AZIMUTHAL STRUCTURES IN THE WIND AND CHROMOSPHERE OF THE HERBIG Ae STAR AB AUR. PRELIMINARY RESULTS FROM THE MUSICOS 1992 CAMPAIGN

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Abstract.

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Abstract. MUSICOS (for MUlti-SIte COntinuous Spectroscopy) is an international project to facilitate and organize world-wide multi-site campaigns in high resolution spectroscopy, in view of obtaining a complete time coverage of various types of variable stellar phenomena.

In the framework of this project a vast spectroscopic campaign was organized in December 1992, involving 8 sites well distributed in longitude around the Earth. The observations concerned three scientific programs, among which was the study of azimuthal structures in the wind and chromosphere of the pre-Main-Sequence Herbig Ae star AB Aur.

The He I 5876 Å line of AB Aur, which is formed in the expanding chromosphere of this star, in the innermost parts of its wind, was monitored at a resolution of 30000, nearly continuously for about 4 days. A spectacular variability of this line was discovered, the profile changing from pure emission to a composite profile including a deep absorption component in the course of a few hours. This variability can be the signature of azimuthal structures in the wind of AB Aur.

We present the data collected during the campaign, and discuss possible interpretations of the spectacular variations of the He I 5876 Å line.

1. The MUSICOS Project and the MUSICOS 1992 Campaign

MUSICOS (MUlti-SIte COntinuous Spectroscopy) is an international project for setting up a network of high resolution spectrometers coupled to telescopes of the 2 m class, well-distributed around the world, and partly dedicated to continuous spectroscopy.

In the framework of this project, a first MUSICOS campaign was successfully organized in 1989 (Catala and Foing, 1990; Catala et al., 1993a; Foing et al., 1994), and a prototype of a spectrograph meeting the requirements of the scientific programs necessitating multi-site observations was constructed (Baudrand and Böhm, 1992). This MUSICOS spectrograph will be duplicated in several places in the world.

A second MUSICOS campaign took place in December 1992, and was focused on three scientific programs:
- search for co-rotating structures in the chromosphere and wind of the Herbig Ae star AB Aur;
- search for nonradial pulsations in the ρ Scuti star θ2 Tau;
- Doppler imaging of active structures for the RS CVn system HR 1099.

Nine sites and telescopes were involved in this campaign: University of Hawaii 2.2 m (Hawaii), Kitt Peak McMath 1.5 m (Arizona), Black Moshannon Observatory 1.6 m (Pennsylvania), William Herschel 4.2 m (Canaries), OHP 1.52 m (France), Vainu Bappu Observatory 1 m (India), Xinglong 2.16 m (China), Anglo-Australian 4 m (Australia), IUE (Space): 24 shifts ESA/NASA. Moreover, AB Aur was also observed in November 1992, 3 weeks before the campaign, with the Penn State Fiber Optic Echelle spectrograph, on the Kitt Peak 2.1 m and Coudé Feed telescopes, for 14 consecutive nights. In addition, a world-wide multi-wavelength campaign was organized for one of the targets, HR 1099, during and around the dates of the MUSICOS 1992 campaign, and involving photometric and spectroscopic observations at various wavelengths, from UV to radio.

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The prototype MUSICOS fiber-fed spectrograph was transported and installed on the University of Hawaii 2.2 m telescope for this campaign, and gave very satisfactory results. Another fiber-fed spectrograph, ISIS, was transported to China.

This campaign was very successful, and produced a vast amount of data, which are still being analyzed. We present below preliminary results of the observation of the chromospheric He I $\lambda$5876 Å line of the pre-Main-Sequence Herbig Ae star AB Aur.

2. The Wind and Chromosphere of AB Aur

The Herbig Ae/Be stars are pre-Main-Sequence objects of intermediate mass (2–5 $M_\odot$). They show conspicuous signs of intense stellar winds, with mass loss rates in the range $10^{-9}$–$10^{-6}$ $M_\odot$ yr$^{-1}$, and of extended chromospheres.

Among them, AB Aur (spectral type A0e, $T_{\text{eff}} = 10000$ K), the brightest Herbig Ae star in the northern hemisphere, has often been considered as the prototype of the whole class. A semi-empirical model of its wind and chromosphere (Catala and Kunasz, 1987) led to an estimate of its mass loss rate ($10^{-8}$ $M_\odot$ yr$^{-1}$) and to the determination of the structure of its chromosphere (maximum temperature $\approx 17000$ K; size $\approx 1.5 R_*$).

Extensive observations of the Mg II and Ca II resonance lines of AB Aur have revealed that these lines are modulated by the star’s rotation, whose period is of the order of 32 hr. Because these lines are formed in the wind of the star, this modulation was interpreted as evidence for the presence of fast and slow streams in the wind, alternating in the line of sight as the star rotates (Praderie et al., 1986; Catala et al., 1986).

This model, built by analogy with the structure of the solar wind, implies the existence of a magnetic field at the base of the wind, controlling the wind structure.

The goal of the MUSICOS 92 campaign was to search for the same type of modulation in a chromospheric line, the He I 5876 Å line (formed at temperatures higher than the star’s effective temperature), to verify whether the rotational modulation is also found close to the stellar surface, and in order to constrain better the azimuthal structure of the wind and chromosphere by time resolved observations.

3. Observations and Data Reduction

Table I is a summary of the main telescopes and instrumentation involved in the observation of AB Aur during the campaign.

Because the instruments were not identical from site to site, different reduction procedures were used for the various sites. These procedures are described in Baudrand and Böhm (1992) for the MUSICOS spectrograph, and in Catala et al. (1993a) for the other instruments. Normalization to the continuum was performed in a homogeneous way for all spectra recorded during the campaign.
TABLE I

Telescopes and instruments

<table>
<thead>
<tr>
<th>Site</th>
<th>Telescope</th>
<th>Spectrograph</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mauna Kea (Hawaii)</td>
<td>2.2 m UH</td>
<td>MUSICOS echelle</td>
<td>2048 × 2048 CCD</td>
</tr>
<tr>
<td>Kitt Peak (Arizona)</td>
<td>1.5 m McMath/Pierce</td>
<td>stellar spectrograph</td>
<td>800 × 800 CCD</td>
</tr>
<tr>
<td>La Palma (The Canaries)</td>
<td>4.2 m William Herschel</td>
<td>Utrecht echelle</td>
<td>640 × 1180 CCD</td>
</tr>
<tr>
<td>OHP (France)</td>
<td>1.52 m</td>
<td>Aurélie</td>
<td>2048 1D CCD</td>
</tr>
<tr>
<td>Xinglong (China)</td>
<td>2.16 m</td>
<td>ISIS fiber-fed</td>
<td>512 × 512 CCD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Felenbok and Guérin, 1988)</td>
<td></td>
</tr>
</tbody>
</table>

The FWHM and wavelength position of the Na I D interstellar lines were measured on all spectra. The wavelength scale was subsequently shifted so that the interstellar lines fall at their rest wavelengths. The spectra were then convolved with gaussians with appropriate widths in order to bring them all to the same resolution, that of the Kitt Peak spectra ($R = 24000$).

4. Preliminary Results

Figure 1 shows a dynamic spectrum of the He I 5876 Å region, built from the data obtained during the MUSICOS 92 campaign on AB Aur. The time coverage in the second half of the observation period is very good, but we experienced some weather problems in the first half, leading to an overall duty cycle of about 50%.

We see spectacular variations in this emission line. The main feature of this line is a blue-shifted emission component variable both in intensity and position, its centroid moving back and forth from $-60$ to $-110$ km s$^{-1}$ in the course of our observations. In addition, a broad absorption component appeared for about 6 hours during the observations. This component has a deep minimum at zero velocity, and extends toward the red with a half-width at half-maximum of about 130 km s$^{-1}$.

A high level of variability is also observed in the 14-day monitoring obtained 3 weeks prior to the MUSICOS campaign, with the Kitt Peak 2.1 m and Coudé feed telescopes. A broad absorption component appears repeatedly, in a seemingly periodic way. A period analysis performed on this data string shows unambiguously the presence of a period around 32 hr, reminiscent of the rotational modulation with the same period observed in the Ca II K line. The interpretation of the variations of this line in terms of a rotational modulation is therefore very tempting.

The variability of the Mg II h and k P Cygni profile of AB Aur, observed with IUE one month before the MUSICOS campaign, is also very conspicuous. These results clearly suggest a periodic variation, with a period close to 35–40 hr, reminiscent of the behavior observed in 1982 and 1984 for these lines.
Fig. 1. Dynamic spectrum of the He I 5875.63 Å line, obtained during the MUSICOS 1992 campaign. The top panel shows two of the spectra. Note the presence of an absorption component extending to the red on the dotted spectrum. The vertical line corresponds to the rest wavelength of the line.

Figure 2 shows the data obtained during the MUSICOS campaign (those of Figure 1), phased with a period of 32.3 hr. This period is that derived from the 14-day monitoring performed 3 weeks before the campaign. One notes the smooth appearance of the line variations on this figure, which confirms their periodicity.

5. A Possible Interpretation: Streams in the Wind and Chromosphere of AB Aur?

The rotational modulation of the Mg II and Ca II resonance lines has been interpreted by a model involving streams in the wind of AB Aur (Praderie et al., 1986; Catala et al., 1986). If these streams originate from the stellar surface, as would be
the case if they are controlled by a surface magnetic field, then we expect that the chromospheric He I 5876 Å line, formed near the base of the wind, is also modulated by the rotation of the stream structure.

Our observations are in agreement with this model, which suggests that the structure of the wind of AB Aur indeed originates from the stellar surface. Following Catala et al. (1993b), we propose that the He I 5876 Å line of AB Aur is the superposition of 2 components:

- A quiet-chromosphere component; this component has (i) an absorption centered at zero velocity, formed at the base of the wind and chromosphere, where the wind velocity is small and the chromospheric temperature is not far above the effective temperature, and (ii) a blue-shifted emission component formed further out in the wind and chromosphere, at higher velocity and temperature.

- A stream component; this component, formed in the streams originating from the stellar surface, is assumed to be in emission, and its position in wavelength is modulated by the rotation of the star; there may be one or several of these streams.

Thanks to the good time coverage of the second half of the MUSICOS observations, it is possible to constrain better the hypothetical stream structure. We computed empirical wind models, including a quiet-chromosphere/wind and streams. We
assumed that the quiet-chromosphere/wind produces both a zero-velocity gaussian absorption component and a blue-shifted gaussian emission component, and that the streams produce additional gaussian emission components. The gaussian broadenings of these various components is assumed to be due to turbulent motions, and we adopted 100 km s\(^{-1}\) for the velocity of these motions, consistent with previous estimates (Catala and Kunasz, 1987; Catala et al., 1993b). The radial velocity \(V_r\) in the wind, both in the streams and outside the streams, the local equivalent widths of the components in the various regions of the wind, are additional parameters of the model. We assumed a projected rotation velocity of 80 km s\(^{-1}\) (Böhm and Catala, 1993). The inclination angle between the rotation axis and the line of sight is unknown, but we must see the star close to edge-on, since the observed \(v\sin i\) leads to an estimate of the rotation period close to the observed one. We adopted \(i = 80^\circ\) for the inclination.

We varied the parameters of this model until a reasonable visual fit to the observed dynamical spectrum was obtained. The minimum number of streams required to reach this agreement is found to be 4. Figure 3 displays the results obtained with a model including 4 streams with the parameters shown in Table II.
As can be seen by comparing Figures 2 and 3, the model reproduces reasonably well the main behavior of the line. Although still imperfect, the agreement of this preliminary simulation with the observations is very encouraging, and will prompt us to pursue the analysis of this stream model.

The proposed model has to be taken with caution. First of all, it is only the result of a simple trial and error procedure, and we have no reason to believe that the proposed solution is unique. In particular, the fact that the streams are all at a latitude of 10° and have the same size, may not be significant. Moreover, the modelling of the line components by simple gaussians is a limitation that could be improved in the future. It is indeed very likely that the various components of the line originate from regions with velocity and temperature gradients. For the moment, various gradients can be crudely accounted for by varying the width of the gaussian components of the model, but a NLTE line transfer calculation in presence of a velocity field (Catala and Kunasz, 1987) would allow us to better model the shape of each component. Finally, these NLTE calculations would also give some indications of the distances at which the various line components are likely to be formed, providing us with the possibility to take into account the radial extension of the different regions of the model, which is not the case for the moment.

### 6. Conclusion

These preliminary results confirm the presence of streams in the wind and chromosphere of AB Aur, and show that they originate from the stellar surface rather than from some more remote part of the wind. The stream structure is presumably controlled by a surface magnetic field. The existence of a magnetic field in such a star is paradoxical, since it is not supposed to possess an outer convection zone, according to standard evolution theory.

This paradoxical behavior may perhaps be accounted for by models involving turbulent subphotospheric motions (Vigneron et al., 1990), possibly leading to a dynamo generation of magnetic fields.

We intend to pursue in more detail the interpretation of our observations in terms of the corotating stream model, in particular by introducing a realistic radiative transfer treatment of the helium line formation.
Acknowledgement

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References