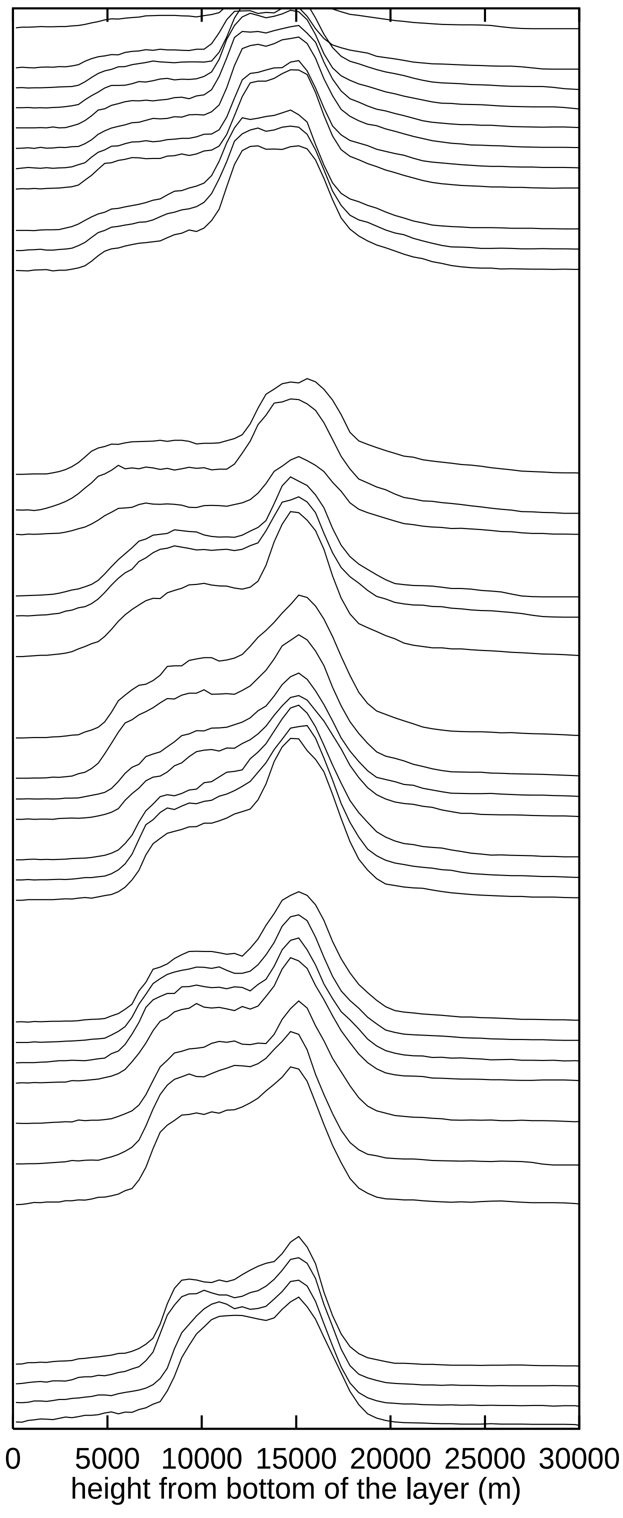

Figure 5. Sodium density profile along the laser guide star strip on 1997 September 22. Each profile is an average over 5 minutes and is smoothed by averaging over 5 pixels. The density profile measurements are relative.

of-view (e.g. Figure 2). The time resolution of these measurements depends on 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 300m on timescales of 30s.

Photon counts from the sodium strip were binned into time intervals from 100ms upwards. The sensitivity of the experiment was such that a variation of ~10% in the brightness of the layer could be detected in 100ms. Power spectra of the time series extracted from continuous segments of the data (up to 40 mins. 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 AND CONCLUSIONS

The sporadic sodium layers observed at Calar Alto show characteristics similar to those found at other sites. The ~2km-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 (~ 140m FWHM), dense, short-lived sporadic layers of the type described by Beatty et al. (1988).[14] This type of layer is generally attributed to meteor trails advected across the observing instrument's field-of-view.

If our observations do turn out to be 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 & Abo (1995)[10] noted a large maximum in the worldwide distribution of sporadic-E[15] 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. 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)[9] 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.

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REFERENCES

1. R. I. Davies, W. Hackenberg, T. Ott, A. Eckart, H. C. Holstenberg, S. Rabien, A. Quirrenbach, and M. Kasper, "ALFA: First operational experience of the MPE/MPIA laser guide star system for adaptive optics," in *Adaptive Optical System Technologies*, *Proc. SPIE* **3353**, 1998.
2. B. R. Clemesha, "Sporadic neutral metal layers in the mesosphere and lower thermosphere," *J.atmos.terr,Phys.* **57, 7**, pp. 725–736, 1995.
3. B. R. Clemesha, V. W. J. H. Kirchoff, D. M. Simonich, H. Takahashi, and P. P. Batista, "Spaced Lidar and nightglow observations of an atmospheric sodium enhancement," *J. Geophys. Res.* **85**, pp. 3480–3484, 1980.
4. U. von Zahn, P. von der Gathern, and G. Hansen, "Forced release of sodium from upper atmospheric dust particles," *Geophys. Res. Lett.* **14**, pp. 76–79, 1987.
5. U. von Zahn and T. L. Hansen, "Sudden neutral sodium layers: a strong link to sporadic E layers," *J.atmos.terr,Phys.* **50, 2**, pp. 93–104, 1988.

6. C. S. Gardner, D. C. Senft, and K. H. Kwon, "Lidar observations of substantial sodium depletion in the summertime arctic mesosphere," *Nature* **332**, pp. 142–143, 1988.
7. K. H. Kwon, D. C. Senft, and C. S. Gardner, "Lidar observations of sporadic sodium layers at Mauna Kea Observatory, Hawaii," *J. Geophys. Res.* **93, D11**, pp. 14199–14208, 1988.
8. G. Megie, "Obsevations of trace metals in the upper atmosphere," in *Laser Remote Chemical Analysis*, R. M. Measures, ed., pp. 333–408, Wiley, New York, 1988.
9. D. C. Senft, R. L. Collins, and C. S. Gardner, "Mid-latitude Lidar observation of large sporadic sodium layers," *Geophys.Res.Lett.* **16, 7**, pp. 715–718, 1989.
10. C. Nagasawa and M. Abo, "Lidar observations of a lot of sporadic sodium layers in mid-latitude," *Geophys.Res.Lett.* **22, 3**, pp. 263–266, 1995.
11. J. G. Timothy and R. L. Bybee *Proc. SPIE* **687**, p. 1090, 1985.
12. R. M. Redfern, A. Shearer, R. Wouts, P. O'Kane, C. O'Byrne, P. D. Read, M. Carter, B. D. Jordan, and M. Cullum, "Crowdwd field photometry using post-exposure image sharpening techniques," in *Stellar Photometry - Current Techniques and Future Developements*, C. J. Butler and I. Elliott, eds., *Proc. IAU Coll* **136**, pp. 147–152, 1993.
13. A. Shearer, R. Butler, R. M. Redfern, M. Cullum, and A. C. Danks, "A search for the optical counterpart of the triple pulsar system PSR B1620-26 in M4," *ApJ* **473**, p. L11, 1996.
14. T. J. Beatty, R. E. Bills, K. H. Kwon, and C. S. Gardner, "CEDAR Lidar observations of sporadic Na layers at Urbana, Illinois," *Geophys.Res.Lett.* **15, 10**, pp. 1137–1140, 1988.
15. E. K. Smith, "Temperate zone sporadic-E maps (f_oE_s) >7MHz," *Radio Sci.* **13**, pp. 571–575, 1978.