The Magnetic Field of the Stripped Primary in the \( \nu \) Sgr System, a Member of the Rare Class of Hydrogen-deficient Binaries

Swetlana Hubrig\(^1\)\(^\odot\), Silva P. Järvinen\(^1\)\(^\odot\), Ilya Ilyin\(^1\)\(^\odot\), and Markus Schöller\(^2\)\(^\odot\)

\(^1\) Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany; shubrig@aip.de
\(^2\) European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany

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Abstract

We present the results of high-resolution spectropolarimetric observations of the optically dominant component in the rare hydrogen-deficient binary system \( \nu \) Sgr. Only a small number of such systems in a very late phase of helium shell burning are currently known. The mass transfer from the donor star in binary systems usually leads to the stripping of its hydrogen envelope. Consequently, since the mass of the secondary increases, it appears rejuvenated. Using a few ESO FORS 1 low-resolution spectropolarimetric observations of this system, Hubrig et al. announced in 2009 the presence of a magnetic field of the order of \(-70\) to \(-80\) G. Here we report on more recent high-resolution ESO HARPS spectropolarimetric observations showing that the primary in \( \nu \) Sgr is a spectrum variable star and possesses a weak magnetic field of the order of a few tens of Gauss. The detection of a magnetic field in this rare hydrogen-deficient binary is of particular interest, as such systems are frequently discussed as probable progenitors of core-collapse supernovae and gravitational-wave sources. Future magnetic studies of such systems would be worthwhile to gain deeper insights into the role of magnetic fields in the evolution of massive stars in binary systems.

Unified Astronomy Thesaurus concepts: Spectropolarimetry (1973); Stellar magnetic fields (1610); Common envelope binary stars (2156); Interacting binary stars (801)

1. Introduction

The binary system \( \nu \) Sgr (=HD 181615) with an orbital period of 137.9343 days was frequently classified in the past as a B star due to the presence of a strong variable emission in the H\(\alpha\) line (e.g., Dudley & Jeffery 1993; Koubský et al. 2006). Koubský et al. (2006) suggested that this system is probably observed in the initial rapid phase of mass exchange between the components. The primary, the hydrogen-deficient star dominating the optical spectrum, is less massive with a most probable spectral type B5II–B8II (Bonneau et al. 2011), while the other, less visible component, is more massive by a factor of 1.57 (Koubský et al. 2006). Recently reported optical interferometric observations of this binary system by Hutter et al. (2021) provided the first direct, visual detection of the hot secondary star, which is 3.59 ± 0.19 mag fainter than the primary. Hutter et al. (2021) assigned the secondary star as spectral type B5 under the assumption that it is a main-sequence star. The stellar parameters of the primary in the \( \nu \) Sgr system, \( T_{\text{eff}} \approx 12,300 \pm 200 \) K and \( \log g = 2.5 \pm 0.5 \), were reported by Kipper & Klochkova (2012). Apart from the strong deficiency of hydrogen, the primary shows a very peculiar chemical composition, with an overabundance of nitrogen and the s-process elements Y, Zr, and Ba. The optical spectrum is extremely rich, exhibiting numerous lines of the ionized metals Ti, Cr, and Fe (e.g., Dudley & Jeffery 1993; Kipper & Klochkova 2012, see also Figure 7 in Hubrig et al. 2009). This richness is due to the low hydrogen abundance and consequently low continuum opacity (e.g., Dudley & Jeffery 1993; Kipper & Klochkova 2012). Interferometric observations in the mid-IR revealed the presence of dust confined to a dense circumbinary optically thick disk with an inner rim of about 20 mas (Netolíček et al. 2009). Due to the intermediate orbital inclination of the system of about 50°, it was suggested that the observed spectrum is a combination of the disk rim and disk face (Netolíček et al. 2009).

Hydrogen-deficient binaries (HdBs) are frequently discussed as probable progenitors of core-collapse supernovae (e.g., Dudley & Jeffery 1993) and possibly gravitational-wave sources (e.g., Laplace et al. 2020). Recent scenarios for Type Ib and Iib supernovae consider binary evolution, where the primary star expands as it evolves until it fills its Roche lobe and then starts mass transfer due to Roche-lobe overflow (e.g., Yoon et al. 2017). The mass transfer from the donor star usually leads to the stripping of the hydrogen envelope. While the secondary’s mass increases due to mass accretion, this component appears rejuvenated. HdBs are very rare and only a small number of such systems in a very late phase of helium shell burning are currently known. Schootemeijer et al. (2018) reported a set of five such systems with \( \nu \) Sgr the most massive one in this category. According to the authors, the donor star in \( \nu \) Sgr fills its Roche lobe again during a late helium shell burning phase, in which it cools and expands. Interferometric observations presented by Bonneau et al. (2011) suggest a radius of 18–49 \( R_\odot \) for the primary, which is much smaller than the 80–130 \( R_\odot \) estimated by Koubský et al. (2006) for the Roche-lobe radius. Also, the more recent interferometric observations by Hutter et al. (2021) suggest a smaller radius of about 24 \( R_\odot \). According to Dudley & Jeffery (1993), the mass of the secondary component is 6.2 \( M_\odot \) and the radius is about 4 \( R_\odot \). The appearance of the frequently discussed strong variable H\(\alpha\) emission in the system \( \nu \) Sgr is probably due to the material originating from the primary during a last phase of intense mass transfer and subsequent storage of hydrogen in a stable accretion disk orbiting around the secondary (Bonneau et al. 2011).
The possible presence of magnetic fields in the complex HdB systems was never considered as one of the critical ingredients in previous theoretical and observational studies. Therefore, this important terrain remained essentially unexplored. Based on a few low-resolution spectropolarimetric observations \( (R \approx 2000–4000) \) obtained in 2005 and 2007 at the European Southern Observatory with the multimode instrument FORS1 (Appenzeller et al. 1998) installed at the 8 m Kueyen telescope, Hubrig et al. (2007, 2009) suggested that \( \upsilon \) Sgr is probably a magnetic variable star. The highest longitudinal magnetic field strengths of \( \langle B_z \rangle = -78 \pm 8 \, \text{G} \) and \( \langle B_z \rangle = -73 \pm 9 \, \text{G} \) were measured in the FORS1 low-resolution polarimetric spectra recorded, respectively, on 2007 August 21 and 31, using the whole spectrum for the measurements, including all available absorption lines.

An unsuccessful attempt to confirm the magnetic nature of \( \upsilon \) Sgr was reported by Silvester et al. (2009), who obtained three high-resolution \( (R \approx 65,000) \) observations with the Narval spectropolarimeter installed at the Telescope Bernard Lyot on Pic du Midi. The polarimetric spectra recorded on 2008 June 18–21 at orbital phases corresponding to conjunction (where the secondary was behind the primary) were analyzed using the least-squares deconvolution (LSD) multilin analysis method (Donati et al. 1997), assuming that the lines used in this method have an identical shape and that the resulting profile is scaled according to the line strength and the sensitivity to the magnetic field. Unfortunately, to create the line mask for the field measurements using the Vienna Atomic Line Database (VALD3; e.g., Kupka et al. 2011), the authors assumed for \( \upsilon \) Sgr a wrong spectral type B2Vpe with \( T_{\text{eff}} = 23,000 \, \text{K} \) instead of spectral type B5V with \( T_{\text{eff}} = 12,300 \, \text{K} \), and in spite of the fact that the optical spectra of \( \upsilon \) Sgr contain numerous spectral lines of ionized metals usually formed in much cooler atmospheres.

Here, we report the results of more recent high-resolution \( (R \approx 115,000) \) spectropolarimetric observations of this unusual system, acquired using the High Accuracy Radial velocity Planet Searcher (HARPSpol) fed by the ESO 3.6 m telescope.

### 2. Observations and Results

The observations were carried out in the framework of the ESO large program “Magnetic fields in OB stars” in 2015 using HARPSpol in visitor mode. The spectropolarimetric observations with this instrument usually consist of four subexposures observed at different positions of the quarter-wave retarder plate. The HARPSpol spectra cover the spectral range of 3780–6910 Å, with a small gap between 5259 and 5337 Å. The data reduction was performed using the HARPSpol reduction software available on La Silla and the normalization of the spectra to the continuum level is described in detail by Hubrig et al. (2013). The barycentric Julian date (BJD) for the middle of the exposure, the corresponding orbital phase, and the signal-to-noise ratio \((S/N)\) of the HARPSpol Stokes \( I \) spectra measured at about 4700 Å are presented in Table 1.

A detailed description of the assessment of the longitudinal magnetic field measurements using HARPSpol is presented in our previous papers (e.g., Hubrig et al. 2018; Järvinen et al. 2020). Similar to our previous studies, to increase the \( S/N \), we employed the LSD technique. In the spectrum of \( \upsilon \) Sgr, numerous lines with a low excitation energy of the lower level show emission wings, indicating the presence of circumstellar gas around the star. Thus, special care was taken to populate our line masks with blend-free lines or lines that are to a lesser extent contaminated by the emission lines. Using VALD3, we created five line masks for five elements, hydrogen (excluding from the mask the strongly variable emission \( \text{H} \alpha \) line), He\( I \), and the iron-peak elements Ti\( II \), Cr\( II \), and Fe\( II \), all based on the stellar parameters of \( \upsilon \) Sgr; \( T_{\text{eff}} = 12,300 \pm 200 \, \text{K} \) and log \( g = 2.5 \pm 0.5 \) (Kipper & Klochkova 2012).

| BJD     | \( \varphi \) | \( S/N \) |
|---------|-------------|----------|
| 2457093.92148 | 0.545 | 1349 |
| 2457094.88906 | 0.552 | 2449 |
| 2457177.71636 | 0.153 | 958 |
| 2457178.92998 | 0.162 | 2192 |
| 2457179.94822 | 0.169 | 1200 |

Note. The columns give the BJD, the orbital phase \( \varphi \) calculated using \( P_{\text{orb}} = 137.9343 \) days and the phase origin \( \text{HJD}_0 = 2433018.13 \) reported by Koubý et al. (2006), and the \( S/N \) measured around 4700 Å.

As a first step, to get better insight into the complex spectrum composition and the spectral variability of \( \upsilon \) Sgr, we investigated the line profile variability using the LSD Stokes \( I \) line profiles based on the different line masks. The LSD Stokes \( I \) spectra calculated for each of the five elements and sorted by similar orbital phases are presented in Figure 1. The comparison of the line profiles calculated for each phase reveals that the primary is a spectrum variable star with small changes appearing already at the timescale of one night. The LSD Stokes \( I \) profiles calculated for the metal lines, especially those calculated for Ti and Cr, appear asymmetric and show a structure in the line cores. If we assume that the changes in the line profiles of the metal lines are related to surface chemical patches, then the rotation period of the primary component should not be too long, of the order of 2 or 3 weeks. Using the value \( \upsilon \sin i = 33 \pm 5 \, \text{km \ s}^{-1} \) for the projected rotation velocity given by Silvester et al. (2009), the stellar radius of \( 24 \ R_\odot \) determined by Hutter et al. (2021), and the disk inclination of about 50° obtained by Netolíčková et al. (2009), the rotation period is about 28 days. No Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015 or Kepler Borucki et al. 2010) data have been obtained for \( \upsilon \) Sgr so far. However, TESS should observe this target in Sector 54 in the middle of 2022.

According to Dudley & Jeffery (1990), the fainter, more massive component, is best visible in the far-UV spectra recorded with the IUE satellite. These spectra have been used by these authors to determine the orbit of the secondary component. To be sure that the secondary component is indeed invisible in our optical spectra, we tried to isolate the contribution of the main-sequence hotter secondary with 6.2 \( M_\odot \) by calculating the LSD Stokes \( I \) profiles using the line mask corresponding to a higher temperature, \( T_{\text{eff}} = 17,000 \, \text{K} \) assuming the spectral type B4\( V \). However, no trace of this hotter second component was detected in our LSD spectra.

It is not clear whether a number of smaller absorption features observed blueward and redward from the absorption profile of the primary in Figure 1 could be assigned to the accumulated matter in the surrounding envelope where it can behave as a pseudo-atmosphere with lines formed in the circumstellar environment. The appearance of similar absorption features was also mentioned.
by Silvester et al. (2009), who suggested that the distortion of the continuum could be due to the smaller number of lines in the mask. However, our tests with line masks containing different numbers of lines confirm the persistence of the features, suggesting that they are probably related to the system’s circumstellar environment. The variety of absorption features observed in the LSD Stokes $I$ spectra could also indicate that different lines trace the circumstellar matter differently, with lines belonging to certain elements formed in a region closer to the primary’s stellar surface while the matter traced by other lines is farther away from the stellar surface. In any case, future studies are necessary to better understand the structure of this system, including the location and the morphology of the line-forming regions that trace different components of the system.

2.2. Magnetic Field Measurements

The fact that the LSD Stokes $I$ profiles calculated for the primary component using different line masks show line profile shapes with different variability character, probably indicating the presence of chemical patches, certainly needs to be taken into account in the analysis of the polarimetric spectra. Therefore, to search for the presence of typical Zeeman features in the LSD Stokes $V$ spectra that would indicate the presence of a longitudinal magnetic field, we employed in our measurements individual line masks belonging to He, Ti, Cr, and Fe and their combinations. The wide hydrogen lines usually suffer from imperfect continuum normalization and were thus not used. We present the calculated LSD Stokes $I$, Stokes $V$, and diagnostic null ($N$) spectra for the different line masks in Figure 2. Null spectra are obtained by combining the circularly polarized spectra in such a way that the polarization cancels out, allowing us to verify that no spurious signals are present in the data. Notably, small Zeeman features are clearly visible in the LSD Stokes $V$ spectra in the observations acquired at four orbital phases. The measured magnetic field strengths, the average effective Landé factors, the line masks employed, and the false alarm probability (FAP) values are listed in Table 2. FAPs are commonly considered to classify the magnetic field detection in the LSD technique: FAP $< 10^{-3}$ is assumed as a definite detection, $10^{-3} < $ FAP $< 10^{-3}$ as a marginal detection, and FAP $> 10^{-3}$ as a non-detection (Donati et al. 1992). As shown in Table 2, we obtain two definite detections at the orbital phases 0.162 and 0.169 with $\langle B_z \rangle = -19 \pm 3$ G and $\langle B_z \rangle = -25 \pm 7$ G, correspondingly, and two marginal detections at the orbital phases 0.545 with $\langle B_z \rangle = +22 \pm 3$ G, and 0.153 with $\langle B_z \rangle = -40 \pm 6$ G.

While only a marginal detection, $\langle B_z \rangle = 22 \pm 3$ G, was achieved in the orbital phase 0.545 close to quadrature (see Figure 1 in Koubský et al. 2006), the weak magnetic field measured on two consecutive nights in 2015 June in the orbital phases between 0.16 and 0.17 close to the superior conjunction is definitely present. The observed small changes in the field strength are likely caused by the slightly changing aspect of the overall magnetic field geometry of the star during its rotation cycle. We also downloaded the publicly available Narval spectra used by Silvester et al. (2009) to search for the presence of a magnetic field. The last plot on the right-hand side of Figure 2 shows the calculated LSD Stokes $I$, Stokes $V$, and diagnostic null ($N$) spectra for the helium mask using the observation with the highest S/N of 1786 at orbital phase 0.723. A low Zeeman feature with $\langle B_z \rangle = -9 \pm 2$ G is still detectable in this plot but FAP = 0.124 indicates non-detection. Clearly, much higher S/N should be achieved in the spectra to be able to measure such weak magnetic fields. Notably, the higher resolution of HARPSpol, in comparison to that of Narval, will permit collecting more photons for a given wavelength bin in future observations, and consequently, to achieve a higher S/N.

It is of interest that according to Koubský et al. (2006), in the orbital cycles when a blueshifted Hα absorption line is observed, it attains its maximum strength around the same conjunction phase when the secondary is in front of the primary and virtually disappears at the other conjunction. This absorption probably originates from a stream flowing between the two stars. Since the
line was observed on some orbital cycles while missing in others, it is quite possible that the mass transfer between the two components is governed by the magnetic field of the primary and the absence of the blueshifted Hα absorption line in some orbital cycles could be explained by the difference between the lengths of the orbital and primary rotation periods.

The chemical abundance of the primary in the system υ Sgr was previously reported as peculiar, but, as far as we know, no study of the variability of spectral lines belonging to different elements has been carried out in the past. The detected variability of the LSD Stokes I profiles calculated for different elements is probably due to a surface inhomogeneous distribution of the chemical elements similar to that detected in magnetic Ap and Bp stars. In line with this suggestion, a number of typical chemically peculiar Ap and Bp stars with surface chemical spots were previously reported to host weak longitudinal magnetic fields of the order of just tens of Gauss (e.g., Donati et al. 1990, 2006; Kochukhov et al. 2018). The fact that magnetic field detections are achieved for certain combinations of line masks, indicates that it is possible that the chemical element patches are intimately related to the magnetic field geometry of υ Sgr. Indeed, previous numerous studies of magnetic Ap and Bp stars have revealed a symmetry between the geometry of the magnetic field and the surface chemical element distribution, i.e., the lines of different elements with different abundance distributions across the stellar surface sample the magnetic field in different ways (e.g., Hubrig et al. 2017). Thus, the structure of the magnetic fields in Ap and Bp stars can be studied by measurements of the magnetic field strength using line masks for individual elements separately.

3. Discussion

For the first time, high-resolution spectropolarimetric observations are discussed for the hydrogen-deficient stripped primary in the system υ Sgr, belonging to the rare class of evolved binaries that are in a mass transfer phase where the primary has ended the core helium-burning phase. Schoenberner & Drilling (1983) suggested that the initial mass of the primary in υ Sgr must have been between 5.6 and 14 $M_\odot$, corresponding to a spectral type in the range of B3–B0.5 on the main sequence, with a radius of the order 4–6 $R_\odot$ (Pecaut & Mamajek 2013). Assuming magnetic flux conservation and the stellar radius of $24 R_\odot$, determined by Hutter et al. (2021), we can speculate that the primary possessed on the main sequence a magnetic field of the order of 400–900 G, which is typical for magnetic early type Bp stars. The system υ Sgr could therefore have originally been a binary with a magnetic Bp star that conserved the magnetic flux during the subsequent evolution.

On the other hand, according to the merger scenario, magnetic fields may be generated by strong binary interaction, i.e., in a stellar merging of two lower-mass stars or protostars, in the course of mass transfer, or during common envelope evolution (e.g., Tout et al. 2008; Ferrario et al. 2009; Wickramasinghe et al. 2014). According to the evolutionary scenario suggested by Schoenberner & Drilling (1983), υ Sgr cannot be the result of a single mass exchange. If υ Sgr underwent common envelope evolution, this could be responsible for the observed magnetic field in the primary of υ Sgr and it would be responsible for the observed stripping of the envelope. Since stripped-envelope stars were suggested to be possible progenitors of various types of supernovae including core-collapse supernovae, more insight into the uncertain physical processes of binary interaction, both from theoretical and observational sides, would be worthwhile.

Admittedly, the measured longitudinal magnetic field is rather weak. On the other hand, since our observations were obtained at five epochs only and the rotation period of the primary is not known, the acquired material is not sufficient to fully characterize the geometry and strength of the magnetic field. It would be worthwhile to obtain new spectropolarimetric data to learn more about the structure of the magnetic field in this interacting binary.

While our observations of the system υ Sgr mainly targeted the detection of the magnetic field, it is necessary to understand
the three-dimensional structure of this system with respect to the magnetic field geometry, the orbit, the disk orientation, and the accretion flow. Importantly, the structure of the circumstellar matter can only be studied by monitoring \( \upsilon \) Sgr over a significant number of nights. A future study of the three-dimensional structure of \( \upsilon \) Sgr needs to be based on the intensity variability of different spectral lines and the measurements of both the radial velocity shifts and the strength of the longitudinal magnetic field. It will provide crucial information necessary to test predictions of existing theories on the evolution of massive stars and allow gaining deeper insights into the role of magnetic fields in binary systems in the context of supernova progenitors.

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Data Availability: The HARPS spectropolarimetric observations used in this article can be obtained from the ESO archive.

ORCID iDs

Swetlana Hubrig @ https://orcid.org/0000-0003-0153-359X
Silva P. Järvinen @ https://orcid.org/0000-0003-3572-9611
Ilya Ilyin @ https://orcid.org/0000-0002-0551-046X
Markus Schöller @ https://orcid.org/0000-0002-5379-1286

References

Appenzeller, I., Fricke, K., Fürtig, W., et al. 1998, The Messenger, 94, 1
Bonneau, D., Chesneau, O., Mouard, D., et al. 2011, A&A, 532, A148
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Donati, J.-F., Howarth, I. D., Jardine, M. M., et al. 2006, MNRAS, 370, 629
Donati, J.-F., Semel, M., Carter, B. D., et al. 1997, MNRAS, 291, 658
Donati, J.-F., Semel, M., & del Toro Iniesta, J. C. 1990, A&A, 233, L17
Donati, J.-F., Semel, M., & Rees, D. E. 1992, A&A, 265, 669
Dudley, R. E., & Jeffery, C. S. 1990, MNRAS, 247, 400
Dudley, R. E., & Jeffery, C. S. 1993, MNRAS, 262, 945
Ferrario, L., Pringle, J. E., Tout, C. A., & Wickramasinghe, D. T. 2009, MNRAS, 400, L71
Hubrig, S., Ilyin, I., Schöller, M., & Lo Curto, G. 2013, AN, 334, 1093
Hubrig, S., Järvinen, S., Madej, J., et al. 2018, MNRAS, 477, 5791
Hubrig, S., Przybilla, N., Korhonen, H., et al. 2017, MNRAS, 471, 1543
Hubrig, S., Schöller, M., Savanov, I., et al. 2009, AN, 330, 708
Hubrig, S., Yudin, R. V., Pogodin, M., et al. 2007, AN, 328, 1133
Hutter, D. J., Tycner, C., Zavala, R. T., et al. 2021, ApJS, 257, 69
Järvinen, S. P., Hubrig, S., Mathys, G., et al. 2020, MNRAS, 499, 2734
Kipper, T., & Klochkova, V. G. 2012, BaltA, 21, 219
Kochukhov, O., Johnston, C., Alecian, E., et al. 2018, MNRAS, 478, 1749
Koubiský, P., Harmance, P., Yang, S., et al. 2006, A&A, 459, 849
Kupka, F., Dubernet, M.-L., & VAMDC Collaboration 2011, BaltA, 20, 503
Laplace, E., Götberg, Y., de Mink, S. E., et al. 2020, A&A, 637, A6
Netolický, M., Bonneau, D., Chesneau, O., et al. 2009, A&A, 499, 827
Pecaut, M. J., & Mamajek, E. E. 2013, ApJS, 208, 9
Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, JATIS, 1, 014003
Schoenberner, D., & Drilling, J. S. 1983, ApJ, 268, 225
Schootemeijer, A., Götberg, Y., de Mink, S. E., et al. 2018, A&A, 615, A30
Silvester, J., Neiner, C., Henrichs, H. F., et al. 2009, MNRAS, 398, 1505
Tout, C. A., Wickramasinghe, D. T., Liebert, J., et al. 2008, MNRAS, 387, 897
Wickramasinghe, D. T., Tout, C. A., & Ferrario, L. 2014, MNRAS, 437, 675
Yoon, S.-C., Dessart, L., & Clocchiatti, A. 2017, ApJ, 840, 14