Progress Report on Sodium Laser Monitoring for Laser Guide Star Adaptive Optics

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Abstract

Laser guide star adaptive optics will be implemented at all major observatories in the next decade. In this paper we describe an experiment to monitor the short and long timescale variations of the altitude profile of mesospheric sodium. This experiment will provide information that will help in the specification and design of the laser guide star system which we hope to install at the William Herschel Telescope and commission in 2003/4.

Key words: Adaptive Optics, Laser Guide Stars

1 Introduction

An adaptive optical system senses the distortions in a wavefront and corrects them in real time, thus potentially providing a groundbased astronomical telescope with diffraction-limited image quality. All large telescopes either have or are being provided with adaptive optics upgrades, and such is the crucial role of adaptive optics (AO) that the first images shown at the dedication of the 8m diameter Gemini North telescope were taken using an AO system [1] : these images showed a spectacular angular resolution in the near infrared approaching the diffraction limit of 0.08 arc seconds, exceeding that of the Hubble space telescope. The 4.2m William Herschel Telescope (WHT) at La Palma will have its AO system, NAOMI, commissioned in 2000, and this will provide excellent image quality in the near IR to wavelengths as short as 0.85μm (see the paper by C. Benn, 2000, these proceedings). Developments in non-astronomical

[1] see http://www.gemini.edu/dedication/dedication.html

adaptive optics are driving costs down and it is now also feasible to equip individual instruments with custom, optimised AO systems.

In order for adaptive optics to be effective, there has to be sufficient light from a guide star in order to sense the wavefront distortion accurately. In practice, the science object itself is always too faint, so normally a bright star in the field (a so-called natural guide star or NGS) is used but this has to lie close to the science object, within the isoplanatic patch. The extent of the isoplanatic patch depends on wavelength ($\theta_0 \propto \lambda^{6/5}$) and in the visible it extends for only a few arc-seconds: therefore the probability of there being a bright enough NGS within the isoplanatic angle of the science object is very small for visible wavelengths, and still very limited even at K (2.2μm), so another source of light is required for wavefront sensing. This is provided by a *laser guide star* (LGS). It should be noted that the use of a single monochromatic laser guide star does not, by itself "solve" the guide star problem, since there remains the problem of sensing the global tilt and the use of a laser guide star also introduces a new source of error due to focus anisoplanatism or the cone effect. Nevertheless, a single laser guide star would dramatically enhance the performance of the NAOMI system on the WHT.

A laser guide star can be made by excitation of the mesospheric sodium layer that lies at an altitude between approximately 85 and 95km. The column density is approximately a few times 10^9 atoms per cm^2 — the absorption of a tuned beam is only a few percent — so it is important to have the most efficient pumping. The laser itself is a rather expensive component as it has to be of relatively high power (5-25W effective continuous power) and finely stabilised to the sodium D_2 line. It is also important to have data on any short time variability of the sodium abundance that might affect the mean height of the layer and hence the focus error of the final image.

We intend to construct a laser guide system for the WHT, closely coupled to the NAOMI adaptive optics system. As a preparatory step to the installation of this system, a series of experiments to measure the variation of the sodium emission with altitude in the layer, and with time, are being conducted as part of a coordinated preparatory study involving the University of Durham, University College London, the Astronomy Technology Centre, Edinburgh and the Isaac Newton Group. The aims of these experiments are:

(1) To measure the integrated sodium column density in the mesosphere
(2) To measure the vertical profile of sodium and its short time variation
(3) To gain experience in the operation of sodium guide star lasers in preparation for an LGS at the WHT

There have of course been extensive studies of the mesospheric sodium layer in the past and these are reviewed by Ageorges et al. (2000): to our knowledge, there are no previous measurements at La Palma and although we expect no surprises (i.e. abundance measurements consistent with those at similar latitudes) it is essential to carry out these measurements as a check. The importance of the third aim should not be underestimated: in our view, there is no substitute for "hands-on" experience in this kind of technological area, even though the final laser type and system complexity is likely to be quite different from that in the present study.

2 Proposed Experiment

By launching a laser, more-or-less at the zenith, tuned to the sodium layer at a mean altitude of $Z \approx 90$km, and observing from the side at a transverse distance of x, we will observe a streak of sodium emission with an image of approximate scale S:

$$S \approx \frac{x}{Z^2} \qquad \text{rad/km} \tag{1}$$

In our case, launching from the liquid nitrogen plant building and observing from the 1m JKT, $x \approx 173$m and the image scale is $S \approx 4.4$ arc-sec per km, providing a resolution on the order of 250m in normal seeing conditions: this vertical resolution is more than adequate for computing the mean layer height as a function of time.

The sodium D_2 line is due to the transition $3P_{3/2}$ to $3S_{1/2}$ and has two peaks due to the hyperfine structure (dominated by that of the lower level) with a Doppler-broadened linewidth in the mesosphere of approximately 1GHz for each peak. In order to make measurements we therefore require a laser stability very much less than 1GHz and sufficiently bright to provide an adequate photon return to record the laser streak in a few tens of seconds on a 1m class telescope. We estimate that the flux F at the telescope should be, ignoring atmospheric absorption, equal to approximately $3{\times}10^5$ photons/sec/W/m^2 for a sodium column density of 10^9/cm^2: this figure is consistent with the observations of Ge et al. (1998).

The laser itself is a ring dye laser, Spectra Physics Model 380D [2], pumped by a 5W (all lines) CW Argon ion laser. This type of laser technology is old, and the Argon ion laser is very inefficient, but the choice of these lasers was dictated by the fact that they were available at almost no cost to the project, apart from a replacement tube for the Argon laser. The output of the ring dye

[2] We are grateful to Prof. Malcolm Dunn of St Andrews University for the extended loan of this laser

laser is stabilised either by using the external cavity of the laser as supplied or preferably using feedback from a sodium absorption cell. [3] The feedback system works by modulating the laser frequency by 30MHz and therefore easily satisfies our stability requirements.

Using this system in the laboratory we have achieved 600mW of power out of the laser, and allowing for launch losses and atmospheric absorption this should place approximately 300mW in the sodium layer resulting in a flux in a 1m telecope on the order of 2×10^5 photons per sec. Even allowing for further losses, this laser should provide an adequate power to record the laser streak with an adequate signal-to-noise ratio in a few tens of seconds on a 1m telescope, and excellent SNR when using the WHT which is 205m distant from the laser launch site.

The laser beam is expanded in two stages, first by a commercial beam expander and then by a custom doublet/aspheric singlet system [4] that provides an unobstructed beam of diameter at the $1/e^2$ intensity points of 250mm with a total clear aperture of 300mm. The design is close to diffraction-limited, and in the absence of atmospheric turbulence should provide a beam intensity diameter of approximately 300mm at the $1/e^2$ points at 90km (i.e. approximately 0.7 arc-seconds diameter). Of course in practice the spot will be broadened due to turbulence and due to defocus and residual aberrations of the launch system and at the time of writing we have not fully resolved how to control the focussed spot quality.

The whole system is mounted on a 3×1.5m optical table situated in the liquid nitrogen cooling plant building that lies approximately equidistant between the WHT and JKT. A hatch has been inserted into the roof for the launch beam, and the isolated nature of the building helps maintain the safety of the system. The beam as launched will be a maximum of 600mW of CW light, typically 300mW, in a beam diameter at the $1/e^2$ points of 25cm: the centre of this beam this is just above the unaided eye-safe limit of approximately 1mW/cm^2, and therefore we shall provide a (human) spotter at all times for aircraft safety. During the course of our experiments we shall monitor the effect of the laser beam on observations at other telescopes: precise details of this part of the programme have not been finalised. We do not expect any significant impact on other telescopes.

[3] We are grateful to Prof. John Griffith of Birmingham University for supplying the design of the feedback circuit, to Dr Tony Cañas of Imperial College for contructing the electronics and to Fred Reavell of Imperial College for constructing additional components of this system.
[4] We are grateful to Jon Maxwell (ICSTM) for designing the key opto-mechanical parts of the launch system.

3 Current Status and Future Programme

The project started in November 1998 and as of early August 1999, the equipment is being assembled in the laboratory, with shipment to La Palma in early September. A first test run is scheduled for September 20-26 1999, with a second following in January 2000 and subsequent runs at approximately three month intervals until Autumn 2000. During the sequence of observation runs we expect a large number of system modifications to be made in the light of experience gained.

A parallel modelling study is being carried out by the University of Durham and University College London and together with these measurements will be used to finalise the specification of the WHT laser guide star system. The choice of laser for the final LGS system is still open, possibilities being a green-pumped (pulsed) dye laser (as at the Keck telescope), an all solid-state frequency-mixed system, or a Raman-shifted fibre laser. The required effective laser power is a key element that drives the cost (and/or operational feasibility) of these lasers, and the present preparatory study will help to establish the required laser power. We hope to commence construction of a full laser guide star system for the WHT in April 2001 at the latest.

4 Acknowledgements

We are grateful to P. Brown (ICSTM), A.A.D. Cañas (ICSTM), M. Dunn (St. Andrews), J. Griffith (Birmingham), A.J. Longmore (ATC, Edinburgh), J. Maxwell (ICSTM), F. Reavell (ICSTM), R.W. Wilson (Cambridge) and others who have so far contributed their time, expertise and/or equipment for this project. We are also grateful to the Particle Physics and Astronomy Research Council (PPARC) for its financial support under Grant PPA/G/S/1997/00864.

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