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LETTER

Letter to the Editor

Laser guide star adaptive optics: measuring the sodium column density using a magneto-optical filter

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Abstract. A general use of the adaptive optics requires an artificial guide star created by focusing a laser beam tuned to the sodium D_2 line. We propose here a system to monitor the column density of the mesospheric sodium layer which is based on the sodium magneto-optical filter already widely used in solar observations. The principal characteristics of this system are high transmission and high spectral resolution which allow to perform measurements in minutes on a relatively small (e.g. 50 cm diameter) telescope, where the filter can easily mounted due to its compactness.

Key words: instrumentation: adaptive optics

1. Introduction

Adaptive optics (AO) systems for atmospheric turbulence compensation require a bright reference star for measuring and correcting wavefront distortion. The star must be within a small field of view (the isoplanatic patch) of the object of interest, which varies from arcseconds to tens of arcseconds increasing with the wavelength of observation. While some sources are bright enough, most astronomical objects are too faint. For these reason a general use of AO requires a laser guide star (LGS) to provide the wavefront information. An artificial guide star can be created by focusing a laser beam tuned to the sodium D_2 line at 5890 Å on the mesospheric sodium layer at about 90 km altitude and observing the resonant scattering. A comprehensive review of these topics can be found in Beckers (1993).

Recent studies (Papen et al. 1996; Jian Ge et al. 1997) have reported that the column density of the layer is temporally variable with timescales from a year down to tens of minutes. The amplitude of the long term (seasonal) variations is function of the latitude of the observing site. When an AO laser system is planned a campaign of measurements of the sodium column density is mandatory in order to refine the design parameters of the laser system and to assess the power requirement. Also a comparison of different systems would be possible only if one knows the returned flux per unitary sodium column. As it was pointed out at the Cargese NATO-ASI School on "LGS AO for astronomy" (September 1997), a monitoring of the sodium layer appears very important, expecially in view of the queue scheduling of LGS AO observing programs at large observatories as the ESO VLT. An extensive discussion of these arguments can be found in Ageorges et al. (1998).

The D_1 line can be resolved in absorption on the sun or on early type unreddened (or slightly reddened) stars using a spectroscopic system with a resolution of about 400,000. This implies the use of big spectrographs or, if spectrographs with smaller resolution are used, large collecting areas and large exposure times in order to reach the higher signal-to-noise ratio needed to measure with a comparable accuracy the unresolved line. The above cited studies have been in fact performed this way. Clearly such systems are not suited for nearly continuous monitoring purposes. On the other hand it can be demonstrated that, with a sufficiently high spectral resolution, a relatively small telescope can collect in minutes the number of photons necessary to measure the equivalent width of the sodium line with a good signal-to-noise ratio. In order to have a small, compact and not too expensive monitoring system, this telescope should have an attached small, compact and not too expensive spectroscopic device. Clearly this device must be neither a spectrograph (too big) nor a Fabry-Perot (difficult to operate), nor an interference filter (too wide bandpass). The sodium magneto-optical filter proposed here fits the above requests: it is compact, stable in wavelength and profile shape, with high efficiency (up to 40% with unpolarized light) and narrow profile width (≥ 20 mÅ).

This filter is based on the magneto-optical activity of the sodium gas embedded in a strong magnetic field. It has a central bandpass that can be fitted to the width of the D_1 mesospheric line, plus two lateral symmetric bandpasses that observe the adjacent continuum. The D_1 equivalent width can be derived by observing the line in absorption on the spectrum of a bright early type (O, B, A) star. Stars of these spectral types do not have (normally) sodium D lines in their spectra. They also must be unreddened or slightly reddened in order to avoid the presence

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of interstellar D lines. But this is true for almost all the bright stars because of their vicinity to the sun.

In the next section we discuss about the exposure time and signal-to-noise in relation to the various parameters; in the third section the filter configuration is described; the fourth section contains the description of how to derive the column density. Conclusions follow in the last section.

2. Observations of the sodium layer

At an altitude of about 90 km a layer of atomic sodium is present, due to the release of this "volatile" metal by the meteors. The thickness of the layer is about 10 km and a typical column density is $3 \times 10^9\,\mathrm{cm}^{-2}$. This column density results in a typical D_1 line equivalent width of 3.5×10^{-4} Å. In order to derive the equivalent width of a sodium D line we proceed as follows. Let us assume to have a filter with three bandpasses. The central bandpass ($B = 50$ mÅ, wide enough to contain the whole line) measures the line, while the lateral bandpasses measure at the same time the continuum. As it can be seen in Sect. 4, from the measurements on the continuum and the one on the line the equivalent width can be derived.

In the central band the ratio of the signal to the background is

$$W_{\mathrm{D}_1}/B = 3.5 \times 10^{-4}/5 \times 10^{-2} = 7 \times 10^{-3}.$$

If we want to reveal variations of W_{D_1} with a 15% accuracy, at least $n_{\mathrm{ph}} = 10^6$ photons have to be detected in order to reach the necessary signal-to-noise ratio of 1000. Considering a star of visual magnitude m_V, the number of detected photons is

$$n_{\mathrm{ph}} = 2 \times 10^2 \times 10^{-0.4 m_V}\, B\, \pi\, D^2\, t\, \eta \qquad (1)$$

where B is the width of the central bandpass in Å, D is the diameter of the telescope in cm, t the exposure time in seconds and η the efficiency of the whole system, i.e. telescope, filter and detector. As an example, observing a star of $m_V = 2$ with a telescope of 50 cm diameter and a system efficiency of 10%, the time requested to reach a signal-to-noise of 1000 is 840 s, for the D_1 line.

The reasons of the choice of the D_1 instead of the D_2 line, which has an equivalent width a factor two larger than the D_1 line, are: i) the Zeeman splitting of the D_1 can be more easily exploited (see next section) to give the three needed bandpasses, and ii) the D_1 line is less affected by the atmospheric water vapour lines.

All the above demonstrates that a relatively small dedicated telescope can collect the desired number of photons in a relatively short time. Moreover a system of this kind can share the telescope with a seeing monitoring system (Sarazin & Roddier 1990). In fact differential image motion monitors (DIMM) use only two small subpupils of their telescope pupil to measure the seeing. If the mask in the postfocal collimated beam is pierced on a mirror at 45° with respect to the beam, the photons not used to measure the seeing can be used to measure the sodium column density. Now the problem is to find a compact, portable, filter of the needed resolution. In our opinion the solution can be the use of the magneto-optical filter.

3. The filter configuration

The magneto-optical filter (MOF), developed by A. Cacciani (Cacciani 1967; Cacciani et al. 1990), is a compact device displaying a very narrow spectral trasmission band (down to 20 mÅ) with intrinsic absolute spectral reference and stability and high peak trasmission (up to 40%). It has been used so far mainly in solar astronomy to detect solar magnetic and velocity fields (Rhodes et al., 1993; Tomczyk et al., 1995). Doppler shifts as low as $1\,\mathrm{cm\,s}^{-1}$ can be measured on the sun.

Its working principle is based on magneto-optical effects on metallic vapours in a magnetic field. Let us suppose to have two perfect crossed polarizers, for example two calcite prisms at 90°. In this condition no light can be transmitted unless a depolarizing element is interposed between them. If we insert for example a third polarizer at arbitrary angle between the crossed ones we get transmission, depending on the angle, because the initial polarization is changed before reaching the second polarizer. Similarly if we insert a retardation plate the initial polarization becomes in general elliptical and can pass through the second polarizer. In these cases however the transmission is wideband while we are interested in changing the polarization only in a narrow wavelength interval. The solution is provided by the (inverse) Zeeman effect and related phenomena (Righi, Macaluso-Corbino) on atomic vapours in and around their spectral absorption lines.

The core of the filter is the sodium cell, a glass cilinder 22 mm wide and 100 mm long containing sodium and krypton as ballast gas. The column density in the cell is controlled by a heater that determine the evaporation of sodium. The cell is embedded in a strong longitudinal magnetic field of 1–2 KG. The light beam, preferably collimated, enters the cell at one of the two circular faces of the cilinder. The shape of the bandpass at the exit of the second polarizer is determined by the values of the sodium temperature and of the magnetic field. The MOF bandpass is schematically represented in Fig. 1. The peaks are due to the polarization plane rotations (Macaluso-Corbino effect), reaching up to 40% (theoretical) transmission in the central one, while the two minima are due to the Zeeman effect, where the (theoretical) transmission is only of the 12.5%.

In solar physics the MOF has been used in double bandpass version to obtain Doppler and magnetic maps of the sun by subtraction of images taken in the red and blue wings of the solar D lines. In this version the filter described above is followed by a second cell unit called wing selector (WS) because selects alternatively one wing of the solar spectral line. The WS is a simple Zeeman cell (i.e. without polarizers) embedded in a longitudinal magnetic field, whose σ components absorb totally their own (circular) polarization. A quarter-wave plate placed after the filter and at 45° with respect to the exit polarizer, makes both bandpasses circularly polarized of the same kind, so that only one of them can be transmitted as desired.

The system we propose here is also formed by two cells in series. The first can be named "band selector" (BS), the second is the MOF. The BS is a cell working in transverse magnetic field with the sodium vapour kept at a temperature as high as

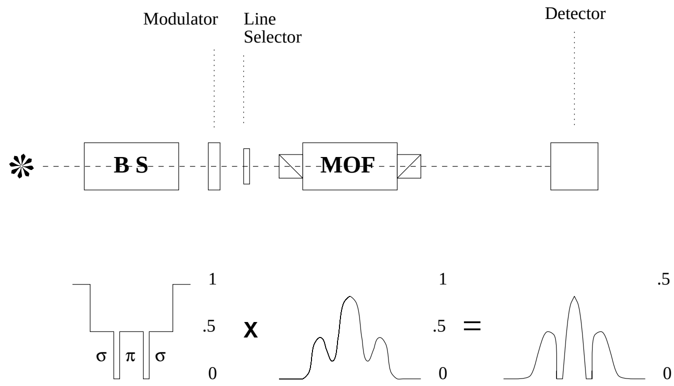

Fig. 1. Sketch of the system configuration. The theoretical trasmission of each component and the final system trasmission are also shown

to have the Zeeman bands (in absorption) saturated. The transverse magnetic field of 3–4 KG allows to work in the Paschen-Back regime for the hyperfine structure (sometimes referred as Back-Goudsmith), so, in the case of the D_1 line, essentially four separated Zeeman components are present simmetric to the rest wavelength of 5896 Å. The internal ones are the π components and the external ones are the σ. Keeping the sodium vapour to a temperature as high as to have the lines strongly saturated in order to merge the two π components, three bands can be created: the central one (π) absorbing the linear polarization parallel to the magnetic field, and the two lateral ones (σ^+ and σ^-) absorbing the linear polarization perpendicular to the magnetic field. In general there is a partial superposition between the lateral bands and the central one. The preference for the D_1 line is due to its simpler structure of the Zeeman splitting in comparison with the D_2 line, which has six Zeeman components where each of the two π is in between of two of the four σ components.

The task of the BS is to transmit only the polarization perpendicular to the magnetic field in the central band, while in the lateral bands it transmits only the polarization parallel to the magnetic field. In the two zones of superposition no light is transmitted because both polarizations are absorbed. This permits to separate the three bands and to regulate the width of the central one by a fine tuning of the temperature and the magnetic field intensity. At wavelengths outside these three bands the light passes unabsorbed. The magnetic field intensity and the sodium temperature of the MOF have to be regulated as to give a filter profile matching as much as possible the profile of the BS. Care has to be taken in keeping the transmission profile as high as possible in correspondence of the π band of the BS.

Between the BS and the MOF an electro-optical half-wave modulator is interposed with its optical axis at 45° with respect to the polarizations of the BS. Its task is to swap the direction of the polarization of the σ bands with the direction of the polarization of the π band. This permits the polarization of the π band and of the σ bands alternatively to match the polarization direction of the first polarizer of the MOF. The detector, located after the MOF, is a single-pixel photon counter, i.e. a photomultiplier or, better, an avalanche photo-diode (APD). An APD is preferred due to its higher quantum efficiency and dynamic range (about 0.65 and 1 MHz, respectively). The measurement will be performed by switching the two polarization directions, allowing in this way the light from the π band and from the σ bands to reach alternatively the detector. The switching frequency will be chosen according to the rate of variation of the atmospheric transparency.

Obviously this system observes both sodium D lines simultaneously. In order to observe only one individual line an additional filter made of a polarizer plus a retardation plate of suitable thickness, can be located after the half-wave modulator. The plate is tailored in such a way to be n waves for D_1 and n+1/2 waves for D_2. This means that D_2 is rotated by 90° and is absorbed by the first polarizer of the MOF. To suppress, instead, the D_1 line it is sufficient to rotate the additional polarizer by 90°.

The light external to the Zeeman bands of the BS reaches the MOF conserving its characteristic of unpolarized light. If this light is not blocked completely by the MOF profile it will results in a pedestal signal $p(\lambda)$ affecting both the π and σ bands. The MOF profile can be adjusted to avoid as much as possible this effect, which, anyway, can be measured in the phase of calibration of the system.

Since the system has an absolute wavelength reference, it is intrinsically stable in wavelength. It is of vital importance, however, to keep the profiles of the BS and the MOF as stable as possible with respect to the profiles measured with a tunable laser on the optical bench because these profiles will be used to derive the equivalent width. The transmission function of the filter section is sensitive to thermal fluctuations through changes in amplitude and in the wavelength position of the Macaluso-Corbino transmission peaks. On the other hand, the BS is only slightly sensitive to temperature changes, the peak absorption wavelengths being determined by the Zeeman effect. The stability of the MOF against thermal fluctuations has been investigated using the integrated solar disk oscillation facility at JPL (Cacciani et al., 1994). In that case the system had been configurated to operate as a Doppler analyzer. The result was that the noise velocity signal due to thermal fluctuations is about $1\,\mathrm{cm\,s^{-1}}$, that implies a thermal stabilization working at a level of ± 0.1 K. This demonstrates that a good thermal stabilization is easily achievable for these devices. A study of the sensitivity of the profile of our system to the temperature fluctuations is anyway to be done in order to evaluate the necessary level of thermal stabilization.

4. Measurement of the sodium column density

The sodium column density is derived by the D_1 line equivalent width, through the formula (Spitzer 1978) of the optically thin case:

$$W_{\mathrm{D}_1} = 8.85 \times 10^{-13}\, \lambda_\mu\, f_{\mathrm{D}_1}\, N_{\mathrm{Na}} \qquad (2)$$

where $\lambda_\mu = 0.5896$ is the wavelength in microns, $f_{\mathrm{D}_1} = 0.32$ the oscillator strength of the line, and N_{Na} the sodium column density. In the case of absorption lines the equivalent width is defined in terms of residual flux $r(\lambda)$ and adjacent continuum level C:

$$W_{\mathrm{D}_1} = \int_{line} (1 - \frac{r(\lambda)}{C})\, d\lambda. \quad (3)$$

This means that in order to derive the equivalent width we have to know both the integral of the line profile over the line full width and the level of the adjacent continuum.

The line profile is measured by the π-band of the MOF:

$$F^{\pi} = \int \psi_{\pi}(\lambda)\, r(\lambda)\, d\lambda \quad (4)$$

where F^{π} is the observed flux and $\psi_{\pi}(\lambda)$ the π-band profile. ψ_{π} depends on the magnetic field configuration in the cell and on the temperature of the sodium vapour. The former does not vary because it is generated by permanent magnets, the latter is kept stable by a thermal stabilization system. For these reasons ψ_{π} can be considered known a priori since it can be measured once for all using a tunable laser. In order to derive $r(\lambda)$ we must assume that the variations of $(1 - r(\lambda))$ are due only to the changes in the column density:

$$r(\lambda) = 1 - K(1 - r_0(\lambda)) \quad (5)$$

where $r_0(\lambda)$ is the line profile at a column density of reference and K is the proportionality constant. F^{π} can be written as

$$F^{\pi} = \int_{\lambda_1}^{\lambda_2} \psi_{\pi}(\lambda)\, d\lambda \,-\, K \int_{\lambda_1}^{\lambda_2} (1 - r_0(\lambda))\psi_{\pi}\, d\lambda \quad (6)$$

where λ_1 and λ_2 are the edge wavelengths of the π band. Since all the integrands of Eq. (7) are known functions, the value of K can be evaluated:

$$K = \frac{\int \psi_{\pi}\, d\lambda \,-\, F^{\pi}}{\int (1 - r_0(\lambda))\psi_{\pi}\, d\lambda}, \quad (7)$$

and $r(\lambda)$ follows from Eq. (5).

From the flux observed in the σ-bands the value of the continuum, considered constant across each band, can be derived:

$$F^{\sigma\pm} = \int \psi_{\sigma\pm}(\lambda)\, C^{\sigma\pm}\, d\lambda = C^{\sigma\pm}\, f^{\sigma\pm}. \quad (8)$$

As above, $f^{\sigma\pm}$ can be determined a priori from the profiles of the σ-bands. The value of the continuum is the average of the measurements in the two σ-bands:

$$C = \frac{1}{2}\,(\frac{F^{\sigma+}}{f^{\sigma+}} \,+\, \frac{F^{\sigma-}}{f^{\sigma-}}). \quad (9)$$

The effect of $p(\lambda)$, the small pedestal signal discussed in Sect. 3, can be evaluated by differentiating the integrand, $R(\lambda)$, of Eq. (3):

$$\Delta R(\lambda) = -\frac{\Delta r(\lambda)}{C} + \frac{r(\lambda)}{C^2}\Delta C.$$

Considering that $p(\lambda) = \Delta r(\lambda) = \Delta C$, we have

$$\Delta R(\lambda) = -R(\lambda)\,\frac{p(\lambda)}{C}. \quad (10)$$

Thus the effect of $p(\lambda)$ on W_{D_1} is that of subtracting a sistematic negative term. Its amount is as small as the ratio of the pedestal signal to the continuum one.

We have now all the ingredients to derive the equivalent width from Eq. (3) and then the column density N_{Na} from Eq. (2).

5. Conclusions

We have described here a system of monitoring of the mesospheric sodium layer column density which appears to be relatively simple, compact, not too expensive and that could be installed on existing seeing monitoring telescopes.

The peak transmission of this system can be high. Neglecting optical losses it reach 40%, i.e. 50% in the BS and 80% in the MOF (the light entering the MOF is totally linearly polarized in the π and σ bands).

Care has to be put in the thermal stabilization of the filter cells since the constancy of the spectral profile is essential in order that the system described here can work with the needed accuracy.

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