Discovery of a very weak magnetic field on the Am star Alhena

A. Blazère,1,2⋆, C. Neiner1, P. Petit2,3
1LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France
2Université de Toulouse, UPS-OMP, Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
3CNRS, Institut de Recherche en Astrophysique et Planétologie, 14 Avenue Edouard Belin, F-31400 Toulouse, France

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Alhena (γ Gem) was observed in the frame of the BRITE (BRight Target Explorer) spectropolarimetric survey, which gathers high resolution, high signal-to-noise, high sensitivity, spectropolarimetric observations of all stars brighter than V=4 to combine seismic and spectropolarimetric studies of bright stars. We present here the discovery of a very weak magnetic field on the Am star Alhena, thanks to very high signal-to-noise spectropolarimetric data obtained with Narval at Télescope Bernard Lyot (TBL). All previously studied Am stars show the presence of ultra-weak (sub-Gauss) fields with Zeeman signatures with an unexpected prominent positive lobe. However, Alhena presents a slightly stronger (but still very weak, only a few Gauss) field with normal Zeeman signatures with a positive and negative lobe, as found in stronger field (hundreds or thousands of Gauss) stars. It is the first detection of a normal magnetic signature in an Am star.

Alhena is thus a very interesting object, which might provide the clue to understanding the peculiar shapes of the magnetic signatures of the other Am stars.

Key words: stars:magnetic field – stars:chemically peculiar – stars:individual:γ Gem

1 INTRODUCTION
1.1 Magnetism in hot stars
Over the last decades, magnetic fields have been discovered in a significant number of hot (A, B, and O) stars, and these fields probably play a significant role in their evolution. However, the detailed properties of hot star magnetism are not well understood yet. About 7% of hot stars are found to be magnetic (Grunhut & Neiner 2015) with dipolar magnetic fields above 300 G. The detection rate for the A-type stars is similar (∼10%, Wolff 1968; Power et al. 2007). In addition, sub-Gauss longitudinal magnetic fields have recently been discovered in a few A and Am stars.

The normal A star Vega was the first ultra-weak field star discovered (Lignières et al. 2009). Its spectropolarimetric time series was interpreted in terms of an ultra-weak surface magnetic field using Zeeman-Doppler Imaging (ZDI). The results of this study support the fact that Vega is a rapidly rotating star seen nearly pole-on. The reconstructed magnetic topology revealed a magnetic region close to the pole with radial field orientation.

In addition, ultra-weak magnetic field signatures have been detected in three Am stars: Sirius A (Petit et al. 2011), β Uma, and θ Leo (Blazère et al. 2016), thanks to very precise spectropolarimetric observations. For these objects, the signature in circular polarization is not of null integral over the line profile but exhibits a positive lobe dominating over the negative one. This peculiar signal, although not expected in the standard Zeeman effect theory, was demonstrated to follow the same dependence on spectral line parameters as a signal of magnetic origin and has been confirmed to be magnetic (Blazère et al. 2016). Preliminary explanations are being proposed to explain the peculiar shape of the signatures. In Am stars, high-resolution spectra have revealed stronger microturbulence compared to normal A stars (Landstreet et al. 2009). The very shallow convective shell producing this turbulent velocity field may host supersonic convection flows (Kupka et al. 2009). This could provide the source of sharp velocity and magnetic gradients needed to produce strongly asymmetric profiles. Shocks traveling in this superficial turbulent zone may also contribute to amplify any existing magnetic field.

Vega, Sirius A, β Uma, and θ Leo may well be the first confirmed members of a new class of magnetic hot stars: the ultra weakly magnetic hot stars. Such ultra weak magnetic fields are difficult to detect due to the weak amplitude of their Zeeman signatures and may exist in other hot stars.
However, ultra weakly magnetic stars are considered a separate class of magnetic stars compared to the ∼7% of stronger field stars, because no magnetic stars exist with a polar field strength between ∼300 G and the Gauss-level fields observed in ultra weak magnetic stars.

To explain this dichotomy between strong and weak magnetic fields in hot stars, Aurière et al. (2007) proposed a new scenario based on the stability of a large scale magnetic configuration in a differentially rotating star: strong magnetic fields correspond to stable configurations and weak magnetic fields to unstable configurations. Another theory to explain the dichotomy is the failed fossil theory (Braithwaite & Cantiello 2013): strong magnetic fields rapidly reach an equilibrium whereas weak magnetic fields are still dynamically evolving towards the equilibrium and decreased due to the instability.

Table 1. Fundamental parameters of the Am stars Alhena and θ Leo.

| Parameter          | Alhena A | θ Leo |
|--------------------|----------|-------|
| Spectral type      | A0IVm    | A2Vm  |
| $T_{\text{eff}}$ (K) | 9280±30$^a$ | 9280±10$^b$ |
| log g              | 3.6$^a$  | 3.65$^c$ |
| Mass ($M_\odot$)   | 2.8±0.01$^b$ | 2.94±0.2$^b$ |
| Radius ($R_\odot$) | 3.9±0.1$^d$ | 4.03±0.10$^e$ |
| $v \sin i$ (km s$^{-1}$) | 15±3$^f$ | 23±3$^f$ |
| Luminosity ($L_\odot$) | 12±1$^b$ | 13±13$^a$ |
| Age (Myr)          | 4±$^b$  | 4±$^b$ |
| Microturb. (km s$^{-1}$) | 2$^e$   | 1$^e$ |

$^a$ Adelman et al. (2015b) $^b$ Zorec & Royer (2012) $^c$ Adelman et al. (2015a) $^d$ Pasinetti Fracassini et al. (2001) $^e$ Royer et al. (2007) $^f$ Royer et al. (2002) $^g$ David & Hillenbrand (2015)

The journal of observations is provided in Table 2.

| Date at the middle of the observations (mid-HJD - 2450000) | S/N | $T_{\text{exp}}$ (s) |
|-----------------------------------------------------------|-----|---------------------|
| 27 Oct 2014                                               | 986 | 4×25                |
| 18 Sep 2015                                               | 1016| 4×35               |
| 19 Sep 2015                                               | 1093| 4×35               |

2 OBSERVATIONS

Data were collected with the NARVAL spectropolarimeter (Aurière 2003, Silvester et al. 2012), installed at the 2-meter Bernard Lyot Telescope (TBL) at the summit of Pic du Midi Observatory in the French Pyrénées. NARVAL is a high-resolution spectropolarimeter, very efficient to detect stellar magnetic fields thanks the polarization they generate in photospheric spectral lines. It covers a wavelength domain from about 375 to 1050 nm, with a resolving power of ∼68000.

We used the polarimetry mode to measure the circular polarization (Stokes V). The 4 sub-exposures are constructively combined to obtain the Stokes V spectrum in addition to the intensity (Stokes I) spectrum. The sub-exposures are also destructively combined to produce a null polarization (N) spectrum to check for spurious detection due to e.g., instrumental effects, variable observing conditions, or non-magnetic physical effects such as pulsations. Alhena was observed on October 27, 2014, and September 18 and 19, 2015. The journal of observations is provided in Table 2.

We used the Libre-Esprit reduction package (Donati et al. 1997) to reduce the data. We then normalized each of the 40 echelle orders of each of the 3 Stokes I spectra with the continuum task of IRAF. We applied the same normalization to the Stokes V and N spectra.

3 MAGNETIC ANALYSIS

To test whether Alhena is magnetic, we use the Least Square Deconvolution (LSD) technique. It is a cross-correlation technique for computing average pseudo-line profiles from a list of spectral lines in order to increase the S/N ratio. Under several rough approximations (additive line profiles, wavelength independent limb-darkening, self-similar local profile shape, weak magnetic fields), stellar spectra can indeed be seen as a line pattern convolved with an average line profile.

We first created a line mask corresponding to the primary component of Alhena. We started from a list of lines extracted from VALD (Piskunov et al. 1995; Kupka & Ryabchikova 1999) for an A star with $T_{\text{eff}}=9250$ K and log g=3.5, with their Landé factors and theoretical line depths. We then cleaned this line list by removing the hydrogen lines, the lines that are blended with hydrogen lines, as well as those that are not visible in the spectra. We also added some lines visible in the spectra that were not in the original list.

1 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The Stokes V profiles show clear Zeeman signatures for all 3 nights. We computed the detection probability of the magnetic signatures are strong enough to be detected in individual LSD Stokes V profiles, while for other magnetic Am stars co-addition of many Stokes V profiles were necessary to extract a magnetic signature (Blazère et al. 2016). Outside the stellar line, we obtained a detection probability between 20% and 40% and a false alarm probability between 7.356×10^{-1} and 5.351×10^{1}, that corresponds to a non detection outside the stellar lines.

Since the diameter of the fibre of Narval is 2.8 arcsec, the two components of the binary have been recorded in the observations. However, the secondary is 5-6 magnitudes fainter than the primary, so only ~2% of the received light comes from the secondary component. Moreover, the secondary is not visible in the spectra. Thus, the contribution of the lines of the secondary are considered negligible unless its radial velocity is very close to the one of the primary. In addition, we ran the LSD analysis with a mask corresponding to a main sequence G star and the signatures in the Stokes V profiles disappeared (see Fig. 2). We thus confirm that the signatures in the Stokes V profiles come from the primary star, i.e. that the Am star is magnetic.

Using the centre-of-gravity method (Rees & Semel 1979) with a mean wavelength of 500 nm and a mean Landé factor of ~1.46 corresponding to the normalization parameters used in the LSD, we calculated the longitudinal field value \(B_1\) corresponding to these Zeeman signatures over the velocity range [-40:8] km s^{-1}.

\[
B_1 \propto - \frac{\int v V dv}{\ln mc \int 1 - I dv} 
\]

\[ (1) \]

where \(v\) (km s^{-1}) is the radial velocity, \(I_0\) (nm) the normalized wavelength of the line-list used to compute the LSD profiles, \(g\) the normalized Landé factor and \(c\) (km s^{-1}) the light velocity. The longitudinal magnetic field value for the three observations, and the corresponding null values, are shown in Table 3. The values of the longitudinal magnetic field is around ~5 G, with an error bar smaller than 3 G. The
values extracted from the N profiles are compatible with 0 G.

The shape of the Zeeman signatures in the Stokes V profiles slightly changed between the observation obtained in 2014 and the ones from 2015. This could be due to a rotational modulation of the longitudinal magnetic field, if the field is oblique compared to the rotation axis, as observed in most hot stars (Grunhut & Neiner 2015). In 2014, the signature would look like a cross-over signature, while in 2015 the negative pole may be observed.

On the contrary, the signatures obtained over two consecutive nights in 2015 did not change. This suggests that either Alhena is an intrinsically slow rotator, or the rotational modulation is small because the star is seen under a specific geometrical configuration with an inclination or obliquity angle close to 0.

4 DISCUSSION AND CONCLUSION

The observations presented in this paper correspond to the first detection of a magnetic field in an Am star with a normal Zeeman signature, i.e. with a positive and negative lobe as seen in the ultra-weakly magnetic A star Vega and in all strongly magnetic hot stars. On the contrary, all the other Am stars studied in spectropolarimetry with a high accuracy exhibit peculiar magnetic signatures with only a prominent positive lobe.

The difference between the field of Alhena and the other Am stars is thus puzzling. In particular, Alhena has very similar stellar parameters as the ones of the magnetic Am star θ Leo. However, the signatures in the Stokes V profiles are very different. θ Leo shows peculiar signatures, while Alhena shows normal signatures. Considering the oblique rotator model, the dipolar magnetic field $B_D$ is at least 3.3 times the maximum observed $B_V$ value (Aurière et al. 2007).

Therefore, the longitudinal field values measured for Alhena point towards a polar magnetic field strength of the order of 15 G, i.e. weak but much stronger than what is observed in θ Leo and the other magnetic Am stars.

An explanation to the difference between the characteristics of the magnetic field observed in Alhena and in other Am stars may be found in their microturbulence value. The microturbulence of Alhena A is ∼1 km s$^{-1}$ (Adelman et al. 2015b), while the one of θ Leo, β UMa, and Sirius A is ∼2 km s$^{-1}$ (Adelman et al. 2015a, 2011; Landstreet et al. 2009). Indeed, the peculiar shape of the magnetic signatures of the latter 3 Am stars is thought to be related to their stronger microturbulence, compared to normal A stars (Blazère et al. 2016).

The very shallow convective shell producing this turbulent velocity field may host supersonic convection flows (Kupka et al. 2009), which could be the source of sharp velocity and magnetic gradients producing strongly asymmetric Zeeman profiles. Alhena A may have a too weak microturbulence to undergo this effect.

Another difference between Alhena and θ Leo is that Alhena is a binary star with a G-type companion, while θ Leo is a single star. However, Sirius is also a binary star and Sirius A does present peculiar magnetic signatures like θ Leo. The distance between the two components of Sirius is larger ($P_{orb}$=50.1 years) than the one of Alhena, nevertheless Alhena is a wide binary as well ($P_{orb}$=12.63 years). However, the orbit of Alhena B is more eccentric ($e$=0.89) than the orbit of Sirius B ($e$=0.59), and there could thus be more tidal interactions between the 2 components of Alhena than between the components of Sirius.

Alhena is thus a very interesting star to understand the magnetism of Am stars and ultra-weak magnetic fields in general. We will continue to observe Alhena in the frame of the BRITE spectropolarimetric survey to obtain more information about its magnetic field. In particular, the comparison between the observations obtained in 2014 and 2015 indicate that the Stokes V profile could be rotationally modulated, although either the rotation period is long or the geometrical configuration leads to only weak modulation. This could be tested, and the geometrical configuration constrained, thanks to more spectropolarimetric observations spread over the rotation period of Alhena A.
