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LINE POLARIMETRY AT THE 30M WITH XPOL: VARIABILITY OF THE MAGNETIC FIELD AROUND THE EVOLVED STAR U HER

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Abstract. Evolved cool stars exhibit an important mass loss that enriches the interstellar medium and, therefore, and participates in the cycle of matter in the Universe. The role of magnetic field within these mass loss phenomena is not fully understood, but can be constrained thanks to observations of various molecular transitions in the circumstellar envelope (CSE) of the star. We observed the SiO maser line emission from an AGB star, U Herculis, to detect the magnetic field in the inner gas region of the envelope, up to 2-4 stellar radii from the photosphere. We used the XPol instrument at the IRAM-30m telescope to monitor the Stokes I, Q, U and V spectra along a monthly basis toward U Her. The goal is to monitor the variation of the magnetic field on a monthly basis. We present positive detection and successful monitoring over one year. A variation of the magnetic field strength is clearly detected. We question the origin of this field, possibly connected to the stellar pulsation, a dynamo or the presence of a companion.

Keywords: masers - polarization - stars: evolution - stars: late-type - stars: magnetic field - radio lines: stars

1 Introduction

Asymptotic Giant Branch (AGB) stars play a major actor in the recycling of the matter of the universe by enriching the interstellar medium (Höfner & Olofsson 2018). The magnetic field is expected to be a potential agent in the mass loss process Pascoli & Lahoche (2008) and in shaping the wind (Balick & Frank 2002). Magnetic field detections from radio observations of the polarization of maser emissions of different molecules allow us to constrain the intensity of the magnetic field in the CSE of these objects: from the innermost zones (typically within 2-5 $R_\star$ from the center of the object) via the SiO masers (Herpin et al. 2006), up to the outermost layers (at several thousand $R_\star$) via the OH masers for oxygen stars (Rudnitski et al. 2010). Radio observations tend to constrain a magnetic field decreasing according to a 1/r law throughout the CSE (Marinho et al. 2024). The magnetic field strength is expected to be of a few Gauss at the surface of various evolved stars. This is supported by the very first detection of a magnetic field at the surface of a Mira star, χ Cyg, (Lèbre et al. 2014, 2-3 Gauss). The origin of this magnetic field is still debated, but mechanisms involving a turbulent dynamo in AGB stars, convection, stellar pulsation, and cool spots can be invoked. Classical $\alpha - \omega$ dynamos are not expected for those slow rotators (i.e., high Rossby number, up to ~ 100) as AGB stars. The detected local weak magnetic field can be generated by turbulent/convective dynamo (Soker 2002, $\alpha^2\omega$). The radial component of the field can then be strongly amplified thought shocks compression above cool spots at the stellar surface (Priest 1987). Hence, a magnetic field of 1-10 Gauss, as detected, can be reached in the vicinity of cool magnetic spots (Soker 2002). It is then interesting to look for a link between the stellar activity (pulsation) and the strength of the magnetic field. This work will present the new observations toward one AGB star in Sec. 2, the result of the monitoring in Sec. 3 and will discuss the results in Sec. 4.

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2 Observations and Methods

In March and May 2022 we have performed polarimetric SiO maser observations of the SiO (v = 1, J = 2-1) maser at 86.2434277 GHz in a new sample of cool evolved stars (Marinho et al. 2024) with the Eight MIxer Receiver (EMIR) receiver on Pico Veleta, Spain, using the XPOL polarimeter (Thum et al. 2008). Each of the four frequency bands of EMIR is equipped with dual-polarization heterodyne mixers. We used the band E90 connected to the VESPA backend, set up in polarimetry mode with a 120 MHz bandwidth and a channel separation of 40 kHz (i.e. ∼0.139 km/s at 86 GHz). The forward and main-beam efficiencies were 0.95 and 0.81 and the half-power beam width was 29 arcsec. In 2024 new observations have been done. We simultanously obtained all four Stokes parameters I, Q, U, and V .

The observed source is U Herculis described in Tab 1 that has been observed for 5 epochs at different optical phases between 2022 and 2024 : 0.06, 0.14, 0.19, 0.25, 0.45. Its pulsation period is 406 days.

Table 1. Source presentation (Andriantsaralaza et al. 2022; Gottlieb et al. 2022)

	RA (J2000) (h m s)	DEC (J2000) (° ’ ”)	Type	d (pc)	v_{LSR} (km/s)	L ($L_\odot$)	T_{eff} (K)	dM/dt ($M_\odot$/yr)
U Her	16:25:47.47	18:53:32.86	Mira (M6.5-8+eB)	271	-16.48	8000	3000	5.9×10^{-7}

The method to derive the magnetic field is fully described in Marinho et al. (2024). Several steps are needed. Stokes V is used for the computation of the magnetic field, and so a particular attention was made when cleaning the spectra from the instrumental spectra. There is an instrumental contamination, resulting of a leakage of Stokes I into Stokes V. Applying a calibration method, we managed to remove most of the instrument polarization. Using the cleaned V spectra, we used a rvm (Tipping & Faul 2003, relevant vector machine) to decompose the spectra in several components. Following the Zeeman-weak field theory, Stokes I is a combination of Gaussians and Stokes V the derivative of Stokes I. The rvm code search for derivative of Gaussians in the spectra. The magnetic field is estimated at the maximum and minimum intensity for each component (see the colored lines in Fig. 1). Considering strongly saturated masers, we followed the Elitzur (1996) theory, where the magnetic field is a function of the circular polarization (V/I). Above a critical value for the linear polarization $p_L > 33\%$, there is one solution for the magnetic field. If $p_L < 33\%$, there are two solutions that have to be considered (shown as green and light green in Fig. 2).

3 Results

The magnetic variability observed in U Her in Marinho et al. (2024) is 0.9-1.5 and 2.4-5.1 Gauss at two nearby epochs, March and May 2022, at stellar optical phases 0.25 and 0.45, respectively, and suggests a possible link with the stellar pulsation. Thanks to the monitoring we began in 2024 with the IRAM-30m, we estimate the magnetic field strength covering stellar phases from 0.06 to 0.19. As it was shown for 2022, the Stokes V spectra have changed. This is demonstrated in Fig. 1 showing one spectrum from March and another one from April 2024 (stellar phases 0.14 and 0.19 respectively). We observe a variation of the spectra all along the monitoring.

The magnetic field has also changed. It has been derived for every epoch of observations and compared with one component, at the same velocity : -16.3 km/s, that appear at every epoch. This evolution is shown in Fig. 2 where there is the magnetic field in green and the stellar phase in black in the back of the figure.

4 Discussion and Conclusion

Both magnetic fields and photospheric/atmospheric dynamics trigger the important mass loss those cool stars encounter (Lèbre et al. 2014, 2015; López Ariste et al. 2019). Using radio observations of polarization of SiO maser emission, Marinho et al. (2024) detected a magnetic field of at least several Gauss within 2-5 $R_\star$ from the center of the object. In this work, we had for one star more periods of observation to see if there is a connection with the phase and so the stellar activity. From the Fig. 2, with the evolution of the magnetic field, we do not see a clear correlation with the phase. It is in contradiction with our hypothesis the stellar activity at the origin

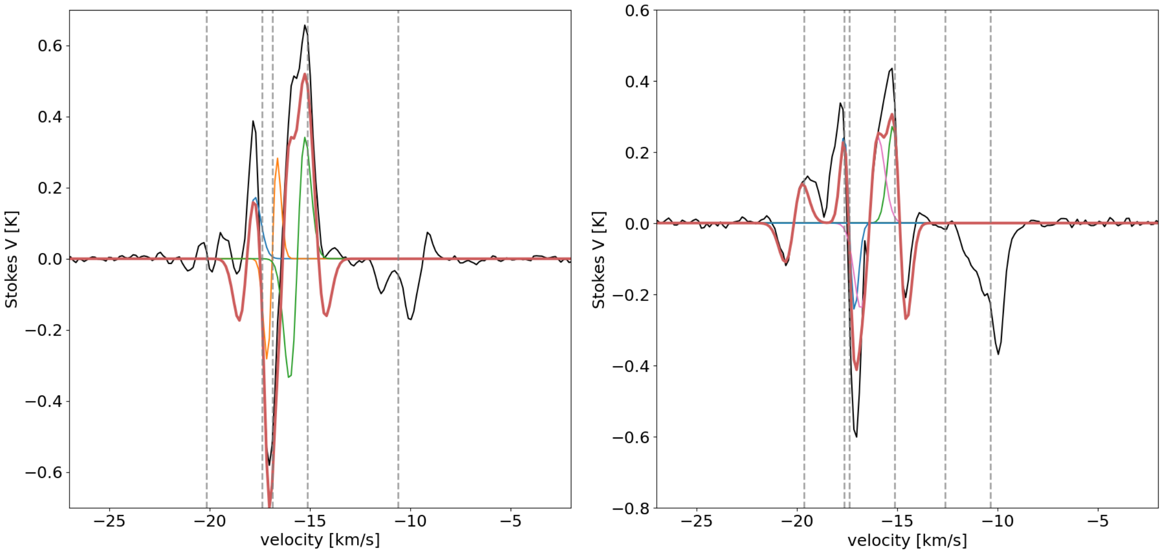

Fig. 1. Stokes V spectra in March (left panel) and April (right panel) 2024. The black lines are the observed cleaned spectra, the red one are the sum of all the component of the decomposition (other colors). The vertical dotted lines indicate the center velocities of the Stokes I components.

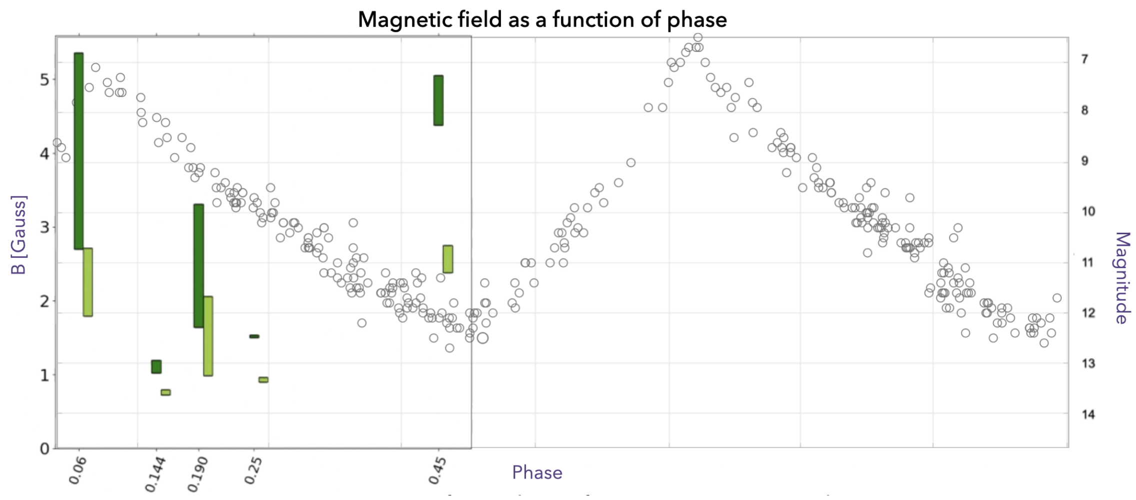

Fig. 2. Evolution of the magnetic field (in green) with the optical phase (in black, from `https://www.aavso.org`). The two shades of green correspond to the two solutions of the magnetic field.

of the detected magnetic field.

The surface magnetic field has been detected for the moment in only one AGB star by the spectropolarimeter Narval at the TBL (Télescope Bernard Lyot), χ Cyg, (Lèbre et al. 2014, 2-3 Gauss). Magnetic activity in the CSE does not appear to be well coupled with what is happening at the photosphere level, but this requires confirmation with better coordination of observations. In the hypothesis that the non-detection of a surface magnetic field is due to the absence of the latter, if the photospheric magnetic fields are so weak or inexistent, then we can wonder what is the origin of the magnetic fields observed in the circumstellar environment. If not linked to the star, the magnetic field detected in the SiO masers could be due to a more local origin.

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