A laser beacon for monitoring the mesospheric sodium layer at La Palma

L. Michaille,1 A. D. Cañas,1 J. C. Dainty,1 J. Maxwell,1 T. Gregory,2 J. C. Quartel,1 F. C. Reavell,1 R. W. Wilson3 and N. J. Wooder1

1 Blackett Laboratory, Imperial College, London SW7 2BZ
2 Isaac Newton Group, Apartado 321, 38780 Santa Cruz de la Palma, Canary Islands, Spain
3 ATC, Astrophysics Group, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE

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ABSTRACT
We report the results of the first laser beacon experiment at the astronomical site of La Palma (Canary Islands). A continuous wave low-power laser (a few hundred mW) system has been set up. The laser, tuned on the sodium D2 line at 589 nm, is launched close to the zenith angle. The emission of the mesospheric sodium layer is observed from a telescope located 160 m away from the laser. The layer is therefore resolved in altitude and the different features of its dynamics are investigated.

Key words: atomic processes – scattering – atmospheric effects – site testing – telescopes.

1 INTRODUCTION
Adaptive optics (AO) is proving to be such a powerful technique for correcting the image degrading effects of atmospheric turbulence that the number of telescopes deploying AO systems is rapidly increasing. It has been shown, however, that the usefulness of an AO system is limited by the number of sufficiently bright stars available to provide a reference wavefront, with the brightness condition becoming more restrictive towards shorter wavelength imaging. One way to increase sky coverage is to create an artificial reference source, or ‘guide star’, by scattering laser light from the atmosphere itself. Rayleigh scatter from molecules in the lower atmosphere can be used (Fugate et al. 1991), as can resonant scatter from a layer of sodium at 90-km altitude in the mesosphere (Foy & Labeyrie 1985). This latter technique has been proposed for the 4.2-m William Herschel telescope at La Palma, and in order to predict the effectiveness of such a system, it is important to know how the sodium layer behaves at this site.

Since the first LIDAR observation by Bowman, Gibson & Sandford (1969), the sodium layer has been studied by numerous groups in different places (see for example Megie & Blamont 1977; Gardner et al. 1986; Papen, Gardner & Yu 1996; Ge et al. 1998) and the results from these have shown that the sodium layer is subject to both short-term and seasonal variations of concentration, and differs from one geographical location to another.

In this paper we show first results of a sodium monitoring programme at La Palma. The principle of our experiment differs greatly from that of LIDAR and was first demonstrated at Calar Alto (Redfern, private communication). In this case, a continuous wave (CW) laser, tuned to the D2 transition of sodium (589.0 nm), is launched close to zenith. Resolving the vertical distribution of the sodium layer is achieved by observing the sodium fluorescence from a telescope some distance from the launch site. This technique avoids problems associated with saturation of the transition that must be taken into account with LIDAR calculations (Megie et al. 1978).1

2 EXPERIMENTAL DETAILS
We give a schematic representation of the experiment in Fig. 1.

2.1 The laser system
We have constructed a CW laser chain producing up to 500 mW at 589-nm wavelength. It comprises a ring-dye laser pumped by an argon ion laser. The argon ion laser (Spectra-Physics 2020) delivers 8 W across its output spectrum. The dye laser (Spectra-Physics 380D) has a four-mirror ring cavity in a ‘Z’ configuration, which includes a three-plate Lyot filter, a thick etalon, a pair of galvoplates (two pieces of glass close to the Brewster angle) and a piezo-actuator controlled mirror. The laser is longitudinally monomode with a very narrow instantaneous full-width at half-maximum (FWHM) of its spectrum (500 kHz) compared with the Doppler broadening of the line (1 GHz) at mesospheric temperature (200 K). To get the maximum power at 589 nm, the usual rhodamine 6G dye in a solution of ethylene glycol is used.

2.2 The sodium lock
To achieve the maximum efficiency of sodium excitation, the laser must be tuned and locked to the maximum of absorption of the D2

1 Recent developments in LIDAR techniques using a modulated CW laser, which circumvent these problems, may yet make this the more convenient method (Redfern, private communication).
line. We built a compact sodium oven to get an absolute stabilization of the laser. The sodium cell is designed to absorb nearly 50 per cent of the light at the bottom of the D\textsubscript{2} line when it is heated to around 130\degree C. The laser provides a 30-GHz continuous tuning by the simultaneous rotation of the galvoplates and of the thick etalon. The sodium D\textsubscript{2} line is found by adjusting the Lyot filter and the etalon during a 30-GHz periodic scan, until the D\textsubscript{2} absorption line is observed.\textsuperscript{2} To lock the laser to the D\textsubscript{2} line, we have used a simple absorption technique. The galvoplates are modulated at 200 Hz, producing a modulation of the laser frequency of a few tens of MHz. A photodiode measures the absorbed intensity through the sodium cell. We have built an electronic device, similar to a lock-in amplifier, which measures the phase difference between the modulation and the absorption signals. This produces an error signal which is fed to the tuning electronics of the laser to lock the wavelength on the D\textsubscript{2} line. The natural mode stability of this dye laser permits the locking system to operate at a few Hz. We estimate that the locking process perturbs the laser frequency from the centre of the absorption line by no more than 100 MHz.\textsuperscript{3} Other groups have used Doppler-free techniques for the sodium lock such as saturated absorption (Quirrenbach et al. 1997) or polarization spectroscopy (Booth 1998). In these cases, the external reference cavity of the laser, including a temperature-stabilized interferometer, has to be used, and the high-frequency jitter of the laser is then corrected by a piezo-mirror. With such a reference cavity, the stabilization can be as good as a few MHz. For our laser, however, the lock using the reference cavity was not stable for more than 10 min. In contrast, our absorption locking method has been fairly robust for our (relatively harsh) working conditions in terms of temperature variations. The system operates stably for several hours at a time, and is able to recover from mode hops of the cavity.

\textsuperscript{2}The D\textsubscript{2} line is discerned from the D\textsubscript{1} since its absorption is larger.

\textsuperscript{3}We have recorded 1 per cent efficiency variation of the absorption which corresponds to a laser being 100 MHz off transition.
2.3 Launch system

For a sodium monitoring experiment it is not absolutely necessary to minimize the spot size of the laser (though the observation of a large spot will produce a spatial average of the layer). For the construction of a Laser Guide Star (LGS)-AO system, however, it is essential to produce a spot size limited by the seeing. In preparation for the proposed LGS-AO system for the William Herschel Telescope, we built a diffraction-limited launch system composed of a commercial beam expander (magnification 16) and a home-made launch telescope (magnification 12). Our launch telescope consists of a custom negative doublet with a 200 mm focal length, a flat mirror at $46^{\circ}5$ and a 35 cm diameter aspheric singlet with 2000-mm focal length, held in horizontal position by a steel tower. The focus of this telescope is adjusted by translating the negative doublet. The transverse mode of the laser is TEM$_{00}$ with a Gaussian profile. From a 1-mm diameter at the $1/e^2$ point, the launch system has been designed to produce a diffraction-limited beam of 25 cm at $1/e^2$. A small beam waist gives a large sodium spot due to diffraction. On the other hand, if the waist is large compared with the aperture, most of the energy is lost. Optimal beam waist is also influenced by the atmospheric turbulence. For a Fried parameter ($r_0$) between 10 and 15 cm, which is characteristic of our site, the optimum beam waist is 20 to 25 cm from a study by Jacobsen (1997). Note that the direction of the launching beam is fixed by the 20-m spatial filter of the commercial beam expander. Between two different alignment procedures of the laser, the possible shift of the LGS in the sky is less than 3 arcsec, equivalent to an apparent altitude motion of 600 m of the image on the CCD.

3 RESULTS

The observations presented here were carried out between 1999 September 20 and 1999 September 26. The laser was launched from a small shed located approximately midway between the Jacobus Kapteyn and William Herschel telescopes (JKT and WHT, respectively) at La Palma, and both of these were used to observe the sodium star. Though we plan to make a more thorough statistical survey of the sodium layer at La Palma (including three more observation periods in 2000), we present here our initial results. These demonstrate that our methodology is sound and show some interesting aspects of the sodium layer dynamics.

3.1 On-axis observation

In addition to the WHT–JKT telescopes, a small Meade telescope (20-cm diameter) placed 3.5 m away from the laser launch was also used to observe the laser backscatter. Images from this telescope replicate more closely those that would be obtained from a telescope actually using an LGS-AO system, where the laser is attached to the side of the telescope (in the case of a bistatic launch system). Fig. 2 shows a 1-min exposure of the SBIG Meade camera. One sees the Rayleigh scattering plume at low altitude (up to about 30–40 km) and the LGS dot above. The Rayleigh observation has been useful to detect occasional strong diffusions by cirrus clouds, revealing non-photometric observation conditions.

3.2 Dynamics of the sodium layer

In this section, we present general features of the dynamics of the sodium layer over one night and point out their significance for LGS-AO.

An image of the laser streak through the sodium layer, taken from the JKT, some 160 m from the laser launch site, is shown in Fig. 3. The streak extends over about 1 arcmin. From the known geometry of the problem and the field characteristics of the CCD (0.33 arcsec pixel$^{-1}$), a geometrical height resolution of 80 m is deduced although seeing increases it to at least 200 m [the typical seeing of the WHT is 0.7 arcsec from a study of Wilson et al. (1999)]. The spot dimension has been deduced from the transverse profile of the streak. The smallest spot observed from the JKT was 1.5 arcsec FWHM, corresponding to a size of 65 cm at 90-km altitude. Spot sizes of 2 arcsec were typical. The diffraction limit for a purely Gaussian beam of 25 cm at $1/e^2$ is 0.6 arcsec, but the turbulence inside the shed housing the laser is responsible for the beam size being larger than the seeing limit.

A sodium density profile is obtained by plotting the background-subtracted signal along the streak. The signal has been integrated along the transverse direction of the streak in order to increase the signal-to-noise ratio of these profiles. With an
exposure time of 1 min, a signal-to-noise ratio of 60 is typical. The absolute determination of the altitude is very difficult in this experiment, compared with the LIDAR experiment where the altitude is easily deduced from the time-resolved signal. We have done a triangulation procedure between the JKT and WHT and obtained a reasonable result around 89 km but the uncertainty of a few km does not allow more precise results. Thus we have arbitrarily set the mean position of the layer at 90 km in Fig. 4. In contrast the relative scale of Fig. 4 is accurate and comes from the CCD pixel-height conversion.

We present in Fig. 4 the sodium profiles during the night of observation of 22 September 1999 in two continuous sets of acquisitions separated by a 3-h break. Note that the vertical banding effect on the data is due to realignments of the optical system introducing a displacement of the beacon in the sky. The two sequences presented in Fig. 4 display quite different behaviour of the sodium layer. In the first part of the night (Fig. 4, left part), the dynamics of the sodium layer undergoes important changes while it remains almost unchanged in the second part of the night (Fig. 4, right part). In the first part of the night, the mean photon return shows a 200 per cent increase. The transmission of the atmosphere varies by less than 15 per cent over a clear night and the sodium concentration is directly responsible for the change in photon return. Similar variations in photon return have been reported previously (Gardner et al. 1986). The sodium concentration also undergoes two sporadic events. The first of these arises at 96-km altitude, one hour before midnight, and lasts 15 min with a high peak sodium density. The second event starts 30 min before midnight, also around 96 km, and lasts at least 2 h. The altitude difference between the sporadic events and the principal layer is about 10 km. In the second part of the night, the sodium concentration varies very little.

The sodium concentration profile of the layer is usually not Gaussian. Some have interpreted the wave structure of the sodium profiles as an effect of gravity waves (Gardner & Shelton 1985). To take into account its frequent asymmetry, Megie & Blamont (1977) fitted the profiles by a modified exponential and derived a width for the layer. We propose to use the equivalent width which is the width of the rectangle with equal area and maximum value as that of the profile (Bracewell 1986). The measured equivalent width varied from 6.5 to 10.5 km over the night of 22 September 1999, and the amplitude of variation of the centroid position was 4.5 km through this night. Note that the short sporadic event produces a centroid variation of 2 km on time-scales as short as 4 min.

The study of the sodium dynamics on this night shows several effects which have to be taken into account when considering use of a sodium guide star for AO. The main parameter is the mean photon return at the telescope. Its value fixes the required laser power to achieve the desired accuracy of the wavefront correction. Nevertheless, variations up to 200 per cent of the photon return in the same night have been observed. As a consequence, a margin of power is needed to cope with lower than average sodium concentration and with guide stars created far away from zenith, where the atmospheric absorption is higher. We estimate that a power between 15 and 20 W of CW laser radiation is necessary for the LGS-AO system at the WHT. Another problem for AO comes from the global vertical movement of the column density induced by a slow displacement of the mean peak of the layer or by the appearance of sporadic events. The 4.2-km variation of the

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**Figure 4.** Relative sodium density above La Palma as a function of height and time on the night of 22 September 1999.
centroid during one night represents a defocus on the AO system which is not acceptable if not corrected. Finally, the sporadic events could disturb an AO system by effectively generating an astigmatic wavefront not related to atmospheric turbulence. Both sporadics shown in Fig. 4 are 10 km away from the mean peak of the layer. However, for both defocus and astigmatism, the time-scale of variation is long (1 min) compared with the dynamical time-scale of the turbulence (1 ms) and should allow for an AO system to compensate.

3.3 Circular polarization enhancement of the photon return

It is well known that optical pumping of the mesospheric sodium can enhance significantly the photon return of the LGS. Optical pumping occurs for a circular polarization of the laser. From the state $3S_{1/2, F=2}$, the sodium atoms can be excited into the state $4P_{1/2, F=3, m_F=3}$. From atomic selection rules, this state can only decay to $3S_{1/2, F=2}$ and not $3S_{1/2, F=1}$. With a linear polarization, the excited state can always decay into $3S_{1/2, F=1}$ where the atom is transparent to the laser line centered at the bottom of the D$_2$ line. Then after a few cycles of pumping and relaxation, the circular polarization leads to higher efficiency of pumping than the linear polarization. The level of optical pumping is governed by the dynamics of the atomic relaxation and laser pulse excitation. This effect has been investigated theoretically for pulsed lasers, leading to 30–35 per cent enhancement (Morris 1994). With a 840-Hz, sum frequency laser, Jelonek et al. (1994) have observed a 41–48 per cent increase. The case of CW optical pumping has been studied by Milonni et al. (1999). An increase of 15 per cent is predicted, in qualitative agreement with 10–30 per cent observed experimentally by Ge et al. (1997). In our experiment, the laser beam is linearly polarized and the circular polarization has been obtained, as usual, by inserting a λ/4 plate at the output of the laser. We report an efficiency increase of 5 ± 1 per cent for 300 mW of laser output.

3.4 Photon return and absolute sodium concentration

The laser pulse format is of fundamental importance in achieving the largest photon return of the sodium beacon. The theory of the photon return from the sodium beacon, depending on the laser format, has been investigated in detail by Milonni, Fugate & Telle (1998). The case of the CW laser has been treated recently (Milonni et al. 1999). The photon return depends on the saturation conditions and the mode structure of the laser. Pulsed lasers with a very short pulse duration and small repetition rate have high peak power and therefore a low saturation intensity. The CW laser has the largest saturation intensity because the peak power is equal to the average power. The mode structure is also ideal because the laser single frequency is fixed on the maximum of absorption of the D$_2$ line. Multimode lasers will have smaller efficiency; most of the modes are not exciting the D$_2$ line at its maximum of absorption.

For a monomode CW laser, it has been shown that the intensity of saturation of the D$_2$ line is about 6 mW cm$^{-2}$. For a 1.5-arcsec LGS spot, the intensity of saturation would be 22 W. In our case, the maximum launched power being below 500 mW, there is no saturation effect. Very generally, well below saturation, the photon return at the telescope can be expressed as (Telle, private communication):

$$\Phi_{\text{LGS}} = \text{SE} \times (C \sec \theta) \times (T \sec \theta)^2 \times P/(H \sec \theta)^2,$$

where SE is the so-called slope efficiency in photon m$^2$ s$^{-1}$ W$^{-1}$ atom$^{-1}$, $C_s$ is the column density of sodium in atom cm$^{-2}$, $T$ is the transmission of the atmosphere at the zenith, $P$ is the average power of the laser after the laser launching system, $H$ is the mean altitude of the sodium layer in metres and $\theta$ is the zenith angle of the laser beam. The slope efficiency depends on the pulse format and the atomic physics of the laser excitation. It characterizes the efficiency of a particular laser to excite the sodium transition. For a CW laser, SE = 260 (Telle, private communication). This value of the slope efficiency predicts the correct photon return in the experiment of Ge et al. (1998). This slope efficiency has been calculated for a circular polarization of the laser. Having worked almost exclusively with a linear polarization, we estimate a slope efficiency for the linear polarization which is equal to 260/1.15 = 226. Considering that $H$ is equal to 90 km, that $\theta = 3^\circ$ and that the typical atmospheric transmission of the site is 0.8 at 589 nm, we deduce that the theoretical flux at the primary mirror per watt of laser is:

$$\Phi_{\text{linear}} = 18 \times 10^9 \times C_s \text{ s}^{-1} \text{ cm}^{-2}. \quad (1)$$

During the week of the experiment, the mean flux at the primary at both the JKT and the small Meade telescope was 8.5 photon s$^{-1}$ cm$^{-2}$ and the mean laser power was 350 mW. The efficiency of the launch system being 60 per cent, the experimental return flux is then $\Phi = 40 \pm 6$ photons per launched W s$^{-1}$ cm$^{-2}$. This value of the flux is scalable up to 10 W of laser for a 1-arcsec LGS spot size. With a transmission of the atmosphere of 0.8, we deduce from equation (1) a mean sodium column density equal to 2.0 ± 0.6 × 10$^9$ atom cm$^{-2}$. Most of the uncertainty comes from the fluctuations of the atmospheric transmission. It is established that the absolute mean sodium concentration and its seasonal variations are related to the latitude. The concentration has a maximum in winter and a minimum in summer. It is assumed that the temperature difference between seasons modifies the kinematic rate of mesospheric reactions (Megie & Blamont 1977). For example Gardner et al. (1986) report a minimum abundance of 2 × 10$^9$ atom cm$^{-2}$ in summer and a maximum of 1.6 × 10$^{10}$ atom cm$^{-2}$ in winter. Recent experiments have been carried out at Kitt Peak whose latitude, 32° N, is close to the latitude of La Palma, 29° N (Ge et al. 1997). They obtained values close to 2 × 10$^9$ atom cm$^{-2}$ for this period of the year which agree with our results.

4 CONCLUSIONS

We have presented the results of the first experiments on mesospheric sodium monitoring at La Palma. For this purpose, we have set up a CW laser system including an 8-W argon ion laser pumping a dye laser locked on the sodium D$_2$ line delivering up to 500 mW at 589 nm. Our custom launch system has enabled us to get spot sizes as small as 1.5 arcsec despite poor seeing at the launch location. By launching the CW laser close to the zenith and observing it from a telescope about 200 m away, spatial profiles have been obtained. The dynamics of the layer has been shown to exhibit very different behaviours in the same night. Important variations in photon return, width and centroid have been observed. Two sporadic events surviving, respectively, 10 min and at least 2 h have been demonstrated. The consequences in terms of focus and astigmatism change for AO have been pointed out; it appears that it is necessary to correct at a time-scale of 1 min for defocus and astigmatism of the LGS. Finally, we
estimate the absolute mean sodium concentration for 1999 September on the site.

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REFERENCES

Fugate R. Q. et al., 1991, Nat, 353, 144

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