EPJ Web of Conferences **64**, 08009 (2014)
DOI: 10.1051/epjconf/20146408009

The magnetosphere of the close accreting PMS binary V4046 Sgr

S. G. Gregory[1,a], V. R. Holzwarth[2], J.-F. Donati[3], G. A. J. Hussain[4], T. Montmerle[5], E. Alecian[6], S. H. P. Alencar[7], C. Argiroffi[8], M. Audard[9], J. Bouvier[10], F. Damiani[8], M. Güdel[11], D. P. Huenemoerder[12], J. H. Kastner[13], A. Maggio[8], G. G. Sacco[14], and G. A. Wade[15]

[1] *School of Physics & Astronomy, University of St Andrews, St Andrews, KY16 9SS, U.K.*
[2] *Freytagstr. 7, D-79114 Freiburg i.Br., Germany*
[3] *UPS-Toulouse/CNRS-INSU, Inst. de Recherche en Astro. et Planétologie, F-31400 Toulouse, France*
[4] *ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany*
[5] *Institut d'Astrophysique de Paris, 98bis bd Arago, FR-75014 Paris, France*
[6] *Obs. de Paris, LESIA, 5, place Jules Janssen, F-92195 Meudon Principal Cedex, France*
[7] *Dept. de Fìsica - UFMG, Av. Antônio Carlos, 6627, 30270-901 Belo Horizonte, MG, Brazil*
[8] *INAF-Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy*
[9] *ISDC Data Center for Astrophysics, Univ. of Geneva, CH-1290 Versoix, Switzerland*
[10] *UJF-Grenoble 1/CNRS-INSU, IPAG, UMR 5274, F-38041, Grenoble, France*
[11] *Dept. of Astrophysics, University of Vienna, Türkenschanzstrasse 17, A-1180 Vienna, Austria*
[12] *MIT, Kavli Inst. for Astrophysics & Space Research, Cambridge, MA 02139, U.S.A.*
[13] *CIS, Rochester Inst. of Technology, 54 Lomb Memorial Drive, Rochester, NY 14623, U.S.A.*
[14] *INAF-Arcetri Astrophysical Observatory, Largo Enrico Fermi 5, I - 50125 Florence, Italy*
[15] *Dept. of Physics, Royal Military College of Canada, Kingston, K7K 7B4, Canada*

Abstract. V4046 Sagittarii AB is a close short-period classical T Tauri binary. It is a circularised and synchronised system accreting from a circumbinary disk. In 2009 it was observed as part of a coordinated program involving near-simultaneous spectropolarimetric observations with ESPaDOnS at the Canada-France-Hawai'i Telescope and high-resolution X-ray observations with *XMM-Newton*. Magnetic maps of each star were derived from Zeeman-Doppler imaging. After briefly highlighting the most significant observational findings, we present a preliminary 3D model of the binary magnetosphere constructed from the magnetic maps using a newly developed binary magnetic field extrapolation code. The large-scale fields (the dipole components) of both stars are highly tilted with respect to their rotation axes, and their magnetic fields are linked.

1 Introduction - V4046 Sgr AB

V4046 Sgr is a nearby (~73 pc) pre-main sequence (PMS) binary[1], and a candidate member of the β Pictoris Moving Group [2]. It is a double lined spectroscopic binary that is still accreting from a large circumbinary disk [3, 4], despite being of an age (~13 Myr) at which the disks of most other

[a] e-mail: sg64@st-andrews.ac.uk

[1] V4046 Sgr may be a quadruple system [1]. [2] first speculated that the distant GSC 07396-00759 (projected separation ~12,350 au) was a companion to V4046 Sgr AB. Our detailed study of this weakly bound object revealed that it is likely a spectroscopic weak-line T Tauri binary system, and was christened V4046 Sgr C[D] by [1].

Table 1. Stellar parameters for V4046 Sgr. $M_{\rm core}$, the mass of the radiative core, M_* & age are derived from the models of [9]. As a synchronised system the stellar rotation periods are the same as the binary orbital period.

Star	$T_{\rm eff}$	$L_*/{\rm L}_\odot$	$M_*/{\rm M}_\odot$	age (Myr)	$M_{\rm core}/M_*$	$P_{\rm rot}$ (d)	Ref. [$T_{\rm eff}$,L_*,$P_{\rm rot}$]
V4046 Sgr A	4370	0.407	0.91	13.0	0.47	2.42	[6, 8, 10]
V4046 Sgr B	4100	0.269	0.87	13.0	0.40	2.42	[6, 8, 10]

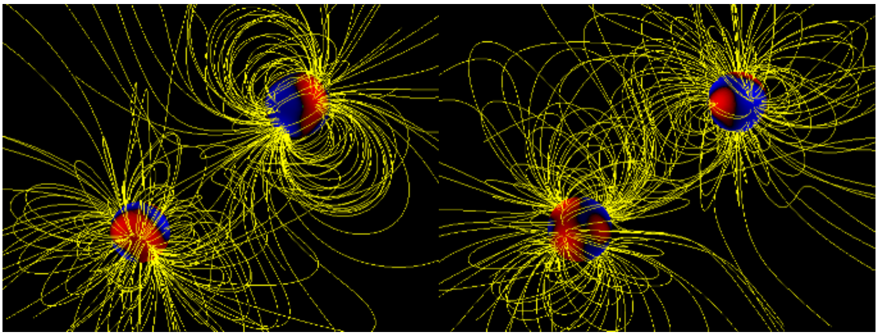

Figure 1. A binary potential field extrapolation from the magnetic maps of V4046 Sgr at two different phases. Only the large-scale field lines are shown for clarity. The magnetic fields of the two stars are linked with field lines connecting the dayside of the primary star (shown in the background/foreground of the left/right image) to the nightside of the secondary. The binary separation is ~8.8 $R_\odot$ [6] and the system is believed to be synchronised and circularised (eccentricity ≤ 0.01; [8]).

PMS stars have dispersed (e.g. [5]). At this age, both stars of the system have developed substantial radiative cores within their interiors [6, 7]. The stellar parameters are listed in table 1. Below we present the main observational findings from a multi-wavelength observing program which targeted V4046 Sgr in 2009, and give brief details of a newly developed binary magnetic field extrapolation code that we are using to model the binary magnetosphere.

1.1 A near-simultaneous multi-wavelength observing program

Near-simultaneous optical and X-ray monitoring of V4046 Sgr was carried out in September 2009, covering ~2.5 and ~2.2 orbital cycles respectively. The main goal of the program was to characterise the 3D magnetic and accretion flow geometry of the system, as well as the properties of the X-ray emitting plasma. Time-resolved optical/X-ray spectra are essential for this purpose, as previously demonstrated for the accreting PMS star V2129 Oph [11, 12].

Optical observations: spectropolarimetric observations were obtained with ESPaDOnS at the Canada-France-Hawai'i Telescope from 3-9 September 2009 [6]. Small rotationally modulated circular polarisation signals were detected in the photospheric absorption lines, but (unusually for accreting PMS stars) no signal was measured in the accretion-related emission lines suggesting that accretion hotspots may be distributed across the stellar surface (consistent with their complex magnetic fields, see below).

A tomographic imaging code was applied to the circularly polarised spectra to produce magnetic maps of each star [6]; the first such maps to be obtained for a close accreting PMS binary. Both stars host highly complex large-scale magnetic fields [6], as has been found for other PMS stars with similar interiors consisting of large radiative cores and outer convective envelopes [7]. The magnetic fields are multipolar with strong toroidal components, while the poloidal components are mostly non-axisymmetric. In particular, the dipole components are weak, of polar strength ∼100 G & ∼80 G on the primary/secondary, and highly tilted relative to the rotation axes (∼60° & ∼90°) with a phase difference of ∼0.7 between the planes of the tilts [6, 7].

Xray observations: the *XMM-Newton* observations of V4046 Sgr, consisting of three ∼123 ks observing segments separated by ∼50 ks gaps, were obtained between 15 & 20 September 2009 [13]. Strong X-ray emission from cool plasma of temperatures 3 − 4 MK and number densities 10^{11} − 10^{12} cm^{-3} was detected (as it was previously by [14]). This plasma, which is cooler and denser than is typical of coronal plasma, is associated with accretion shocks, where gas channelled along magnetic field lines slams into the stellar surface at supersonic speeds.

The emission lines in the X-ray grating spectra produced by the high density plasma displayed periodic flux variations with a period of 1.22 ± 0.01 d, half of the binary orbital period of 2.42 d [13]. This is the first time that rotationally modulated accretion shock X-ray emission has been detected from a PMS star. At first glance this appears inconsistent with the optical observations, as it suggests discrete accretion hotspots. However, the accretion column/spot geometry may indeed be complex as X-rays from accretion shocks can only be detected at certain viewing angles when hotspots are not obscured by the dense accreting gas [12].

2 The magnetosphere of V4046 Sgr AB extrapolated from magnetic maps

A new binary magnetic field extrapolation code has been developed, allowing for the construction of 3D models of the joint magnetosphere of binary stars from observationally derived magnetic maps [15]. The models are generated in the framework of the potential field-source surface approximation, in which the magnetosphere is taken to be current-free and the effect of magnetised winds is mimicked through magnetic fields being purely radial on the source surface.

The magnetic field, $\vec{B} = -\nabla\Psi$, in the current-free region is determined by the solution of Laplace's equation, $\nabla^2\Psi = 0$, subject to boundary conditions given on the source surface and on the surface of the two stellar components. The starting point for the binary field extrapolation is the *ansatz*,

$$\Psi(\vec{r}) = \sum_{\ell m}\left(\alpha_\ell^m a_\ell^m + \beta_\ell^m b_\ell^m\right) + \sum_{\ell m}\left(\gamma_\ell^m g_\ell^m + \delta_\ell^m d_\ell^m\right) + \sum_{\ell m}\left(\epsilon_\ell^m e_\ell^m + \zeta_\ell^m z_\ell^m\right). \tag{1}$$

The three sums on the RHS describe the contributions of the source surface, primary surface and secondary surface to the total potential Ψ, where $a_\ell^m(\vec{r}_0)$, $b_\ell^m(\vec{r}_0)$, $g_\ell^m(\vec{r}_1)$, $d_\ell^m(\vec{r}_1)$, $e_\ell^m(\vec{r}_2)$, and $z_\ell^m(\vec{r}_2)$ are solid spherical harmonics with $\vec{r}_0$, $\vec{r}_1$, and $\vec{r}_2$ being vectors connecting the centre of the spheres representing the source surface, the primary star, and the secondary star, respectively, to the point $\vec{r}$. By applying a least-squares fit of observed magnetic surface maps and source surface conditions, we derive the equation

$$\mathbf{A}\begin{pmatrix}\vec{\alpha}\\ \vec{\beta}\\ \vec{\gamma}\\ \vec{\delta}\\ \vec{\epsilon}\\ \vec{\zeta}\end{pmatrix} = \mathbf{B}\begin{pmatrix}\vec{\chi}\\ \vec{\sigma}\end{pmatrix} + \mathbf{C}\begin{pmatrix}\vec{\rho}\\ \vec{\varsigma}\end{pmatrix} \tag{2}$$

where the matrices $\mathbf{A}, \mathbf{B}$, and $\mathbf{C}$ contain sums of products of solid spherical harmonics and their gradients, which depend only on the geometrical properties of the binary/source surface system. The vectors $\vec{\chi}, \vec{\sigma}, \vec{\rho}$ and $\vec{\varsigma}$ on the RHS of equation (2) are the known expansion coefficients of the magnetic maps of the primary and secondary star. The system of equations (2) is solved for the expansion coefficients $\vec{\alpha}, \vec{\beta}, \vec{\gamma}, \vec{\delta}, \vec{\epsilon}$, and $\vec{\zeta}$ using a singular value decomposition (SVD) algorithm. Full details of the binary magnetic field extrapolation method will be given in a forthcoming paper [15].

A field extrapolation from the magnetic maps of V4046 Sgr [6] is shown in figure 1. The large-scale magnetic field of each star is highly tilted, and there are "S-shaped" field lines connecting through the interior region of the binary from the dayside of the primary to the nightside of the secondary [16]. With such a field configuration it is unlikely that local circumstellar disks, distinct from the global circumbinary disk, can form around each star; as was suggested for V4046 Sgr based on hydrodynamic simulations [17]. This will be addressed in a future paper, and presented alongside detailed calculations of the accretion spot/flow geometry of the system [16].

Acknowledgements

SGG acknowledges support from the Science & Technology Facilities Council (STFC) via an Ernest Rutherford Fellowship [ST/J003255/1]. GAW is supported by a Discovery Grant from the Natural Science & Engineering Research Council of Canada (NSERC).

References

[1] J.H. Kastner, G.G. Sacco, R. Montez, D.P. Huenemoerder, H. Shi, E. Alecian, C. Argiroffi, M. Audard, J. Bouvier, F. Damiani et al., ApJL **740**, L17 (2011)

[2] C.A.O. Torres, G.R. Quast, L. da Silva, R. de La Reza, C.H.F. Melo, M. Sterzik, A&A **460**, 695 (2006)

[3] K.A. Rosenfeld, S.M. Andrews, D.J. Wilner, H.C. Stempels, ApJ **759**, 119 (2012)

[4] K.A. Rosenfeld, S.M. Andrews, D.J. Wilner, J.H. Kastner, M.K. McClure, ApJ in press [astro-ph/1308.4358] (2013)

[5] E.E. Mamajek, *Exoplanets and disks: their formation and diversity, AIP Conference Proceedings, Vol. 1158* (American Institute of Physics, Melville NY, 2009), pp. 3-10

[6] J.-F. Donati, S.G. Gregory, T. Montmerle, A. Maggio, C. Argiroffi, G. Sacco, G. Hussain, J.Kastner, S.H.P. Alencar, M. Audard et al., MNRAS **417**, 1747 (2011)

[7] S.G. Gregory, J.-F. Donati, J. Morin, G.A.J. Hussain, N.J. Mayne, L.A. Hillenbrand, M. Jardine, ApJ **755**, 97 (2012)

[8] H.C. Stempels, G.F. Gahm, A&A **421**, 1159 (2004)

[9] L. Siess, E. Dufour, M. Forestini, A&A **358**, 593 (2000)

[10] G.R. Quast, C.A.O. Torres, R. de La Reza, L. daSilva, M. Mayor, *The formation of binary stars: proceedings of IAU S200* (Astronomical Society of the Pacific, San Francisco CA, 2000) pp. 28-30

[11] J.-F. Donati, J. Bouvier, F.M. Walter, S.G. Gregory, M.B. Skelly, G.A.J. Hussain, E. Flaccomio, C. Argiroffi, K.N. Grankin, M.M. Jardine et al., MNRAS **412**, 2454 (2011)

[12] C. Argiroffi, E. Flaccomio, J. Bouvier, J.-F. Donati, K.V. Getman, S.G. Gregory, G.A.J. Hussain, M.M. Jardine, M.B. Skelly, F.M. Walter, A&A **530**, A1 (2011)

[13] C. Argiroffi, A. Maggio, T. Montmerle, D.P. Huenemoerder, E. Alecian, M. Audard, J. Bouvier, F. Damiani, J.-F. Donati, S.G. Gregory et al., ApJ **752**, 100 (2012)

[14] H.M. Günther, C. Liefke, J.H.M.M. Schmitt, J. Robrade, J.U. Ness, A&A **459**, L29 (2006)

[15] V.R. Holzwarth, A&A, in prep. (2013)

[16] S.G. Gregory, V.R. Holzwarth, J.F. Donati, G.A.J. Hussain, T. Montmerle, E. Alecian, S.H.P. Alencar, C. Argiroffi, M. Audard, J. Bouvier et al., MNRAS, in prep. (2013)

[17] M. de Val-Borro, G.F. Gahm, H.C. Stempels, A. Pepliński, MNRAS **413**, 2679 (2011)