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Estimating the Atmospheric Sodium Density from Keck Laser Guide Star Photometry

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ABSTRACT

The Na Column density is estimated from a combination of the outgoing Keck laser power, the return flux measured with AO acquisition camera (ACAM), and a model of the laser interaction with the sodium layer atoms. These measurements allow one to fit for the Na column density which is a free parameter in the model of the laser beam interacting with sodium atoms. Using Keck AO data, the Na density was measured to be 2.47×10^9 atoms cm^{-2} averaged over 23 nights of AO observation in the spring and summer of 2006. This return is comparable to the median Na density of 3.60×10^9 atoms cm^{-2} measured previously on Maui.[1,2]

1. Introduction

In the past year, the Starfire Optical Range (SOR) has published laser guide star photon returns from its CW solid state laser that are much higher per watt of laser power compared to returns from the Keck and Lick lasers. The Keck and Lick Observatories both use similar pulsed dye lasers to create sodium guide stars. The interaction of the sodium atom with laser photons is complicated by a number of factors including beam polarization, pulse width, pulse duty cycle, spot size at the sodium layer, matching of the laser wavelength to the shape of the D2 sodium line, etc.. Current models for the interaction of laser light with the sodium layer predict large differences in the measured return between CW and pulsed lasers. Unfortunately, a direct comparison between models and laser returns has to date not been accomplished because measurements of the abundance of the sodium atoms were not made at the same time as the measurements of the laser guide star brightness. The structure of the sodium layer is known to be variable on both short and long time scales. Factors of two in density are typical in the course of several hours during a night of observation. The variation in sodium layer also complicates the comparison between lasers at different locations. Without a direct measurement of the Na abundance, another approach is to make a large number of return measurements and verify that the return is consistent with the mean Na abundance measured by other methods such as LIDAR.

The rest of this note details the comparison of measured return from the Keck dye laser (April-July 2006) and measured Na abundance reported from the Maui MALT experiment for the years 2003-2005. The model of the laser interaction with the sodium layer from Milonni[3] is used to predict the sodium abundance and these values are compared to the average from the Maui MALT experiment. The next sections detail the experimental technique and analysis.

2. Keck Laser Return Data

At the start of each night of LGS AO observation, the brightness of the laser guide star is recorded with ACAM. The return of ACAM has been calibrated as of fall 2005. The details of the calibrations of LGS return are given in KAON 337. The reported V magnitudes are corrected for atmospheric extinction. The magnitude is also corrected for the difference between the AO system transmission at the standard V photometric band and narrow band laser light at 589 nm. The laser power launched to the sky was estimated from the power measured at the final laser amplifier and from the transmission of the remaining optics in the laser beam train. The transmission of the remaining 3 lenses, 1 window, and 6 fold mirrors was taken to be 72%. The ACAM estimated V magnitude was converted to photons/cm2/sec measured at the telescope pupil. This conversion is accomplished assuming that the flux for a zero V band magnitude star is 936000 photons/sec/cm2 and an atmospheric transmission of 85%. The ACAM data and the laser power are given in Table 1.

The laser model of ref 3 was used to predict the sodium column density from measured ACAM returns on 23 nights. The flux at the telescope pupil in photons cm^{-2} sec^{-1} is given by,

$$F = \frac{1}{32\ln 2}\left(A\tau_p + 1\right)\frac{T_{atmos} C_s R_p a^2}{z^2}\ln\left(1 + \left(\frac{4\ln 2}{\pi}\right)\frac{T_{atmos} T_{beam} P_{laser}}{R_p I_{sat} a^2 \tau_p}\right) \qquad (1)$$

where P_{laser} is the average output laser power, τ_p is the laser pulse length, R_p is the pulse repetition rate, I_{sat} = 5W/cm^2 is the saturation intensity for pulsed lasers, A =1/(16ns) is the radiative decay rate for sodium atoms, a is the spot FWHM at the sodium layer, z is the range to the sodium layer from the telescope, Cs is the sodium column density in atoms cm^{-2}, T_{atmos} is the atmospheric transmission, and T_{beam} is the beam train transmission.

Using Eq. (1) and the measured return and laser power, we were able to fit the sodium column density from the ACAM data. The average sodium abundance from this data was 2.47x10^9 atoms cm^{-2} averaged over 23 nights of AO observation in the spring and summer of 2006.

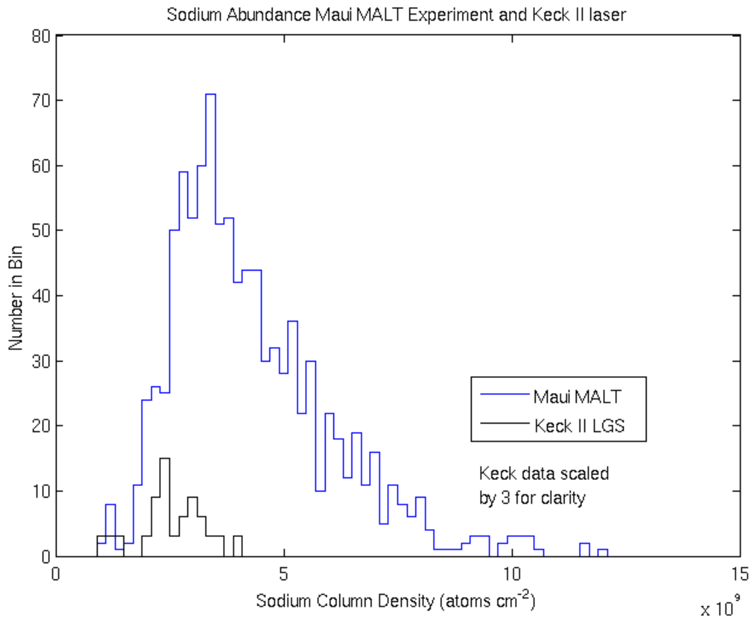

Figure 1 Sodium column density distribution of Maui MALT data (blue curve) and Keck II data (black curve) from this study. The Keck LGS data estimated average sodium abundance is 2.47x10^9 atoms cm^{-2}. This return is comparable to the median Na density measured previously on Maui of 3.60x109 atoms cm^{-2}**.**

3. Discussion

The measured photon return from the Keck LGS is consistent with the sodium abundance measured during the Maui MALT experiment. The histogram of both data sets is shown in Figure 1 for comparison. The median of the Maui data is of 3.60x10^9 atoms cm^{-2} and the average of the Keck data is 2.47x10^9 atoms cm^{-2}. These numbers differ by ~50%. Several reasons may account for this difference. The ACAM photometry errors are estimated to be 0.2 magnitudes (See KAON 337) and the ACAM photometry was found to be shifted lower by 0.2 magnitudes relative to measurement made by the GEMINI AO system (see KOAN 338). Either of these effects would account for 20% of the difference between the measurements. In addition the data from Keck were mostly recorded during the summer months of May and June when

Na abundance is expected to be lowest; in contrast the Maui data are over the course of several years. Hourly variations are seen in the Na layer as well, with the peak abundance occurring around 5 hours after midnight and minimum abundance occurring around 3 hours before midnight. The amplitude of the daily variation is about 70% of the peak value. The Keck LGS measurements were all taken during the start of the night when the Na density is typically the lowest for that night. A final cause for the discrepancy is the laser model represented by Eq. (1) could be overestimating the return flux by some unknown factor.

Table 1 Data from the Keck LGS AO used to estimate the sodium abundance

Date Day	Month	Year	Stacked Image Na Alt (km)	V mag	Unstacked Image Thickness (km)	Amp Power Watts	Launched Power Watts
1	7	2006	86.3	10.2	10.8	10.05	7.24
30	6	2006	86.8	10.1	10.4	10.10	7.27
21	6	2006	87.9	9.65	10.8	10.50	7.56
20	6	2006	87.6	9.6	8.9	11.20	8.06
18	6	2006	86.9	9.8	13.7	11.50	8.28
17	6	2006	86.8	10	10.4	10.90	7.85
5	6	2006	86.6	10	8.1	7.40	5.33
4	6	2006	86.9	10.04	10	7.90	5.69
3	6	2006	87.1	9.8	7	10.65	7.67
26	5	2006	86.1	10.5	10.4	10.90	7.85
25	5	2006	87.6	9.5	10.1	10.60	7.63
24	5	2006	86.6	10	12.1	11.15	8.03
23	5	2006	86.1	9.6	11.7	10.90	7.85
22	5	2006	85.7	10.9	10.4	10.80	7.78
21	5	2006	85	9.8	10.5	11.35	8.17
5	5	2006	84.5	10.6	7.7	10.90	7.85
4	5	2006	85.6	9.5	7.7	10.90	7.85
3	5	2006	87	9.9	7.2	10.40	7.49
2	5	2006	84.8	9.7	9.9	10.20	7.34
4	4	2006	86.8	9.9	9.4	10.80	7.78
21	3	2006	86.2	9.9	5.7	10.50	7.56
7	2	2006	91.4	9.5	8.8	9.95	7.16
6	2	2006	88.7	9.8	8	10.00	7.20

References

1. Maui MALT web site, http://eoslserver.csl.uiuc.edu/Research/Maui/NaLidar/index.html
2. C. Neyman, „Sodium Abundance Data Complied from the Maui Mesosphere and Lower Thermosphere Experiment", KAON submitted.
3. P. Milonni, R. Fugate, J. Telle, "Analysis of measured Photon Return form Sodium Beacons", JOSA A, Vol. 15, No. 1,1998.
4. C. Gardner, unpublished LIDAR results.