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Impact of space-based instruments on magnetic star research: past and future

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Abstract. Magnetic stars are observed at a large variety of spectral ranges, frequently with photometric and spectroscopic techniques and on time scales ranging from a 'snap shot' to years, sometimes using data sets which are continuous over many months. The outcome of such observations has been discussed during this conference and many examples have been presented, demonstrating the high scientific significance and gains in our knowledge that result from these observations. A key question that should be addressed is, what are the advantages and requirements of space based research of magnetic stars, particularly in relation to ground based observations? And what are the drawbacks? What are the hopes for the future? In the following, we intend to present an overview that addresses these questions.

Key words: stars: magnetic field – space vehicles: instruments

1. Observations from space

The principal advantages of space-based observations are (i) quasi-continuous monitoring, avoiding the strict diurnal cycle imposed by the sun, and (ii) access to wavelength ranges invisible from Earth's surface.

Space-based observations in the visual spectral domain have delivered information about stellar surface properties and internal stellar structure by observing flux and spectral line variations in a wide range of frequencies. Non-periodic phenomena, like flares, have been particularly helpful to understand the interaction of stars and their environment with a magnetic field. In the UV range, effects of a stellar wind confined by (oblique) magnetic fields have been prominently investigated. Extending the energy range of observations to the X-ray regime has provided access to understanding large-scale shocks in magnetospheres. Figure 1 illustrates the utility of such multispectral observations for investigating the magnetospheric physics of hot stars.

Of course, there are also drawbacks associated with space-based observations. Instruments for observations in space are typically more expensive and

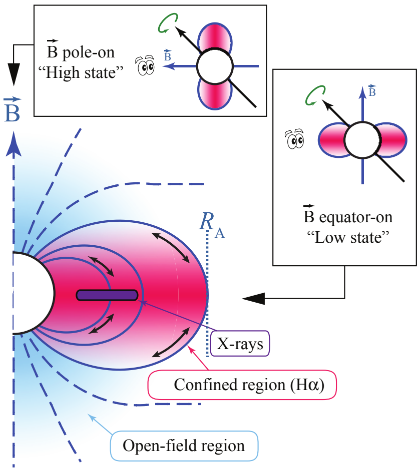

Figure 1. Schematic of the dynamical magnetosphere of a magnetic O-type star. Solid blue lines indicate regions below the last closed magnetic loop that confine the wind, located near the Alfvén radius $R_{\rm A}$. The bulk of the X-rays are produced in the region indicated in purple. The insets illustrate the view of an observer as the star's rotation changes the orientation of the magnetosphere, which allows disentangling of the effects due to the star and its environment. Source: (Petit et al., 2015)

less advanced than that available for ground based observations. Space missions are also inherent more risky, and usually limited in lifetime. However, the most long-lived space telescope is probably the Hubble Space Telescope (**HST**), which still produces amazing science after the first successful servicing mission in December 1993 - 25 years ago!

2. Current and past satellite projects

Quite a number of space instruments have contributed significantly to the topic of this conference. We present here only a subset of the most productive projects, which is necessarily incomplete and biased.

2.1. X-ray

ESA's **XMM-Newton** (launched in 1999) is working with a 0.7 m telescope and operates in the 0.15 to 15 keV range. In the same year, NASA launched the **Chandra** telescope, with a 1.2 m telescope and operating in the 0.1 to 10 keV range. Each of these facilities boasts imaging and spectroscopic capabilities. In particular, the Chandra high resolution grating spectrometer provides the capability to resolve X-ray emission line shapes, and to infer detailed velocity fields and regions of spectrum formation. We address in the following four, of many more highlights:

– Magnetically confined winds are X-ray sources and a large series of Chandra and XMM-Newton observations of massive magnetic stars have been analysed, with the evidence that X-ray luminosity is strongly correlated with the stellar wind mass-loss-rate (Nazé et al., 2014), what is confirmed by additional XMM observations (see Fletcher et al., 2017, and these proceedings, and Fig. 2).

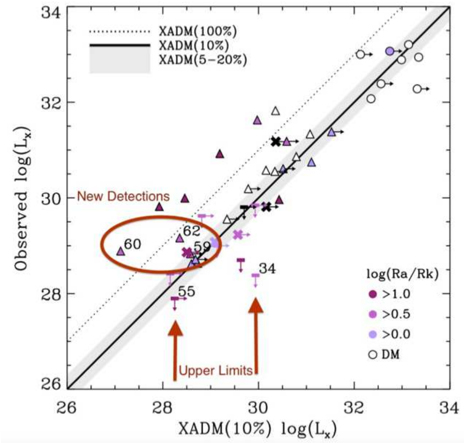

Figure 2. The predicted versus observed X-ray luminosity (Nazé et al., 2014), updated with new X-ray observations. The B-type stars in triangles, the O-type stars in circles and the undetected sources in rectangles (indicating upper limits). The color scheme corresponds to the size of the centrifugal magnetosphere (CM) with the darker the color having a larger CM and the white only having a dynamical magnetosphere (DM). Source: Fletcher et al. (2017)

– X-ray studies of cataclysmic variable and symbiotic stars teach a lot about the physics of accretion, disks and the interaction between accretion flow and magnetic field. They are important for the study of the Galaxy we live in, including its collective X-ray emission, and they provide valuable insight into the evolution of close binaries (Mukai, 2017).

– An impressive systematic study of all magnetar-like outbursts for which extensive X-ray monitoring campaigns are available is published by Coti Zelati et al. (2018). Magnetars are strongly magnetised (up to $B \approx 10^{15}$ G) isolated X-ray pulsars with luminosities $L_X \approx 10^{31} - 10^{36}\,\mathrm{erg\,s^{-1}}$. The authors investigate the correlation between different parameters (e.g., the luminosity at the peak of the outburst and in quiescence, the maximum luminosity increase, the decay timescale and energy of the outburst, the neutron star surface dipolar magnetic field and characteristic age).

– Isolated neutron stars (INS) come in an unexpected variety. The observed spectral and timing properties indicate that different energy sources, besides the obvious cooling of the primeval internal heat, are at play in powering such thermal-like components. The effects of a strong and dynamic magnetic field are especially evident in the paroxysmic behaviour of soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs). There is evidence for a closer connection between radio pulsars and magnetars than previously thought (see the review by Mereghetti, 2011).

2.2. UV

The most prominent UV satellite was probably the International Ultraviolet Explorer (**IUE**), which was observing between 1978 and 1996 with a 0.45 m telescope in the 115 to 325 nm spectral range. The **HST** produced science also in the optical and IR regions, but was ground braking in UV, when launched in 1990 with a 2.5 m telescope and *STIS* working in the 114 to 318 nm range and

COS in the 90 to 320 nm range. Contrary to IUE, which delivered high cadence, long timebase data, HST primarily produces snapshots. Also for UV we present some highlights:

– The appearance and evolution of discrete absorption components (DACs) is interpreted by Kaper et al. (1999) for O-type stars in terms of a model invoking fast and slow streams which interact due to the rotation of the underlying star. The interacting regions (CIRs) corotate with the star while the wind material is flowing through them. The observations suggest that the stellar wind includes more than one CIR, most likely two (cf. Kaper et al., 1997). The wind variability periods they derive are a direct measure of the DAC recurrence timescales and, in their interpretation, is equal to an integer fraction (most likely 1/2) of the stellar rotation period. The authors discuss the origin of the CIRs: are non-radial pulsations, surface magnetic fields, or other physical mechanisms responsible for the surface structure creating fast and slow wind streams?

– β Cep is the first upper main-sequence pulsating star with confirmed detection of a weak dipolar magnetic field (less than about $B_{long} = 100\,\mathrm{G}$). The data seem to be consistent with an oblique dipolar magnetic rotator model and the maximum wind absorption, derived from IUE spectra, originates in the magnetic equatorial plane (Henrichs et al., 2013).

– V 2052 Oph (B2IV-V) is the second discovered magnetic pulsating B star. UV delivered a very precise value of the rotation period. The star has no extra internal mixing due to the presence of the magnetic field which inhibits mixing (Briquet et al., 2012). A magnetic analysis of this star is presented by Neiner et al. (2012).

– ω Ori (B3Ve) is the first classical Be star showing indirect magnetic indicators (Neiner et al., 2003).

2.3. Optical

The majority of space instruments contributing to understanding magnetic fields associated to stars are working in the visual spectral range and we address some of the highlights in the following:

MOST

This is a Canadian Space Agency funded mission, launched in 2003 and still working. It was jointly operated by Dynacon Inc., the University of Toronto Institute for Aerospace Studies and the University of British Columbia, with the assistance of the University of Vienna, and now by Microsat Systems Canada Inc (MSCI). Please consult https://science.ubc.ca/feature/MOST for more details. Some MOST research highlights in the field are:

– ξ Per (B1Ib): This is the first convincing case '...with possible bright-spot generation via a breakout at the surface of a global magnetic field generated by a subsurface convection zone...' (Ramiaramanantsoa et al., 2014).

– HR 5907 (B2V): detection of a large-scale polar surface magnetic field of 10 to 16 kG. Longitudinal magnetic field and Hα variations are consistent with an oblique rotator, indicating a non-degenerate and magnetic massive star (5.5 $M_\odot$) with the shortest period (0.51 d) yet known (Grunhut et al., 2012).

– WR 110 has revealed during a month of observations properties of a co-rotating interaction region (CIR), which allows probing the mysterious origin of the CIR phenomenon rooted at the stellar surface, e.g. as a phenomenon related to magnetism or pulsations (Chené et al., 2011).

– 10 Aql (A7VpSrEu) provided first evidence for finite mode lifetimes in roAp stars (Huber et al., 2008).

– κ^1 Cet (G5V): all of the photometric periods found to date can be explained by spots at different latitudes. The apparent persistence of this period for some 35 years, corresponding to spot latitude-ranges of 50° to 60°, might be due to large-scale magnetic structures with solar-like differential rotation (see Fig. 3).

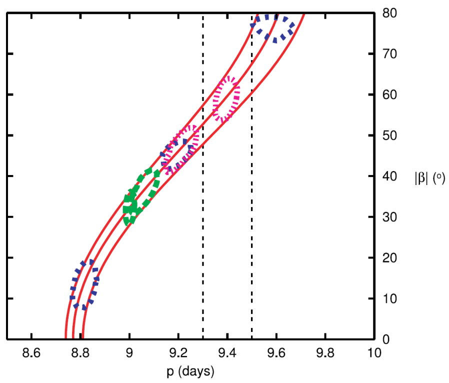

Figure 3. κ^1 Ceti: Likelihood contours for the latitude and spot period are shown by dots for each spot – 2003 (green), 2004 (blue) and 2005 (pink). The central red curve is the solar-period, latitude relation, indicating a differential rotation being closely solar. Source: (Walker et al., 2007)

CoRoT

It is based on a concept which was proposed already in 1993 by C. Catala, M. Auvergne and A. Baglin in answer to a call for ideas for “small missions”. CoRoT was developed under the lead of CNES with a wide European cooperation, was launched in 2006 and operated till 2012. For more details please consult https://corot.cnes.fr/en/COROT/index.htm. Some highlights are:

– HD 43317 (B3IV): photometric data of unprecedented precision, complemented by ground-based spectroscopy and polarimetry, allow to study the effect of magnetism in the mixing processes inside a star (Briquet et al., 2013).

– Close-in massive planets interact with their host stars through tidal and magnetic mechanisms, possibly related with hot Jupiters. The unique advantages of CoRoT and Kepler observations to test these models are pointed out by Lanza (2011).

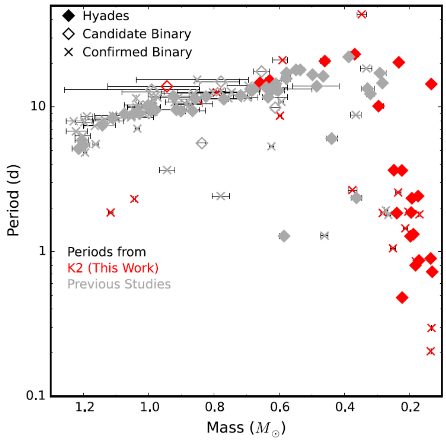

Figure 4. Mass-period distribution for all Hyades with measured periods. Source: Douglas et al. (2016)

– HD 49933 (F3V): observed variations in mode frequencies are related to its magnetic activity. HD 49933 is thus the second star after the Sun for which the frequency dependence of the p-mode frequency shifts with magnetic activity has been measured (Salabert et al., 2011).

Kepler

Kepler was launched in 2009, fully operational till 2013, then in a modified operation active in K2-mode. Few highlights:

– Beyond stellar middle-age the efficiency of magnetic braking is dramatically reduced, implying a fundamental change in angular momentum loss beyond a critical Rossby number (Metcalfe et al., 2016).

– K2 is the first opportunity to measure rotation periods for many Hyades simultaneously (Fig. 4), being also sensitive to fully convective M dwarf members. The deficit of single rapid rotators more massive than $\approx 0.3\,M_\odot$ indicates that magnetic braking is more efficient than previously thought, and that age-rotation studies must account for multiplicity (Douglas et al., 2016).

– The asteroseismology of Red Giant stars has continued to yield surprises. The observed suppression of dipole oscillation modes in Red Giants can be used to detect indirect evidence of the presence of strong magnetic fields in the stellar cores (Stello et al., 2016).

– HD 188774 (A7.5 IV-III) is the first known magnetic main-sequence δ Sct star. This challenges analysis and interpretation of the Kepler results for the class of A-type stars (Neiner & Lampens, 2015).

BRITE-Constellation

BRITE-Constellation was built, launched and is operated thanks to support from the Austrian Research Promotion Agency (FFG) and the University of

Vienna, the Canadian Space Agency (CSA), the Foundation for Polish Science & Technology (FNiTP MNiSW), and the National Science Centre (NCN). Please consult http://www.brite-constellation.at for more details. The BRITE observations are completed by a ground-based spectropolarimetric survey (see Neiner et al., 2016). Recent science highlights are:

– ρ Pup (F5IIkF2IImF5II) is the second confirmed magnetic δ Scuti star (Neiner et al., 2017)

– γ Gem (A1.5 IV): the BRITE spectropolarimetric survey provided first detection of a standard Zeeman pattern in an Am star, with $B_{pol} \approx 30\,\mathrm{G}$, while all other magnetic Am stars show peculiar Zeeman profiles with a single lobe and ultra-weak field strengths (Blazère et al., 2016).

– i Car (B3V) & 27 Tau (B8 III): combining magnetic and seismic information is the only way to probe the impact of magnetism on the physics of non-standard mixing processes inside hot stars (Neiner et al., 2015).

3. Projects in the future

Several space missions are in preparation for the coming decades that will contribute to drastically extend our knowledge of stellar magnetism. In particular high-resolution UV spectropolarimetry is being developed for the **Arago** project and the **Pollux** instrument on LUVOIR. These missions would open a brand new window on magnetic stars and their environment. On the X-ray side, the **Athena** mission will have capacities well beyond XMM-Newton and Chandra and allow us in particular to study magnetospheres.

Arago

Arago is a space project candidate for a M-size mission at ESA led by France (PI: C. Neiner). Arago is a 1.3-m telescope that would perform high-resolution full-Stokes (IQUV) spectropolarimetry simultaneously in the UV and Visible wavelength ranges from 119 to 888 nm. The targets would be observed during a full stellar rotation period to obtain comprehensive 3D maps all the way from their sub-photosphere to the frontiers of their immediate circumstellar environment (Fig. 5). In addition, high-fidelity multi-parameter information on statistical stellar and planetary samples would be obtained thanks to snapshot observations of a large number of targets.

The final goal of Arago is to follow the life cycle of matter, and, therefore, the entire life cycle of stars and planets from their formation from interstellar gas and grains to their death and feedback into the interstellar medium (ISM). Arago's high-resolution spectropolarimeter would be the only facility able to simultaneously deliver all pertinent diagnostics throughout the UV and Visible domains.

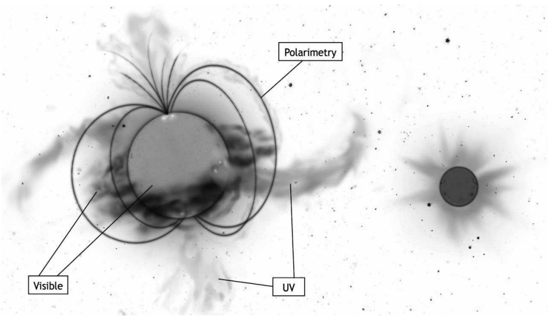

Figure 5. Core issues for Arago will be the links of circumstellar events to stellar surface structures. Copyright: S. Cnudde

Pollux on the LUVOIR

LUVOIR is one of four Decadal Survey Mission Concept Studies initiated by NASA in January 2016. It is a concept for a highly capable, multi-wavelength 15-m observatory with ambitious science goals, led by NASA. This mission would enable a great leap forward in a broad range of astrophysics, from the epoch of re-ionization, through galaxy formation and evolution, to star and planet formation. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable - or even inhabited.

LUVOIR will be equipped with 4 instruments: a coronagraph, a multi-resolution visible and IR spectrograph, a multi-object low and medium resolution UV spectrograph and imager, and a high-resolution UV spectropolarimeter called Pollux.

Pollux is a European instrument led by France (co-PIs: C. Neiner and J.-C. Bouret). It is a full-Stokes (IQUV) spectropolarimeter working at very high-resolution (120000) in 3 bands from the FUV (92 nm) to the near-UV (390 nm).

Athena

Athena is an ESA L-size mission planned to be launched in 2028 (PI: P. Nandra). The main goals of Athena are to map the hot gas structures in the Universe, determine their physical properties, track their evolution, find and study massive black holes. However, Athena will also be an ideal tool to study magnetospheres around stars.

Athena includes two instruments: X-IFU which provides high spectral resolution imaging in the 0.2–12 keV domain, and WFI which permits high count rate, mid-resolution spectroscopy over a large field-of-view in the 0.2–15 keV domain.

References

Blazère, A., Neiner, C., & Petit, P. 2016, *Mon. Not. R. Astron. Soc.*, **459**, L81

Briquet, M., Neiner, C., Aerts, C., et al. 2012, *Mon. Not. R. Astron. Soc.*, **427**, 483

Briquet, M., Neiner, C., Leroy, B., Pápics, P. I., & MiMeS Collaboration. 2013, *Astron. Astrophys.*, **557**, L16

Chené, A.-N., Moffat, A. F. J., Cameron, C., et al. 2011, *Astrophys. J.*, **735**, 34

Coti Zelati, F., Rea, N., Pons, J. A., Campana, S., & Esposito, P. 2018, *Mon. Not. R. Astron. Soc.*, **474**, 961

Douglas, S. T., Agüeros, M. A., Covey, K. R., et al. 2016, *Astrophys. J.*, **822**, 47

Fletcher, C. L., Petit, V., Nazé, Y., et al. 2017, in IAU Symposium, Vol. **329**, *The Lives and Death-Throes of Massive Stars*, ed. J. J. Eldridge, J. C. Bray, L. A. S. McClelland, & L. Xiao, 369–372

Grunhut, J. H., Rivinius, T., Wade, G. A., et al. 2012, *Mon. Not. R. Astron. Soc.*, **419**, 1610

Henrichs, H. F., de Jong, J. A., Verdugo, E., et al. 2013, *Astron. Astrophys.*, **555**, A46

Huber, D., Saio, H., Gruberbauer, M., et al. 2008, *Astron. Astrophys.*, **483**, 239

Kaper, L., Henrichs, H. F., Fullerton, A. W., et al. 1997, *Astron. Astrophys.*, **327**, 281

Kaper, L., Henrichs, H. F., Nichols, J. S., & Telting, J. H. 1999, *Astron. Astrophys.*, **344**, 231

Lanza, A. F. 2011, *Astrophys. Space Sci.*, **336**, 303

Mereghetti, S. 2011, *Astrophys. Space Sci. Proc.*, **21**, 345

Metcalfe, T. S., Egeland, R., & van Saders, J. 2016, *Astrophys. J., Lett.*, **826**, L2

Mukai, K. 2017, *Publ. Astron. Soc. Pac.*, **129**, 062001

Nazé, Y., Petit, V., Rinbrand, M., et al. 2014, *Astrophys. J., Suppl.*, **215**, 10

Neiner, C., Alecian, E., Briquet, M., et al. 2012, *Astron. Astrophys.*, **537**, A148

Neiner, C., Buysschaert, B., Oksala, M. E., & Blazère, A. 2015, *Mon. Not. R. Astron. Soc.*, **454**, L56

Neiner, C., Hubert, A.-M., Frémat, Y., et al. 2003, *Astron. Astrophys.*, **409**, 275

Neiner, C. & Lampens, P. 2015, *Mon. Not. R. Astron. Soc.*, **454**, L86

Neiner, C., Wade, G., Marsden, S., & Blazère, A., 2016, *ArXiv e-prints* [arXiv:1611.03285]

Neiner, C., Wade, G. A., & Sikora, J. 2017, *Mon. Not. R. Astron. Soc.*, **468**, L46

Petit, V., Cohen, D. H., Wade, G. A., et al. 2015, *Mon. Not. R. Astron. Soc.*, **453**, 3288

Ramiaramanantsoa, T., Moffat, A. F. J., Chené, A.-N., et al. 2014, *Mon. Not. R. Astron. Soc.*, **441**, 910

Salabert, D., Régulo, C., Ballot, J., García, R. A., & Mathur, S. 2011, *Astron. Astrophys.*, **530**, A127

Stello, D., Cantiello, M., Fuller, J., Garcia, R. A., & Huber, D. 2016, *Publ. Astron. Soc. Aust.*, **33**, 11

Walker, G. A. H., Croll, B., Kuschnig, R., et al. 2007, *Astrophys. J.*, **659**, 1611