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DOPPLER IMAGING OF THE HERTZSPRUNG GAP STAR OU ANDROMEDAE

ANA BORISOVA[1], UWE WOLTER[2],
RENADA KONSTANTINOVA-ANTOVA[1] and K. P. SCHRÖDER[3]

[1]*Institute of Astronomy, Bulgarian Academy of Sciences,*
BG-1784, Sofia, Bulgaria
[2]*Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany*
[3]*Departamento Astronomia, Universidad de Guanajuato,*
GTO CP 36000, Mexico
E-mail: uwolter@hs.uni-hamburg.de

Abstract. OU And (HD 223460, HR 9024) is a moderately fast-rotating early G-type giant star, located in the Hertzsprung gap. As found by earlier Zeeman-Doppler imaging campaigns (ZDI), its surface magnetic field is dominated by a simple geometry: all Doppler images of OU And created so far show a polar spot, which appears to be stable at least on the timescale of several years. In combination with evolutionary models, this suggests that OU And has been an Ap-star during its main sequence phase. Our data cover close to ten years: 2008 to 2017. Using high-resolution spectra from two sites (NARVAL and TIGRE), we create photospheric Doppler images (DI) and, furthermore, analyze the evolution of OU And's chromospheric emission. Our analysis shows that, during all our observations, OU And has only shown feeble surface features apart from the pronounced polar spot. Furthermore, we find that in several instances these weak features move, evolve or disappear during less than one stellar rotation. We perform a systematic error analysis of the chromospheric activity indices on a subset of our TIGRE data. In this way, we find that our measurements of chromospheric activity vary weakly, but significantly on timescales of days up to weeks, but without any obvious rotational modulation. **In the framework of these proceedings we only outline our methods and results. For details, we refer to our article which has been submitted to the Bulgarian Astronomical Journal.**

1. INTRODUCTION

Our target OU And (HD 223460, HR 9024) is a single giant of spectral class G1 III (Gray et al. 2001) with moderate emission in the Ca II H&K lines (Cowley & Bidelman 1979, who did not further quantify the emission). It exhibits X-ray emission (Gondoin 2003, Ayres 2007) and is a moderate rotator with a projected rotational velocity of 21.5 km/s, making it an interesting target for Doppler imaging (DI) studies. Its position in the Hertzsprung-Russel diagram is in the Hertzsprung gap with an effective temperature of 5360 K and 2.85 solar masses.

The focus of our study is the characterization of OU And's activity on timescales up to several years. To this end, we use the longest time series of spectroscopic observations available for OU And to date - covering the years 2008 to 2017.

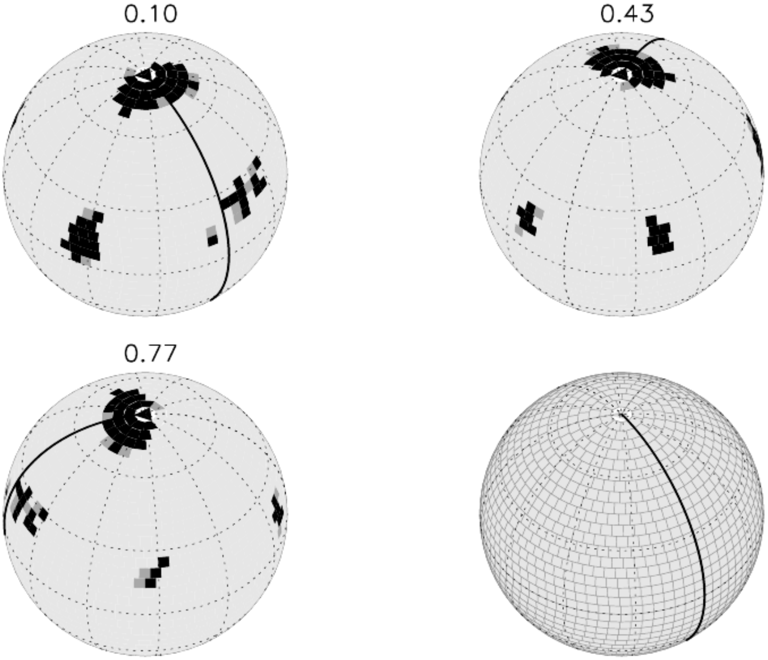

Figure 1: Photospheric Doppler image (DI) of OU And computed from our 2008 NARVAL spectra, using our DI package CLDI. All maps show the same surface for the indicated rotation phase; the sub-observer longitude at phase zero is marked by a thick line. The fourth map shows the empty surface grid used for our DI, it has 2048 elements, each extending by 4.5x4.5 square degrees. Black and gray elements indicate a spot filling factor of 100% and 50%, respectively.

2. OBSERVATIONS

Observations were carried out (i) with the NARVAL spectropolarimeter mounted on the 2 m telescope Bernard Lyot at Pic du Midi Observatory, France. Furthermore, (ii) we observed a long time series of spectra of OU And using the HEROS spectrograph of the 1.2m TIGRE robotic telescope at the La Luz observatory, near Guanajuato in central Mexico.

Using NARVAL, OU And was observed during the second semesters of 2008, 2013 and 2015. We observed 121 spectra of OU And using TIGRE/HEROS from November 2014 to September 2017, usually taking a few spectra per year. In addition, we performed one densely sampled campaign that covered nearly 3 stellar rotations during 14 observing nights from 2017 Sep 2 to 2017 Nov 14.

3. DOPPLER IMAGING THE NARVAL SPECTRA

To obtain spectral line profiles from the unpolarized (Stokes I) component of our NARVAL spectra, we use our least-squares deconvolution method, called "selective least-squares-deconvolution" (sLSD). Described in detail in Wolter et al. (2005), it uses comparatively narrow spectral regions, usually a few 10 Å wide to compute an average broadening profile of the lines in the region under study. We use our implementation of Doppler imaging, called Clean-like Doppler imaging (CLDI, see Wolter et al. 2005 & 2008) to reconstruct starspots on OU And's surface, i.e. cooler regions in its photosphere. Similar to the image deconvolution method CLEAN used in radio astronomy it performs an iterative reconstruction of the stellar surface, building up an increasingly good model of the observed line profiles.

The Doppler images of OU And were constructed with the same values of as those used for the ZDI imaging of Borisova et al. (2016, BEAL16). We made an attempt to independently estimate the rotation period and stellar inclination on the basis of the goodness of the line profile fit. Unfortunately, given the overall moderate rotation phase coverage of our spectra and - at times - fast spot evolution (compared to the rotation period) the CLDI tomography of our NARVAL data does not allow to determine the rotation period at all.

Based on the discussion of Doppler imaging caveats in our main journal article on OU And, we summarize here that we consider the polar spot, found in all our DIs of OU And, to be real. This means we are certain that it is not an imaging or line profile modeling artifact. See e.g. Bruls, Solanki & Schüssler (1998) for a detailed discussion of this aspect. Yet, the shape and size of the polar spot shown in our DI maps are only poorly defined, given the relatively small vsini, the potential uncertainties in stellar inclination, the partially uneven phase sampling and, maybe most importantly, the rather weak line profile deformations in our spectra of OU And. The same restrictions apply to the non-polar features of our DI: they are real in the sense of not being imaging or data artefacts. Yet, their precise positions, shapes and sizes are not well constrained by our DI.

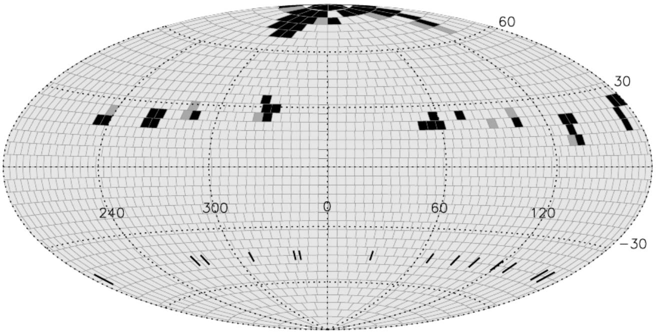

Figure 2: Aithoff projection of our DI based on the 2013 (upper panel) and 2015 (lower panel) NARVAL spectra. The sub-observer longitude at phase zero is the meridian at the centre, marked by zero. Rotation phases sampled with spectra are indicated by marks on the southern hemisphere. Rotation progresses with decreasing surface longitude, i.e. from left to right in this projection. As discussed in our main journal article, we did not use the complete 2015 spectra as input to the CLDI, because intrinsic spot evolution during less than one rotation inhibited the construction of a DI.

4. WHAT DO WE LEARN ABOUT OU AND ?

Strictly speaking, our CLDI Doppler images are maps of photospheric brightness in a narrow subinterval of the visible spectrum. However, in the context of 'cool' stars, like OU And, the CLDI maps can be interpreted as good proxies of temperature maps, though they lack a temperature calibration (see e.g. Wolter et. al., 2005).

Keeping that in mind, our (proxy) temperature maps of OU And for 2008 and 2013 are in a good agreement with the magnetic maps published in BEAL16, which were taken strictly contemporaneously. Our temperature maps confirm the reality of a persistent and large polar spot on OU And, as already found by BEAL16. Furthermore, like the magnetic maps, our temperature maps show smaller cool spots closer to the equator. Unfortunately, we cannot trace the evolution and precise location of these spots on the basis of of our dataset.

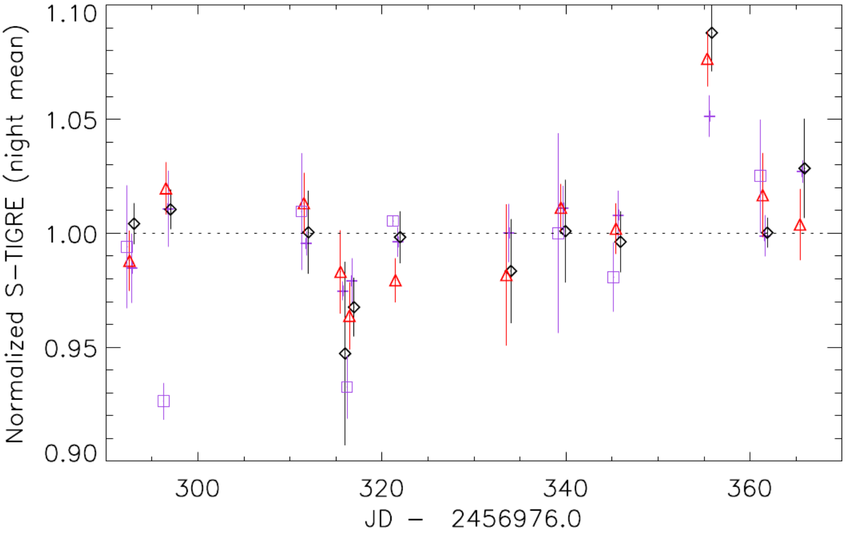

Figure 3: All activity indices measured in our densely time-sampled TIGRE spectra in September 2015. Here, we only show the robustly estimated mean and 1-sigma standard deviation for each night, which is computed after an outlier rejection from typically ten spectra. All points are slightly shifted along the abscissa for each night for better visibility, the corresponding spectra were taken strictly simultaneously. Different symbols represent different lines: the S-Index is represented by violet squares; the TIGRE indices for the Ca IR are marked by blue plus symbols (8489 A), black diamonds (8542 A) and red triangles (8662 A), respectively. Each line index is normalized to the median of its time series.

Our study of the activity indices spans the period 2008 to 2017. In agreement with BEAL16, we found only modest variations in chromospheric activity, e.g. with an amplitude of a few percent peak-to-peak in terms of the Ca II H&K S-index. In the framework of our study, OU And showed the most pronounced chromospheric variations in 2013; this holds true for all activity indices and the corresponding chromospheric emission line profiles. As already discussed by BEAL16, we presume that OU And is an Ap star descendant that has evolved close to the end of the Hertzsprung gap, still retaining a relatively fast rotation from its main sequence phase.

5. CONCLUSIONS

We performed photospheric Doppler imaging (DI) and studied the chromospheric activity of the late-type single giant OU And, based on high resolution spectroscopic data from the period 2008 to 2015. We compared our temperature maps with magnetic maps of the same star created by Zeeman Doppler imaging (ZDI) and presented by Borisova et al. 2016, referenced as BEAL16 here. Both DI methods and studies find a persistent polar spot and weaker, only marginally resolved, lower latitude features on OU And. Furthermore, we studied the chromospheric activity of OU And, based on the spectra taken with the NARVAL instrument, combining them with spectral time series taken with TIGRE/HEROS. In total, our spectroscopic dataset spans the years 2008 to 2017. We find a weak long-term variation of OU And's chromospheric emission and no clear indications of a rotational modulation.

As in the case of other tentative activity cycle candidates, we believe that further spectroscopic long-term studies of OU And will be required to support of refute the reality of a cycle in this case. Such studies will need to span a decade or more. We are continuing to observe OU And with a coordinated use of our telescope facilities in Bulgaria, using the echelle spectrograph ESPERO, and in Mexico, using the HEROS spectrograph.

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The lead author of this article, AB, died unexpectedly in December 2017. Ana initiated this study and we have completed it along the lines set out by her and UW several years ago. We mourn the loss of an esteemed colleague and a great person. May Ana rest in peace.

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