A SYSTEM FOR THE MONITORING OF THE MESOSPHERIC SODIUM LAYER USING A MAGNETO-OPTICAL FILTER

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ABSTRACT. A general use of the adaptive optics require 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 (MOF) 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 (50 cm) telescope, where the MOF can easily mounted due to its compactness.

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; Jan 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. But it is clear that a continuous monitoring is necessary if we want, by calibrating the returned flux, to control the good functioning of the system. Also a comparison of different systems would be possible only if one knows the returned flux per unitary column.

The D_2 line can be resolved in absorption on the sun or on early type 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 error 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. The sodium magneto-optical filter proposed here can do that; it is a compact device, stable in wavelength and profile shape, with high efficiency (up to 40% with unpolarized light) and narrow profile width (≥ 20 mÅ); and it is also not too expensive.

2. Observations of the sodium layer

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 (in the case of D_2 line $B = 50$ mÅ, wide enough to contain the whole line) measures the flux, while the lateral bandpasses measure at the same time the continuum. The sodium column density is derived by the D_2 line equivalent width, through the formula (Spitzer 1978) of the optically thin case:

$$W_{D_2} = 8.85\,10^{-13}\,\lambda_\mu\, f_{D_2}\, N_{Na} \tag{1}$$

where $\lambda_\mu = 0.5890$ is the wavelength in microns, $f_{D_2} = 0.65$ 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:

$$W_{D_2} = \int_{line} (1 - \frac{r(\lambda)}{C})\, d\lambda \tag{2}$$

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. A detailed derivation of the equivalent width will be discussed in a forthcoming paper (Patriarchi & Cacciani, 1998).

Considering a typical equivalent width of $7\,10^{-4}$ Å, the ratio of the signal to the background is

$$W_{D_2}/B = 7\,10^{-4}/5\,10^{-2} = 1.4\,10^{-2}$$

If we want to reveal variations of W_{D_2} one tenth of this value, at least $n_{ph} = 5\,10^5$ photons have to be detected in order to reach the necessary signal-to-noise ratio of 700. Considering a star of visual magnitude m_V, the number of detected photons is

$$n_{ph} = 2\,10^2\,10^{-0.4 m_V}\, B\, \pi\, D^2\, t\, \eta \tag{3}$$

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 700 is 420 s, for the D_2 line. This demonstrates that a relatively small dedicated telescope can collect the desired number of photons in a relatively short time. Now the problem is to find a compact, portable filter of the needed resolution. In our opinion the solution can be the magneto-optical filter.

3. The filter configuration

The magneto-optical filter (MOF), developed by A. Cacciani (Cacciani 1965; Cacciani et al. 1991), 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. Doppler shifts as low as 1 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 Nicol's 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 sodium column density 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 ligth 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.

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 is followed by a second cell unit called wing selector (WS) because selects one wing at a time 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 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 cell 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 to have the Zeeman bands (in absorption) strongly saturated. The transverse magnetic field of 3-4 KG allows to work in the Paschen-Back regime, so three bands are present: 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.

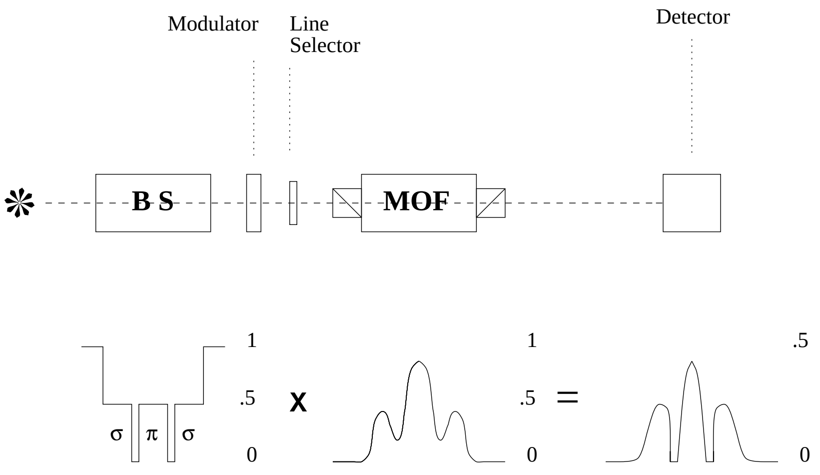

Fig. 1. Sketch of the system configuration. The theoretical trasmission of each component and the final system trasmission are also shown

The task of the BS is to transmit in the central band only the polarization perpendicular to the magnetic field and in the lateral bands 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.

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 change the polarization perpendicular into parallel, and viceversa. This permits the polarization of the π band and of the σ bands alternatively to match the polarization direction of the first Nicol's prism 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 at a time. In order to observe only one individual line a retardation plate of suitable thickness located after the half-wave modulator and at 45° with respect to the MOF Nicol's prisms can be 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 Nicol's prism of the MOF. To suppress, instead, the D_1 line the thickness of the plate should be n-1/2 waves for the D_1 line and n waves for the D_2 line.

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. 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 cm s^{-1}, that implies a thermal stabilization working at a level of ± 0.1 K. This demonstrates that a good thermal stabilization is possible for these devices. It is anyway to be done a study on the sensitivity of the profile of our system to the temperature fluctuations in order to evaluate the necessary level of thermal stabilization.

4. 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 (DIMM) (Sarazin & Roddier 1990).

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.

References

Beckers J.M., 1993, ARA&A 31, 13

Cacciani A., 1967, Atti Soc. Astr. Ital., p. 3

Cacciani A., Rosati P., Ricci D., Egidi A., Apporchaux T., Marquedant R.J., Smith E,J., 1990 (first version) and 1994, Jet Propulsion Laboratory internal report D11900, Pasadena

Jian Ge, Angel J.P.R., Jacobsen B.D., Roberts T., Martinez T., Livingston W., McLeod B., Lloyd-Hart M., McGuire P., Noyes R., 1997, in "Eso Workshop on laser technology for laser guide star adaptive optics astronomy", Eso Proc. 55, ed. N. Hubin, p. 10

Papen G.C., Gardner C.S., Yu J., 1996, in "Adaptive Optics" vol. 13, OSA Technical Digest Series, Washington DC, p. 96

Sarazin M., Roddier F., 1990, A&A 227, 294

Spitzer L., 1978, "Physical processes in the interstellar medium", John Wiley & Sons, New York