# PolarBase: A Database of High-Resolution Spectropolarimetric Stellar Observations 

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#### Abstract

PolarBase is an evolving database that contains all stellar data collected with the ESPaDOnS and NARVAL high-resolution spectropolarimeters, in their reduced form, as soon as they become public. As of early 2014, observations of 2000 stellar objects throughout the Hertzsprung-Russell diagram are available. Intensity spectra are available for all targets, and the majority of the observations also include simultaneous spectra in circular or linear polarization, with the majority of the polarimetric measurements being performed only in circularly polarized light (Stokes $V$ ). Observations are associated with a cross-correlation pseudoline profile in all available Stokes parameters, greatly increasing the detectability of weak polarized signatures. Stokes $V$ signatures are detected for more than 300 stars of all masses and evolutionary stages, and linear polarization is detected in 35 targets. The detection rate in Stokes $V$ is found to be anticorrelated with the stellar effective temperature. This unique set of Zeeman detections offers the first opportunity to run homogeneous magnetometry studies throughout the H-R diagram. The Web interface of PolarBase is available at http://polarbase.irap.omp.eu.


Online material: color figures

## 1. INTRODUCTION: THE NARVAL AND ESPADONS SPECTROPOLARIMETERS

The ESPaDOnS spectropolarimeter (Donati et al. 2006) has been operational at the Canada-France-Hawaii Telescope (CFHT; Mauna Kea Observatory) since early 2005. NARVAL (Aurière 2003) is a strict twin of Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS), available at Télescope Bernard Lyot (TBL; Pic du Midi Observatory) since late 2006. The development of these two high-resolution optical spectropolarimeters was primarily motivated by their capabilities for detecting and characterizing stellar magnetic fields through the Zeeman effect. This science objective imposed strong constraints on the instrumental design, which has to combine a polarimeter and a spectrograph.

Their polarimetric module performs measurements in circular (Stokes $V$ ) or linear (Stokes $Q$ and $U$ ) polarization and is installed at the Cassegrain focus of the telescope to avoid

[^0]any oblique reflection prior to the polarimetric analysis. Once split into two orthogonal polarization states, the light emerging from the polarimeter is sent to the spectrograph through a fiber link. As will be discussed in § 3, the polarimetric sensitivity of modern instruments is greatly enhanced by their capability for repeating the measurement of Zeeman signatures over a large number of spectral lines. To cover a wide spectral window in a single exposure, ESPaDOnS and NARVAL incorporate a cross-dispersed echelle spectrograph, offering coverage of the entire optical domain ( 370 to 1000 nm ), with limited gaps of a few nanometers in the near-infrared portion of the spectrum. Both spectropolarimeters have a spectral resolving power of $\approx 65,000$ in polarimetric mode, as required to resolve narrow spectral lines, and therefore recover the detailed shape of polarized Zeeman signatures present in individual spectral features. They also have a higher resolving power of $\approx 76,000$ when used for classical spectroscopy alone. For a more detailed description of ESPaDOnS and NARVAL, including a comparison of their performances and recent instrumental upgrades, we refer the reader to the very complete paper of Silvester et al. (2012).

The polarimetric accuracy, spectral resolution, spectral coverage, and global throughput of ESPaDOnS and NARVAL constitute an impressive improvement compared to their predecessors, mainly MUlti SIte COntinuous Spectroscopy (MuSiCoS) at TBL (Baudrand \& Böhm 1992; Donati et al. 1999) and SemelPol at the Anglo-Asutralian Telescope (Donati et al. 2003). This leap forward has already led to spectacular scientific results involving magnetic field measurements throughout most of the

Hertzsprung-Russell diagram (H-R diagram from now on). Classes of stars explored by the twin spectropolarimeters include massive stars (Donati et al. 2006), Ap stars (Aurière et al. 2007), Vega-like stars (Lignières et al. 2009), Sun-like stars (Petit et al. 2008; Marsden et al. 2013), M dwarfs (Morin et al. 2008, 2010), cool giants and supergiants (Aurière et al. 2009, 2010) and young stars (Donati et al. 2007; Alecian et al. 2008).

Public ESPaDOnS and NARVAL data are separately made available by their host observatory. Raw and reduced ESPaDOnS data are offered at Canadian Astronomy Data Center (CADC) (http://www2.cadc-ccda.hia-iha.nrc-cnrc.gc.ca), and reduced NARVAL data can be accessed through the TBL Legacy database (http://tblegacy.bagn.obs-mip.fr). PolarBase is grouping all reduced data together with enhanced query and online plotting facilities. More advanced modeling is also offered in addition to the reduced data, in the form of cross-correlation pseudoline pro files and magnetic detection flags.

## 2. REDUCED SPECTROPOLARIMETRIC DATA

The data reduction is automatically performed in real-time at TBL and CFHT, using the Libre-Esprit reduction pipeline specifically developed for both twin spectropolarimeters and implementing the algorithm described by Donati et al. (1997). The reduction software performs optimal extraction of the spectrum (in all available Stokes parameters), following the approach of Marsh (1989) and Horne (1986). A first wavelength calibration is achieved using Th-Ar spectra taken during the night of observation and is refined at the end of the reduction process by using telluric bands superimposed on each stellar spectrum as radial velocity references. Using this strategy, the final radial velocity accuracy is on the order of $20-30 \mathrm{~ms}^{-1}$ (Moutou et al. 2007).

Libre-Esprit produces spectra with and without continuum normalization. PolarBase offers both types of reduction output, except when one of the modes was rejected by our quality checks (see § 6), or when one of the reduction modes was not initially computed by the observatory. Note that any continuum polarization is subtracted by default during data reduction, as the optical design of ESPaDOnS and NARVAL is not optimized for continuum polarization measurements.

In polarimetric mode, spectra are produced by the combination of four subexposures taken with the polarimetric optics rotated at different angles about the optical axis, following the approach of Semel et al. (1993). The corresponding Stokes $I$ spectrum is obtained by adding together the four subexposures (note that Stokes $I$ spectra are also derived from each subexposure and made available in PolarBase). Using other combinations of the subexposures, it is possible to obtain two "null" spectra (Donati et al. 1997) that are not expected to contain any signal. The "null" spectra are used to check for spurious polarized signatures (of stellar or instrumental origin). Figure 1 illustrates, over a small wavelength domain, the Stokes $I, V$ and "null" spectra of a normalized ESPaDOnS observation reduced with Libre-Esprit.


FIg. 1.-Extract of a normalized spectrum of II Peg, observed with ESPaDOnS on 2005 July 14, around three Fe I spectral lines with high Landé factors. The Stokes $V$ and $I$ spectra are illustrated in the top and bottom panels, respectively. Three Zeeman signatures are clearly visible in the Stokes $V$ spectrum. The middle panel displays one of the two "null" spectra. Note that Ic stands for the continuum intensity. (after Petit 2006) See the electronic edition of the PASP for a color version of this figure.

The PolarBase spectra are made available in their native ASCII format, where data are organized in columns. Table 1 lists the content of the ASCII files, depending on the data type. The number of spectral bins is given in the second line of the file, as well as the number of data columns (which depends on the data type). In polarimetric mode, five data columns are provided, so that the file contains a total of six columns, if we also consider the left column listing the wavelength (expressed in nanometers). In spectroscopic mode, only two data columns are listed (plus one for wavelength). ESPaDOnS offers a

TABLE 1
Format of ASCII PolarBase Data Files for Reduced Spectra ("Spec.") and LSD Profiles ("LSD")

| Col. \# | Spec. (pol) | Spec. (I) | LSD (pol) | LSD (I) |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 0 | $\ldots \ldots$ | Wav. | Wav. | RV | RV |
| 1 | $\ldots$. | Int. | Int. | Int. | Int. |
| 2 | $\ldots$. | Pol. | $\sigma_{\text {int }}$ | $\sigma_{\text {int }}$ | $\sigma_{\text {int }}$ |
| 3 | $\ldots$. | Null 1 | - | Pol. | - |
| 4 | $\ldots$. | Null 2 | - | $\sigma_{\text {pol }}$ | - |
| 5 | $\ldots$. | $\sigma_{\text {int }}$ | - | Null 1 | - |
| 6 | $\ldots$. | - | - | $\sigma_{\text {null }}$ | - |

Notes.-"Wav." stands for the wavelength (in nanometers) and "RV" stands for the radial velocity (in $\mathrm{km} \mathrm{s}^{-1}$ ). "Int." and "Pol." correspond to intensity and polarized data (normalized or not). "Null 1" and "Null 2" are the check parameters described in § 2. The parameter " $\sigma$ " stands for the uncertainty of a given type of data.
seldom-used "star+sky" spectroscopic mode, where the skylight is injected in a dedicated fiber. In PolarBase ASCII files produced for this mode, the intensity column contains the stellar spectrum from which the sky contribution was subtracted.

For each spectrum, a second ASCII file is also provided that contains metadata relevant to the observation. The target name, coordinates, time of observation (in date/time format, Heliocentric Julian date or Geocentric Julian date), and signal-tonoise ratio ( $\mathrm{S} / \mathrm{N}$ ) in each spectral order can be found in this complementary file.

## 3. LEAST-SQUARES DECONVOLUTION OF SPECTRA

The capability of ESPaDOnS and NARVAL for detecting very weak polarized signatures (most of the time below the noise level of reduced spectra) is improved by (and, most of the time, requires) the simultaneous extraction of the polarimetric signal from all available photospheric lines.

Each normalized PolarBase spectrum was processed with the least-squares deconvolution method (hereafter LSD; Donati et al. 1997; Kochukhov et al. 2010), to extract a mean pseudoline profile in all available Stokes parameters, using here the implementation of Donati et al. (1997). Here, free parameters in LSD models are optimized by following a procedure similar to the one employed by Marsden et al. (2013), and the resulting scale factors are listed in Tables 2 and 3. This multiline approach requires the selection of a list of spectral lines that matches the photospheric properties of the target. The line list used to compute the LSD profile is created from a query of the Vienna Atomic Line Database (VALD) atomic database (Kupka et al. 2000), with lines in the wings of Balmer and Helium lines removed from the list. In the current operation of PolarBase, we rely on the SIMBAD database to provide us with an approximate spectral type of the target, from which we select a line mask of the closest effective temperature ( $T_{\text {eff }}$ ), using the relation between spectral type and temperature given by Gray (2005). We crudely assume that the surface gravity of the star is a main-sequence surface gravity (at the $T_{\text {eff }}$ of the target) and also assume a solar metallicity. When the target is a SB2 (or any more complex stellar association), the line mask is chosen to match the effective temperature of the primary component.

Considering this series of crude approximations, we recommend to limit the use of PolarBase LSD profiles as a preliminary help to check for the presence of a polarized signature (Fig. 2). It is our experience that an incorrect line mask will not produce a spurious polarized signature in a nonmagnetic target. However, an incorrect line list will reduce the amplitude of the polarized signature in the LSD profile, so that some weak Zeeman signatures may stay below the noise level, whereas a better line list might have revealed their presence.

PolarBase LSD line profiles are downloadable in ASCII format, following the column distribution described in Table 1. As for reduced spectra, basic information about the LSD model

TABLE 2
Table of Scale Factors Used to Generate the LSD Profiles (Spectral Types O to F)

| Sp. Type | $d_{0}$ | $g_{0}$ | $\lambda_{0}(\mathrm{~nm})$ |
| :---: | :---: | :---: | :---: |
| O4 | 0.1693 | 1.110 | 541.3416 |
| O5 | 0.1693 | 1.116 | 549.3795 |
| O6 | 0.1671 | 1.108 | 537.3378 |
| 07 | 0.1693 | 1.109 | 536.1185 |
| O8 | 0.1933 | 1.141 | 535.6516 |
| 09 | 0.1959 | 1.140 | 510.0581 |
| B0 | 0.2307 | 1.240 | 510.5091 |
| B1 | 0.2361 | 1.256 | 533.1491 |
| B2 | 0.2377 | 1.257 | 573.0493 |
| B3 | 0.2593 | 1.231 | 535.3934 |
| B4 | 0.2874 | 1.185 | 545.0606 |
| B5 | 0.2687 | 1.191 | 612.7151 |
| B6 | 0.3266 | 1.138 | 580.1827 |
| B7 | 0.3556 | 1.119 | 571.3179 |
| B8 | 0.3325 | 1.163 | 711.4965 |
| B9 | 0.4090 | 1.166 | 510.6888 |
| A0 | 0.4143 | 1.209 | 501.7136 |
| A1 | 0.4219 | 1.198 | 542.4850 |
| A2 | 0.4219 | 1.198 | 543.4444 |
| A3 | 0.4303 | 1.201 | 545.0059 |
| A4 | 0.4303 | 1.201 | 545.0059 |
| A5 | 0.4524 | 1.201 | 556.1013 |
| A6 | 0.4657 | 1.208 | 550.2700 |
| A7 | 0.4625 | 1.209 | 557.1888 |
| A8 | 0.4625 | 1.209 | 557.1888 |
| A9 | 0.4688 | 1.206 | 555.6388 |
| F0 | 0.4688 | 1.206 | 555.6388 |
| F1 | 0.4877 | 1.212 | 556.8212 |
| F2 | 0.4877 | 1.212 | 556.8212 |
| F3 | 0.4877 | 1.212 | 574.2867 |
| F4 | 0.4812 | 1.210 | 581.6153 |
| F5 | 0.4812 | 1.210 | 581.6153 |
| F6 | 0.5053 | 1.213 | 582.9365 |
| F7 | 0.5053 | 1.213 | 582.9365 |
| F8 | 0.5294 | 1.212 | 577.4088 |
| F9 | 0.5225 | 1.211 | 579.8654 |

(e.g., $\mathrm{S} / \mathrm{N}$ of the LSD profile) are listed in a separate ASCII file. The second file also gives a probability of signal detection, following the prescription of Donati et al. (1992). Detection probabilities are computed within the line profile and in the neighbouring continuum, both for the relevant Stokes parameter and for its associated "null" line profile. A flag is given that classifies the detection probability as a "definite," "marginal," or "no" signal detection, following the conventions detailed by Donati et al. (1997).

## 4. DATABASE

The technical architecture of PolarBase is based upon PostgreSQL9.0 and Python scripts. The full software is divided into three different parts:

1. Data integration software, designed to feed the database with new sets of data released each semester by TBL and CFHT.

TABLE 3
Same as Table 2 for Spectral Types G to M

| Sp. Type | $d_{0}$ | $g_{0}$ | $\lambda_{0}(\mathrm{~nm})$ |
| :---: | :---: | :---: | :---: |
| G0 | 0.5294 | 1.211 | 577.3031 |
| G1 | 0.5225 | 1.210 | 584.1816 |
| G2 | 0.5225 | 1.210 | 597.6029 |
| G3 | 0.5225 | 1.208 | 605.4862 |
| G4 | 0.5225 | 1.208 | 605.4862 |
| G5 | 0.5363 | 1.210 | 589.6192 |
| G6 | 0.5363 | 1.210 | 589.6192 |
| G7 | 0.5486 | 1.207 | 601.1477 |
| G8 | 0.5486 | 1.207 | 601.1477 |
| G9 | 0.5554 | 1.208 | 615.4197 |
| K0 | 0.5554 | 1.208 | 615.4197 |
| K1 | 0.5550 | 1.210 | 603.7351 |
| K2 | 0.5625 | 1.214 | 612.8669 |
| K3 | 0.5625 | 1.214 | 612.8669 |
| K4 | 0.6887 | 1.206 | 629.8284 |
| K5 | 0.6887 | 1.206 | 629.8284 |
| K6 | 0.6887 | 1.206 | 629.8284 |
| K7 | 0.6887 | 1.206 | 629.8284 |
| K8 | 0.6751 | 1.221 | 665.0525 |
| K9 | 0.6751 | 1.221 | 665.0525 |
| M0 | 0.6751 | 1.221 | 665.0525 |
| M1 | 0.6751 | 1.221 | 665.0525 |
| M2 | 0.6188 | 1.245 | 672.9030 |
| M3 | 0.6188 | 1.245 | 672.9030 |
| M4 | 0.6188 | 1.245 | 672.9030 |
| M5 | 0.6188 | 1.245 | 672.9030 |
| M6 | 0.6188 | 1.245 | 672.9030 |
| M7 | 0.6188 | 1.245 | 672.9030 |
| M8 | 0.6188 | 1.245 | 672.9030 |

The corresponding algorithms are implemented as objectdesigned Python scripts.
2. The query software (developed in Python) is used to access the database and manipulate data through the user Web interface.
3. User Web interface.

The integration and query software make use of the SIMBAD database to collect basic stellar parameters of the targets and store these metadata into a specific section of the database. Metadata missing in SIMBAD are attributed the " -999 " value in PolarBase. Regular SIMBAD checks are performed to update the list of available metadata. There are two types of data available in PolarBase, with reduced spectra (normalized or not) and LSD line profiles. Each one is treated through an independent integration pipeline and consistency check, looking for corrupted data (wrong format or inconsistent quantities) and evaluating the data quality (e.g., through thresholds in the signal-to-noise ratio) to make sure that the content available to the user is of high quality.

## 5. WEB INTERFACE AND VIRTUAL OBSERVATORY

The user interface uses Asynchronous JavaScript and XML (AJAX) with Rialto, Jquery and Dygraphs frameworks to give the user a state-of-the-art browsing experience. All data avail-


Fig. 2.-Example LSD profile for the G8 dwarf $\xi$ Bootis A, observed with NARVAL on 2008 February 11. The Stokes $V$ and $I$ cross-correlation profiles are illustrated in the top and bottom panels, respectively. A strong Zeeman signature is detected in the Stokes $V$ line profile. The middle panel illustrates one of the two "null" LSD profiles. Ic stands for the continuum intensity. (after Morgenthaler et al. 2012) See the electronic edition of the PASP for a color version of this figure.
able can be accessed through this interface (http://polarbase.irap .omp.eu). The query criteria are divided into different groups:

1. Object characteristics (name, magnitude, spectral type...)
2. Parameters related to a specific observation (air mass, date, observing mode, Stokes parameter...)
3. Data quality and LSD results (signal-to-noise ratio, detection of a polarimetric signal).

When the database is queried for a specific object name (given alone or along with other parameters), we first check whether the specified name is found in the database. If not, then a SIMBAD query is used to cross-match the name given by the user, SIMBAD results and PolarBase content. The database then returns a list of observation blocks matching requested criteria. The blocks contain spectra (normalized and not normalized) and LSD output that can all be plotted, zoomed in and out and downloaded.

In addition to the ASCII files accessible through its Web interface, Polarbase offers FITS format files through its Virtual Observatory (VO) portal, with VO services directly derived from the set of services available for the TBLegacy archive (http://tblegacy.bagn.obs-mip.fr).

## 6. STELLAR TARGETS

Among all objects observed with ESPaDOnS and NARVAL, we have selected for PolarBase stellar targets with a SIMBAD entry. We therefore exclude all observations of solar system
bodies and extragalactic objects, as well as stellar observations with object names that could not be resolved using the SIMBAD database. Taking into account all public observations available so far (collected before 2013), we end up with around 1290 stars observed with ESPaDOnS and 961 stars observed with NARVAL, corresponding to a total of 2004 observed targets ( 247 objects being observed with both instruments).

The distribution of PolarBase targets over the sky is shown in Figure 3, displaying a denser accumulation of observations in the plane of the Milky Way. Thanks to the location of Mauna Kea Observatory at lower latitude, ESPaDOnS offers a better sampling than NARVAL at lower declination (down to $-50^{\circ}$, vs. a minimum declination of $-20^{\circ}$ with NARVAL). Due to pointing limitations of TBL at high declinations (with a maximum accessible declination of around $75^{\circ}$ ), ESPaDOnS also gives easier access to stars closer to the northern celestial pole (maximum observed declination of $85^{\circ}$ in PolarBase).

PolarBase stars sample a wide range of spectral types, from O4 to M9 (Figure 4), with a $60 \%$ majority of the targets being cooler than F5. In the H-R diagram, PolarBase targets are mainly distributed over the main sequence, with a relative lack of targets of A spectral type. A number of stars are also located at higher luminosities, including both pre-main-sequence targets and evolved objects. We note a dearth of stars in the lower-left quadrant of the diagram, showing the scarcity of observing programs dedicated to compact objects. A $60 \%$ majority of stars hotter than F5 were observed with ESPaDOnS, owing to the contribution of the MagnetIsm in MassivE Stars (MiMeS) survey (Wade et al. 2013), while the observation of targets cooler than F5 was more evenly distributed between both instruments.


Fig. 3.-PolarBase targets located in a sky map. The right ascension is expressed in hours, and the declination is expressed in degrees. Pink triangles and black circles are objects observed by ESPaDOnS and NARVAL, respectively, while green squares illustrate stars observed by both instruments. See the electronic edition of the PASP for a color version of this figure.

## 7. CHARACTERISTICS OF OBSERVED SPECTRA

The content of PolarBase was cleaned from low-quality spectra, using simple filters to automatically remove problematic observations. In particular, we discarded 5755 spectra for which the pointing coordinates differed from the object coordinates by more than $1^{\circ}$ (in right ascension or declination). We also removed from the database 10,634 spectra with peak S/N lower than 100 (most of them concerning cool stars), and 1328 observations with peak $\mathrm{S} / \mathrm{N}$ greater than 3000 (since they are likely affected by partial CCD saturation). The search for tiny Zeeman signatures requires high $\mathrm{S} / \mathrm{N}$ ratios, so that low $\mathrm{S} / \mathrm{N}$ spectra are a minority in PolarBase, with $58 \%$ of available spectra having a peak S/N above 500 and $18 \%$ of them above 1000 before LSD processing (see Fig. 5).

Most PolarBase objects are variable and were therefore repeatedly observed with ESPaDOnS or NARVAL. As of early 2014, the total number of independent observations is equal to $\approx 90,000$. Since most observations are offered with and without continuum normalization, the total number of spectra in PolarBase is about twice this amount. Queries for observations of a given object at a specific date are possible with the Web interface of PolarBase.

## 8. POLARIMETRIC SIGNATURES

A $64 \%$ majority of PolarBase targets were observed in the Stokes $V$ polarimetric mode, and $8 \%$ of the observed stars benefit from linear polarization measurements (most of them being intermediate-mass stars). Among all stars observed at least once in Stokes $V, 24 \%$ provided us with at least one


Fig. 4.-PolarBase targets located in the Hertzsprung-Russell diagram. The $N$ quantity in the color bar stands for the number of objects in each bin. Stellar luminosities are derived from apparent $V$ magnitudes and parallax measurements listed in SIMBAD, as well as bolometric corrections taken from Gray (2005). See the electronic edition of the PASP for a color version of this figure.


Fig. 5.-Number of normalized PolarBase spectra, as a function of their peak signal-to-noise ratio per $1.8 \mathrm{~km} \mathrm{~s}^{-1}$ velocity bin in Stokes $I$ (before LSD processing). See the electronic edition of the PASP for a color version of this figure.
definite detection in the LSD line profile, leading to a total of 307 objects with polarimetric signatures that are likely attributable to a photospheric magnetic field.

As a simple example of data mining that can be easily performed with PolarBase, we show in Figure 6 the fraction of stars with at least one signal detection in Stokes $V$, as a function of spectral type. An anticorrelation between field detection and effective temperature is clearly observed in this plot. The lowest detection rate is obtained for O stars, with a $5 \%$ detection rate consistent with findings from the MiMeS survey (Wade et al. 2013). Much higher detection rates of around $50 \%$ are obtained for K and M spectral types. Interestingly, detection rates from late F to early K matches quite well the $40 \%$ detection rate reported by Marsden et al. (2013) from the Bcool catalog of mainsequence stars, although the present plot also incorporates pre-main-sequence stars and cool evolved stars at these spectral types. Our detection rate of about $20 \%$ for late B and early A stars is somewhat higher than previous estimates by Wolff (1968) and Vogt et al. (1998), although our uncertainties are relatively large. It is also interesting to note the lack of any magnetic detection for late A stars.

We must, however, stress that several biases may affect these detection rates in one direction or the other. First, we emphasize again that the line masks used for our LSD models are approximate masks chosen from the SIMBAD spectral type of the target. The effect of an approximate line mask is expected to be more pronounced for O stars, for which the scarcity of available lines requires a more careful selection of spectral features to incorporate in the LSD model. Detection rates reported here may therefore give an underestimated value (Wade et al. [2013], however, propose $7 \%$, in close agreement with our value). On the other hand, many observing programs carried out with ESPaDOnS or NARVAL concentrated on targets specifically


FIG. 6.-Fraction of objects for which Stokes $V$ signatures were detected at least once in LSD line profiles, as a function of spectral type. Anticorrelation is observed between detection rate and effective temperature. The uncertainties are computed from binomial statistics. See the electronic edition of the PASP for a color version of this figure.
selected from the assumption that they may host a detectable field, as suspected from, e.g., high chromospheric (or coronal) emission in the case of cool stars. This is particularly true for M dwarfs that were selected from their high activity (Morin et al. 2008, 2010), so that the PolarBase sample of M stars may lead to an overestimate of field detection rates in the coolest part of the H-R diagram. The lack of magnetic detections in A stars cooler than A3 is likely biased by the low number of NARVAL and ESpaDOnS programs dedicated to Ap stars, but it may also confirm a drop of the prevalence of the Ap phenomenon in stars cooler than A4 (Power et al. 2007).

## 9. FUTURE SCIENCE AND VO DEVELOPMENTS

The data content of PolarBase is meant to progressively evolve. The main reason is the growing amount of public data available for inclusion in the database, with new observations released every semester by the host observatories of ESPaDOnS and NARVAL.

PolarBase is also evolving to offer an increasing number of systematic measurements derived from the spectra and LSD profiles. Future quantities that will progressively enrich spectral analysis include the S-index (a classical quantity evaluating Ca II H and K core emission) and other similar chromospheric emission indices computed for $H_{\alpha}$ and for the Ca II infrared triplet (following the work of Marsden et al. [2013]).

LSD models will progressively gain better accuracy with the use of refined line masks. This step will, however, require a more precise determination of stellar fundamental parameters, through spectral classification tools applied to PolarBase
spectra. Quantities derived from the improved LSD models will then include radial velocity and $v \sin (i)$ measurements (from Stokes $I$ LSD profiles), and longitudinal field measurements using the first moment of Stokes $V$ line profiles (Rees \& Semel 1979).

A very important aspect of our work is to make sure that PolarBase always matches up to the latest revisions of the IVOA (International Virtual Observatory Alliance) formats and protocols (description of flux provided in the data, BAND query parameter and other updates) of both SSAP (Simple Spectral Access Protocol, ver. 1.1, IVOA recommendation of 2012 February 10) and SDM (IVOA Spectral Data Model, ver. 2.0, IVOA proposed recommendation of 2013 April 25, under review). A first improvement will be that Polarbase will not only offer SSAP access but also a Cone Search service. A second objective is to share LSD models through the VO, which will require a VO compliant description of their content. Extension of the VO capabilities of Polarbase to the use of the Parameter Description

Language (PDL, ver. 1.0, IVOA proposed recommendation of 2013 November 14, document still under review) will also be investigated to ensure optimal interoperability with other VO providers.

This research has made use of the SIMBAD database operated at Centre de Données astronomiques de Strasbourg (CDS), Strasbourg, France, and of NASA's Astrophysics Data System. PolarBase data are a compilation of a large number of observing runs, and we are deeply grateful to all the PIs for their talented work in acquiring this exceptional library of spectra. We are grateful to the referee, G.A. Wade, for constructive comments and very useful bug reports. This work has only been possible due to the brilliance of the late Meir Semel, from Observatoire de Paris-Meudon. Sadly, Meir passed away during 2012, but his memory and influence on spectropolarimetry will live on.

Facilities: CFHT, TBL

## REFERENCES

Alecian, E., et al. 2008, MNRAS, 385, 391
Aurière, M. 2003, EAS Publications Series, 9, 105
Aurière, M., Donati, J.-F., Konstantinova-Antova, R., Perrin, G., Petit, P., \& Roudier, T. 2010, A\&A, 516, L 2

Aurière, M., et al. 2007, A\&A, 475, 1053
——. 2009, A\&A, 504, 231
Baudrand, J., \& Böhm, T. 1992, A\&A, 259, 711
Donati, J.-F., Catala, C., Landstreet, J. D., \& Petit, P. 2006, in ASP Conf. Ser. 358, Solar Polarization 4, ed. R. Casini, \& B. W. Lites (San Francisco: ASP), 362
Donati, J.-F., Catala, C., Wade, G. A., Gallou, G., Delaigue, G., \& Rabou, P. 1999, A\&AS, 134, 149
Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., \& Collier Cameron, A. 1997, MNRAS, 291, 658

Donati, J.-F., Semel, M., \& Rees, D. E. 1992, A\&A, 265, 669
Donati, J.-F., et al. 2003, MNRAS, 345, 1145
-_. 2006, MNRAS, 370, 629
--. 2007, MNRAS, 380, 1297
Gray, D. F. 2005, The Observation and Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)
Horne, K. 1986, PASP, 98, 609
Kochukhov, O., Makaganiuk, V., \& Piskunov, N. 2010, A\&A, 524, A 5
Kupka, F. G., Ryabchikova, T. A., Piskunov, N. E., Stempels, H. C., \& Weiss, W. W. 2000, Baltic Astron., 9, 590

Lignières, F., Petit, P., Böhm, T., \& Aurière, M. 2009, A\&A, 500, L 41
Marsden, S. C., et al. 2013, preprint (arXiv:1311.3374)
Marsh, T. R. 1989, PASP, 101, 1032
Morgenthaler, A., et al. 2012, A\&A, 540, A 138
Morin, J., Donati, J.-F., Petit, P., Delfosse, X., Forveille, T., \& Jardine, M. M. 2010, MNRAS, 407, 2269

Morin, J., et al. 2008, MNRAS, 390, 567
Moutou, C., et al. 2007, A\&A, 473, 651
Petit, P. 2006, in ASP Conf. Ser. 358, Solar Polarization 4, ed. R. Casini, \& B. W. Lites (San Francisco: ASP), 335
Petit, P., et al. 2008, MNRAS, 388, 80
Power, J., Wade, G. A., Hanes, D. A., Aurière, M., \& Silvester, J. 2007, in Proc. Physics of Magnetic Stars, ed. I. I. Romanyuk, \& D. O. Kudryavtsev (Conference held in the Special Astrophysical Observatory of the Russian AS, August 28-31, 2006), 89
Rees, D. E., \& Semel, M. D. 1979, A\&A, 74, 1
Semel, M., Donati, J.-F., \& Rees, D. E. 1993, A\&A, 278, 231
Silvester, J., Wade, G. A., Kochukhov, O., Bagnulo, S., Folsom, C. P., \& Hanes, D. 2012, MNRAS, 426, 1003
Vogt, N., Kerschbaum, F., Maitzen, H. M., \& Faundez-Abans, M. 1998, A\&AS, 130, 455
Wade, G. A., et al. 2013, preprint (arXiv:1310.3965)
Wolff, S. C. 1968, PASP, 80, 281


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