Joint Magnetospheres of Star-planet Systems

Holzwarth, Volkmar; Gregory, Scott G.

Published in:
Proceedings of the 18th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Joint Magnetospheres of Star-planet Systems

Volkmar Holzwarth[1], **Scott G. Gregory**[2]

[1]*Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany*

[2]*School of Physics & Astronomy, University of St Andrews, St Andrews KY16 9SS, UK*

Abstract. The proximity between close-in hot Jupiters and their host star is expected to give rise to star-planet interactions. One signature of such interactions can be the observed phase shift between the location of enhanced chromospheric emission and the orbital phase of the exoplanet. Here, we investigate the magnetic interaction of a hot Jupiter with its magnetically active host star in the framework of a potential magnetic field approximation. The focus of our work is on the structure of the joint magnetosphere of the system, in particular, on the locations of inter-connecting magnetic field flux on the stellar and planetary surfaces. For the host star a realistic magnetic surface map, reconstructed from Zeeman-Doppler imaging observations, is used. The planetary magnetic field is taken to resemble a magnetic dipole perpendicular to the orbital plane. Our results show single- and double-loop magnetic field structures inter-connecting stellar surface regions at different latitudes with opposite polarity regions around the poles of the exoplanet.

1. Introduction

The large number of confirmed exoplanet systems goes along with a considerable number of close-in hot Jupiters with orbits only a few stellar radii above the surface of their host star (see Tab. .1, last column). The close proximity in such systems is expected to entail enhanced star-planet interactions (SPI) through magnetic and tidal processes (Shkolnik 2013). Previous investigations considered different aspects of SPI, such as chromospheric activity caused by magnetic fields (e.g. Lanza 2009) or the erosion of planetary atmospheres through the impact of stellar winds (Grießmeier et al. 2004; Lanza 2013).

Here, we focus on magnetic interactions and analyse the structure of the joint magnetosphere of a close-in exoplanet and its host star in the framework of the potential field source surface (PFSS) approximation. Our main objective is the determination of the properties of

Table .1.: Geometric system parameters of selected close-in exoplanets ($R_{\rm ep}$: exoplanet radius; $R_\star$: host star radius; a: star-planet separation). The list is ordered by the ratio $a/R_\star$ (last column). Source: NASA Exoplanet Archive.

system name	$R_{\rm ep}[R_{\rm Jupiter}]$	$R_\star[R_\odot]$	$a[au]$	$a/R_\star$
Kepler-91	1.38	6.3	0.072	2.46
WASP-103	1.53	1.44	0.020	2.96
WASP-12	1.79	1.57	0.023	3.14
Kepler-10	0.13	1.06	0.017	3.42
WASP-19	1.38	1.02	0.017	3.49
WASP-18	1.17	1.23	0.020	3.54
55 Cnc	0.18	0.94	0.016	3.62
KELT-1	1.11	1.46	0.025	3.63
OGLE-TR-056	1.36	1.36	0.024	3.77
WASP-33	1.50	1.44	0.026	3.81
Kepler-207	0.14	1.59	0.029	3.92

inter-connecting magnetic field structures and possible locations of enhanced stellar chromospheric activity and planetary surface regions exposed to penetrating coronal material. The latter aspect is particularly important for planetary science, since high-energetic particles resulting from flaring events in the stellar corona may interact with and heat the planetary atmosphere, modify its chemistry and change, for instance, the spectral surface albedo of small, rocky planets. Based on the assumption that the exoplanet is sufficiently close to its host star for wind ram pressures to be negligible, our work complements earlier investigations considering the impact of stellar winds on planetary magnetospheres (e.g. Vidotto et al. 2013).

2. Model description

Originally introduced by Schatten et al. (1969) for the case of the Sun, the PFSS model assumes that plasma emanating from the stellar surface follows the magnetic field until, beyond the Alfvénic point, it starts to dominate the outflow, carrying the magnetic field with it. The radius of the source surface corresponds to the distance at which the magnetic field is dragged into the purely radial direction. In dependence on the magnetic field distribution on the stellar surface the PFSS model yields open wind zones, from which stellar plasma emanates in the form of magnetised winds, and dead zones, in which closed magnetic loops retain million-degree plasma from escaping the stellar corona. Our SPI model excludes any mechanical interaction, because the potential magnetic field is *per se* force-free and, thus, exerts neither force nor torque on the exoplanet.

In the framework of the PFSS approximation the region of interest is current-free and the magnetic field, $\mathbf{B} = -\nabla\Psi$, described by the gradient of a potential function, Ψ. Owing to the solenoidal condition of the magnetic field, Ψ is a solution of the Laplace equation, $\nabla^2\Psi = 0$, subject to specific boundary conditions. The potential function is expanded in terms of solid spherical harmonics:

$$\Psi(\mathbf{r}) = \sum_{l,m} c_{lm}^{(ss)} r^l Y_l^m(\hat{\mathbf{r}}) + \sum_{l,m} \frac{c_{lm}^{(\star)}}{r^{l+1}} Y_l^m(\hat{\mathbf{r}}) + \sum_{l,m} \frac{c_{lm}^{(ep)}}{r'^{l+1}} Y_l^m(\hat{\mathbf{r}}') \quad (1)$$

where $\mathbf{r}' = r'\hat{\mathbf{r}}' = \mathbf{r} - \mathbf{r}_{\rm ep}$ and $\mathbf{r}_{\rm ep}$ is the actual position of the exoplanet (Fig. .3). We consider

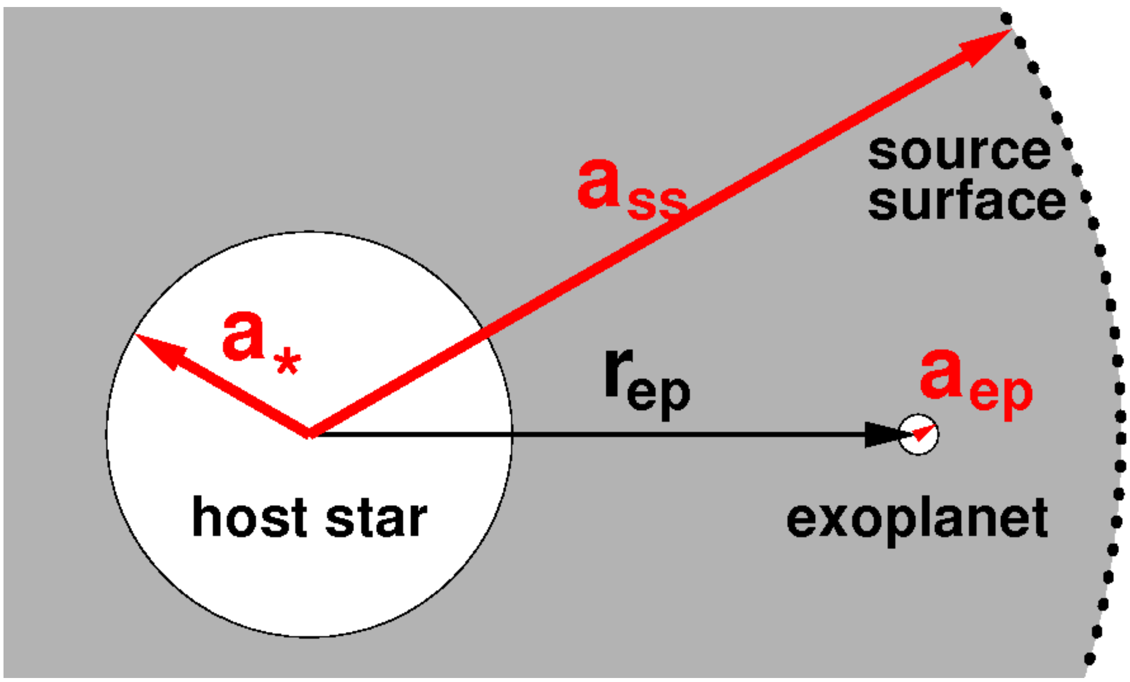

Figure .1.: Schematic exoplanet system. The region of interest (grey) is bounded at the outside by the source surface (dotted line) and inside by the stellar and planetary surfaces.

a star-exoplanet system with a separation of $r_{\rm ep} = 3\,R_\odot$, a stellar radius of $a_\star = 1\,R_\odot$, a Jupiter-sized exoplanet of radius $a_{\rm ep} = 0.1\,R_\odot$, and a source surface with radius $a_{\rm ss} = 4\,R_\odot$.

The coefficients of expansion in Eq. (1) are determined subject to boundary conditions given for the star, the exoplanet, and the source surface. Figure .2 shows the observed radial magnetic field distribution of the primary component of V4046 Sgr (Donati et al. 2011), which we use to specify the magnetic moments of the host star. For the exoplanet we assume a magnetic dipole oriented perpendicular to the orbital plane with a polar surface field strength of 100 G, which is about 10 times the average field strength of Jupiter (Christensen et al. 2009). The coefficients of the source surface expansion depend on the stellar and planetary magnetic moments and are calculated to make the magnetic field at the source surface purely radial. For a more detailed description of how the coefficients of expansion are determined see Holzwarth & Gregory (2014).

3. Results and Discussion

3.1 Stellar magnetic field

Figure .3 shows a snapshot of the joint magnetosphere resulting from the potential field extrapolation described above. One part of the stellar magnetic field forms open wind zones, whereas another part of the stellar magnetic flux is organised in closed loops connecting surface regions of opposite polarities. According to the complexity of the observed surface magnetic field distribution these loops cover a wide range of length scales, from regional arcades to global loops connecting both hemispheres of the star. Furthermore, our results also show more localised magnetic field structures which inter-connect the stellar and planetary surfaces (Fig. .4).

We are particularly interested in the inter-connecting magnetic field structures in the lower stellar atmosphere, since their footpoints indicate possible locations of planet-induced enhanced stellar activity signatures. Some observations of stars hosting close-in exoplanets show azimuthal offsets between the position of the exoplanet and enhanced chromospheric emission (Shkolnik et al. 2003; Shkolnik 2013). Our results are in general agreement with this observational feature, showing offsets between footpoints and exoplanet of up to 45°.

The type of the inter-connecting magnetic structure as well as the offset depend on the underlying magnetic field distribution on the stellar surface and on the orbital phase of the exoplanet. The sequence shown in Fig. .5 illustrates how the type of the inter-connection changes from single- to double-loop field structures during the approach and passage of magnetic polarity boundaries on the stellar surface. In contrast to double-loop structures, which

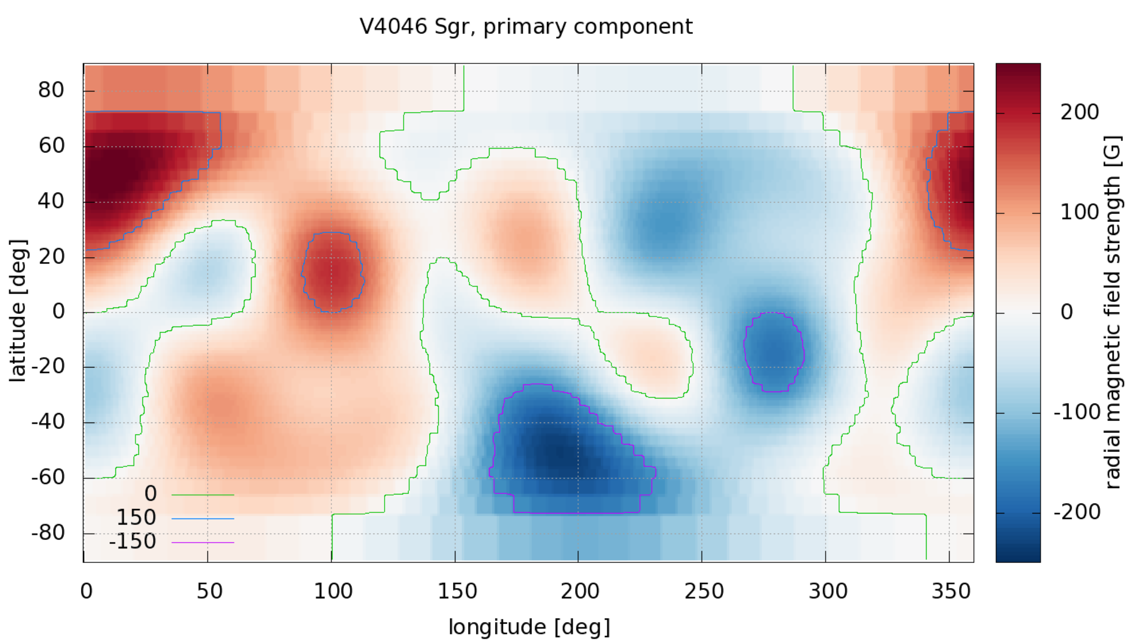

Figure .2.: Surface distribution of the radial magnetic field strength on the primary component of the pre-main sequence binary V4046 Sgr, reconstructed from Zeeman-Doppler imaging observations (Donati et al. 2011).

span large azimuthal angles of up to 90º, inter-connecting single-loop structures show somewhat smaller offsets between their stellar footpoint and the exoplanet. More observations of close exoplanet systems are needed to provide better constraints on this dichotomy of single- and double-loop inter-connections with small and large phase shifts, respectively.

Further properties of stellar footpoints are discernible in Fig. .6, which shows inter-connecting loops for different orbital phases of the exoplanet from slightly above the orbital plane. When the exoplanet orbits close to a polarity boundary on the stellar surface, the footpoint is spread-out, with inter-connecting field lines tracing the boundary. In contrast, when the exoplanet is above an extended region of uni-polar flux, the footpoint is concentrated at the location of highest magnetic flux. This behaviour also holds in the case of double-loop structures, where the footpoint of each loop – connecting both poles of the exoplanet with opposite polarity regions – may be located at significantly different latitudes. The latter finding is important in the investigation of slow- and fast-rotating host stars, since

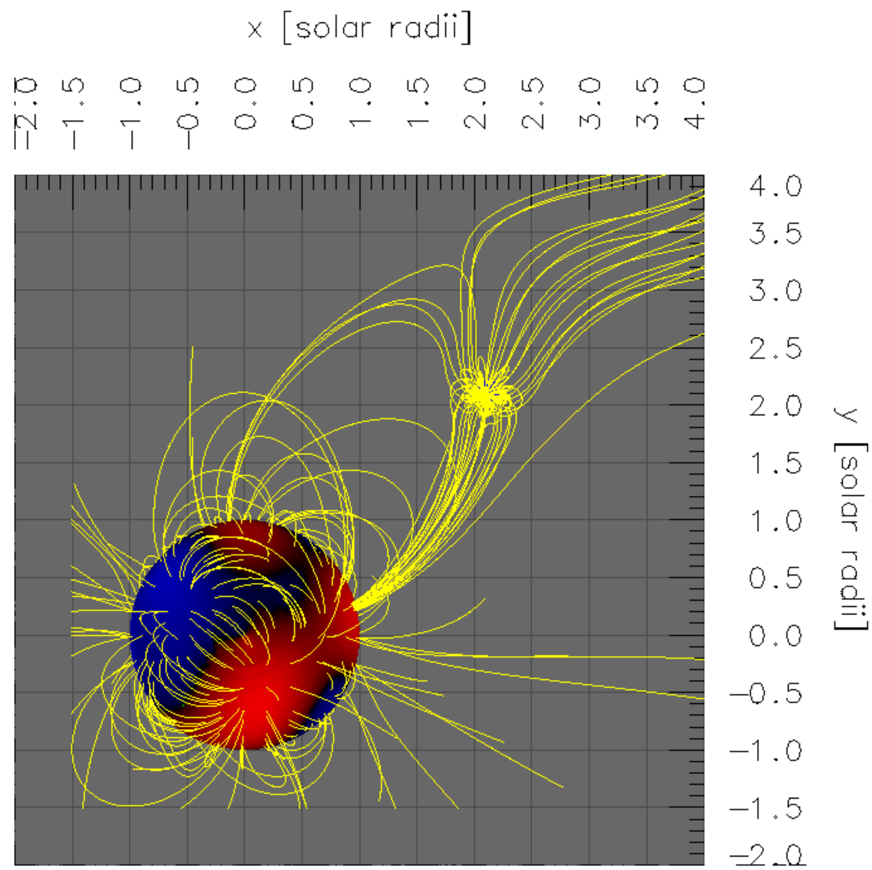

Figure .3.: Joint magnetosphere showing magnetic field lines (yellow) forming closed loops on the star and on the exoplanet, 'open' stellar wind-bearing magnetic field lines, and field lines inter-connecting between the star and the exoplanet in a double-loop structure. Colour-shading of the stellar and planetary surfaces corresponds to magnetic field strengths from −300 G (blue) to 300 G (red).

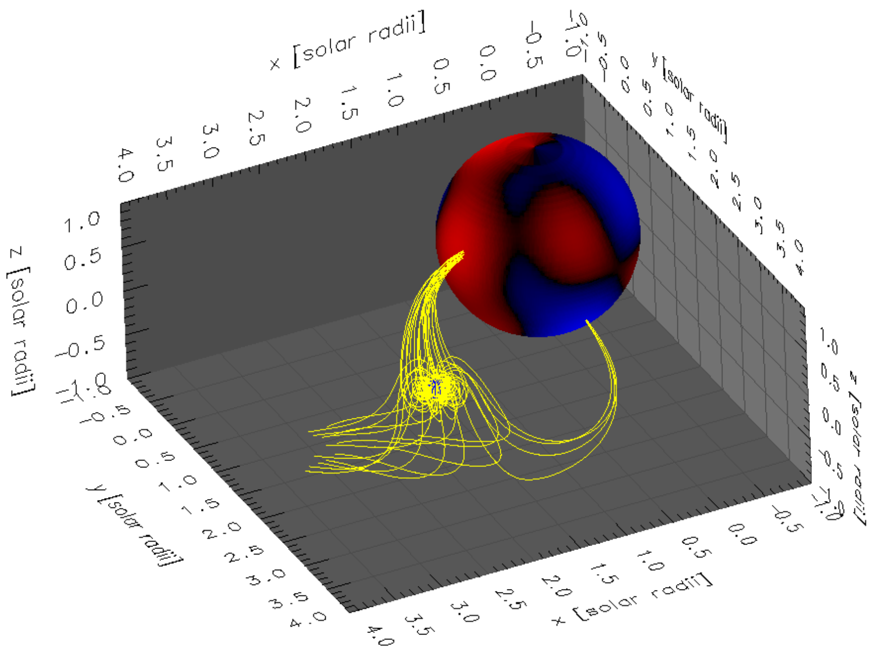

Figure .4.: Side view of the double-loop magnetic field structure inter-connecting star and exoplanet with opposite polarity magnetic field regions.

the magnetic flux of rapidly rotating active stars is predominantly located at high stellar latitudes (Schüssler & Solanki 1992; Holzwarth 2007). Consequently, planet-induced magnetic activity signatures may also occur at high stellar latitudes and possibly on opposite hemispheres of the star.

3.2 Planetary magnetic field

The focus concerning the planetary magnetic field is on the identification of surface regions inter-connected to the star and, thus, exposed to infalling stellar material. We find that both polar regions of the exoplanet are characterised by 'open' magnetic flux, which is either connected to the star or subject to the stellar wind (Fig. .7). In case of a single-loop field structure the polar region of one hemisphere is inter-connected with an opposite polarity region on the stellar surface, whereas magnetic flux of the polar region in the other hemisphere is carried away from the star by the stellar wind. In case of a double-loop field structure, both poles are inter-connected with opposite polarity regions on the stellar surface, thus roughly doubling the exposed surface area. At low latitudes, near the equatorial polarity boundary, the planetary surface is covered by closed, loop-like magnetic field structures.

In analogy to the gravitational interaction of a two-body system, where Hill spheres describe the region of dominant gravitational influence, the concept of *magnetic* Hill spheres (MHS) is used to describe regions of dominant magnetic influence around star and exoplanet. In Fig. .7 we identify the MHSs with the two regions inside the magnetic iso-surface separating the stellar and planetary domain. Changes in the planetary magnetic field hardly affect the stellar footpoints of inter-connecting field structures, since they are predominantly determined by the field distribution in the stellar MHS. Likewise the size and location of exposed planetary surface regions mainly depend on the actual planetary magnetic moments. For instance, a reversal of the polarity of the planetary magnetic field, as it may occur in the course of a planetary dynamo cycle, only changes the magnetic field structure in the vicinity of the planet (see Fig. .7). A polarity reversal – or, in general, any intermittent or cyclic variability – of both planetary and stellar magnetic fields adds to the intrinsic time-dependence of the inter-connecting field structures caused by the exoplanet approaching and passing polarity boundaries of the stellar magnetic field in the course of its orbital revolution.

Further detailed investigations of star-exoplanet systems considering different (observed or simulated) stellar and planetary magnetic field distributions and orbital parameters have to be carried out to determine the long-term averaged amount of planetary surface exposure to high-energetic particles originating from the stellar corona.

Acknowledgements. SGG acknowledges support from the Science & Technology Facilities Council (STFC) via an Ernest Rutherford Fellowship [ST/J003255/1].

References

Christensen, U. R., Holzwarth, V., & Reiners, A. 2009, *Nature* , 457, 167

Donati, J.-F., Gregory, S. G., Montmerle, T., et al. 2011, MNRAS, 417, 1747

Grießmeier, J.-M., Stadelmann, A., Penz, T., et al. 2004, A&A, 425, 753

Holzwarth, V. 2007, Mem. S.A.It., 78, 271

Holzwarth, V., Gregory, S. G. 2014, this proceedings

Lanza, A. F. 2009, A&A, 505, 339

Lanza, A. F. 2013, A&A, 557, A31

Schatten, K. H., Wilcox, J. M., & Ness, N. F. 1969, Solar Phys., 6, 442

Schüssler, M., & Solanki, S. K. 1992, A&A, 264, L13

Shkolnik, E., Walker, G. A. H., & Bohlender, D. A. 2003, ApJ, 597, 1092

Shkolnik, E. L. 2013, ApJ, 766, 9

Vidotto, A. A., Jardine, M., Morin, J., et al. 2013, A&A, 557, A67

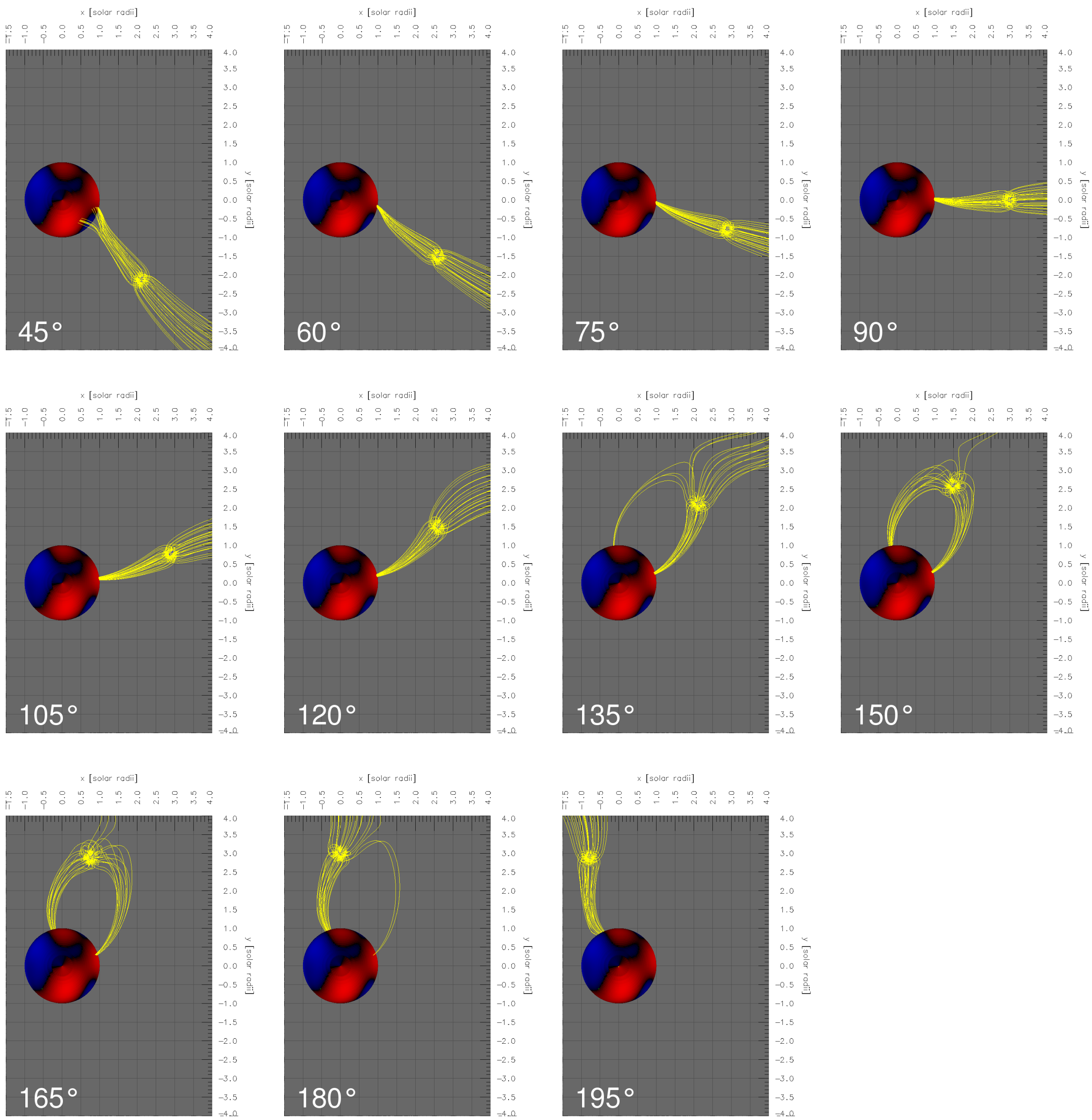

Figure .5.: Inter-connecting magnetic field structures at different orbital phases of the exoplanet; azimuthal angles (white label) are with respect to the magnetic map shown in Fig. .2.

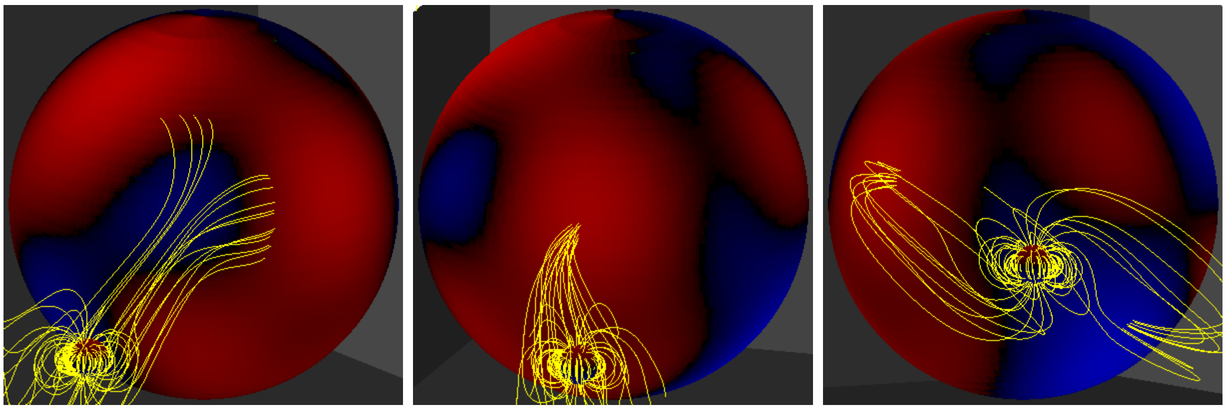

Figure .6.: Stellar footpoints of inter-connecting loop structures for different orbital phases of the exoplanet: wide-spread footpoint tracing the polarity boundary (left), localised single-loop structure (middle); localised double-loop structure.

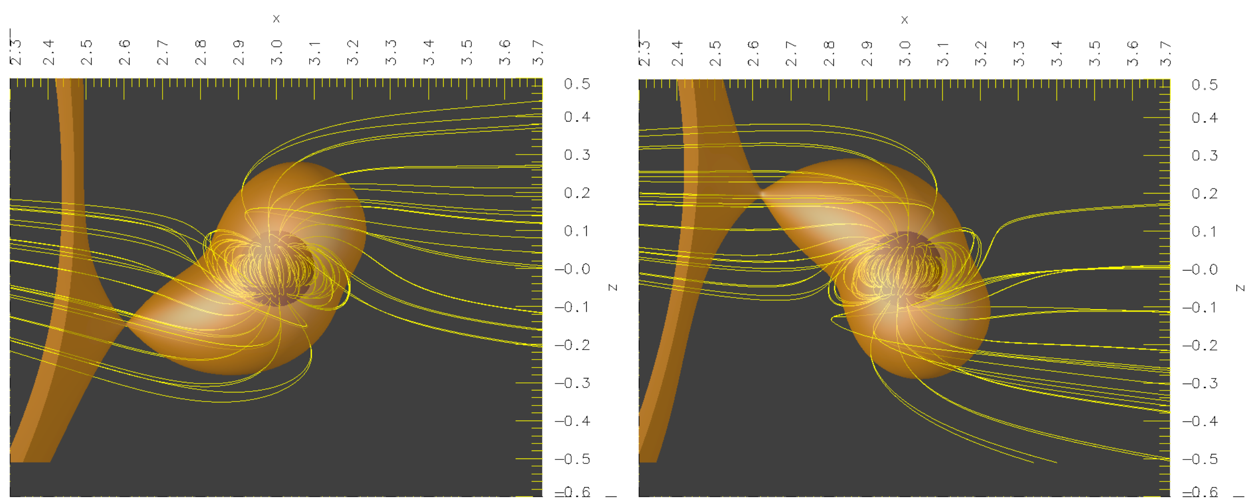

Figure .7.: Magnetic field in the vicinity of the exoplanet for a magnetic dipole being parallel (left) and anti-parallel (right) to the z-axis; the host star (not visible) is located to the left. The 6 G-isosurface (shaded) separates regions in which either the stellar or the planetary field dominate the magnetic interaction, giving rise to the concept of magnetic Hill spheres.