Stellar activity analysis of Barnard’s Star: Very slow rotation and evidence for long-term activity cycle

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ABSTRACT

The search for Earth-like planets around late-type stars using ultra-stable spectrographs requires a very precise characterization of the stellar activity and the magnetic cycle of the star, since these phenomena induce radial velocity (RV) signals that can be misinterpreted as planetary signals. Among the nearby stars, we have selected Barnard’s Star (GJ 699) to carry out a characterization of these phenomena using a set of spectroscopic data that covers about 14.5 years and comes from seven different spectrographs: HARPS, HARPS-N, CARMENES, HIRES, UVES, APF, and PFS; and a set of photometric data that covers about 15.1 years and comes from four different photometric sources: ASAS, FCAPT-RCT, AAVSO, and SNO. We have measured different chromospheric activity indicators (Hα, Ca II HK and Na I D), as well as the FWHM of the cross-correlation function computed for a sub-set of the spectroscopic data. The analysis of Generalized Lomb-Scargle periodograms of the time series of different activity indicators reveals that the rotation period of the star is 145 ± 15 days, consistent with the expected rotation period according to the low activity level of the star and previous claims. The upper limit of the predicted activity-induced RV signal corresponding to this rotation period is about 1 m/s. We also find evidence of a long-term cycle of 10 ± 2 years that is consistent with previous estimates of magnetic cycles from photometric time series in other M stars of similar activity levels. The available photometric data of the star also support the detection of both the long-term and the rotation signals.

Key words: stars: activity – stars: magnetic cycles – stars: rotation – stars: individual: Barnard’s star (GJ 699)

1 INTRODUCTION

Since the discovery of the first extrasolar planet in 1992 (Wolszczan & Frail 1992) and the detection of the first ex-
planets have been detected using different techniques\textsuperscript{1}. One of the most commonly used methods is the radial velocity (RV) technique, which has been applied to find 773 extrasolar planets around 576 stars. The majority of these stars are G or K type (with a percentage of 42% and 33% respectively), and only 49 of them are M-dwarfs (8% of the total sample), the first one detected in 2001 around GJ 876 (Marcy et al. 2001). The search for Earth-like planets around these M-type stars takes advantage of having greater amplitudes in the RV planetary signals due to the low mass of their parent star. Also, this type of stars is the most common stellar type in the Milky Way (Chabrier & Baraffe 2000). However, stellar activity in M-dwarfs can produce signals with periods commensurate with the “habitable zones” around these stars, where liquid water could potentially exist on the surface of a planet. Distinguish whether signals arise from orbiting planets or stellar activity can be challenging. The signals produced by stellar activity are on the timescale of the rotation period of the star, but we also have to take care of the long-period signals associated with Doppler shifts caused by the magnetic cycle of the star (Dravins 1985; Campbell et al. 1988) already reported around M stars (Gomes da Silva et al. 2012; Robertson et al. 2013; Díez-Alonso et al. 2018). Photon noise of the measurements is a key selection criteria of stellar samples in RV search programs. The high SNR of nearby stars makes them very interesting targets for low mass exoplanets searches. Among the nearby stars, we have selected the closest single M-dwarf to the Solar System: Barnard’s Star (GJ 699).

Barnard’s Star is well known for being the second closest stellar system to the Sun. Located at a distance of 1.8 parsecs (Brown et al. 2018), and with an age between 7 and 10 Gyr (Ribas et al. 2018), GJ 699 is the star with the highest proper motion known to date (Barnard 1916), which causes Doppler shifts due to secular acceleration (Stumpff 1985; proper motion known to date (Barnard 1916), which causes Doppler shifts due to secular acceleration (Stumpff 1985; Robertson et al. 2013; Díez-Alonso et al. 2018). This reduces the effects of spots and plages in the spectra used in this work were collected at the 3.6 m telescope of La Silla Observatory, Chile (Mayor et al. 2003). The search for Earth-like planets around 576 stars. The majority of these stars are G or K type (with a percentage of 42% and 33% respectively), and only 49 of them are M-dwarfs (8% of the total sample), the first one detected in 2001 around GJ 876 (Marcy et al. 2001). The search for Earth-like planets around these M-type stars takes advantage of having greater amplitudes in the RV planetary signals due to the low mass of their parent star. Also, this type of stars is the most common stellar type in the Milky Way (Chabrier & Baraffe 2000). However, stellar activity in M-dwarfs can produce signals with periods commensurate with the “habitable zones” around these stars, where liquid water could potentially exist on the surface of a planet. Distinguish whether signals arise from orbiting planets or stellar activity can be challenging. The signals produced by stellar activity are on the timescale of the rotation period of the star, but we also have to take care of the long-period signals associated with Doppler shifts caused by the magnetic cycle of the star (Dravins 1985; Campbell et al. 1988) already reported around M stars (Gomes da Silva et al. 2012; Robertson et al. 2013; Díez-Alonso et al. 2018). Photon noise of the measurements is a key selection criteria of stellar samples in RV search programs. The high SNR of nearby stars makes them very interesting targets for low mass exoplanets searches. Among the nearby stars, we have selected the closest single M-dwarf to the Solar System: Barnard’s Star (GJ 699).

Previously work carried out on this star (Suárez Mascareño et al. 2015; Astudillo-Defru et al. 2017) has revealed a low level of chromospheric emission ($\log R'_{HK}=-5.86$ and $\log R'_{HK}=-5.69$, respectively), which is usually related to slow rotators. Using these two values in the relation between the rotation period and the activity level of the star predicted by Suárez Mascareño et al. (2016) gives an expected rotation period of 152 and 112 days, respectively. This range is in good agreement with the previous value of 130 days given by Benedict et al. (1998) through a photometric study using the Hubble Space Telescope. Also Suárez Mascareño et al. (2015) reported a 148.6-day rotation period obtained from a time-series analysis of spectroscopic indexes using HARPS data.

Recently, Ribas et al. (2018) reported the discovery of a super-Earth like planet orbiting Barnard’s Star at an orbit of 233 days with a minimum mass of 3.3 Earth masses. We will focus on the stellar activity and magnetic cycle characterization through a multi-spectrograph analysis of several activity indexes, complemented by a multi-instrumental analysis of photometric time-series, which leads to detect and increase the precision in the rotation period value and also to detect a long-term activity cycle in the star.

2 DATA

2.1 Spectroscopic Dataset

For this work we have used spectra taken with seven different spectrographs, whose main properties are shown in Table 2. HARPS (High Accuracy Radial velocity Planet Searcher) is a fiber-fed echelle spectrograph installed in 2003 at the 3.6 m telescope of La Silla Observatory, Chile (Mayor et al. 2003). The spectra used in this work were collected between April 2007 (BJD=2454194.9) and September 2017

| Table 1. Stellar properties of Barnard’s Star. |
|-----------------|-----------------|-----------------|
| Parameter       | GJ 699          | Ref.            |
| RA (J2000)      | 17:57:48.50     | [1]             |
| DEC (J2000)     | +34:41:36.11    | [1]             |
| $\mu_\alpha$ cos $\delta$ (mas yr$^{-1}$) | -802.8 ± 0.6    | [1]             |
| $\mu_\delta$ (mas yr$^{-1}$)            | +10392.5 ± 0.4  | [1]             |
| Distance [pc]   | 1.8266 ± 0.0001 | [1]             |
| $m_B$           | 11.24           | [2]             |
| $m_V$           | 9.51            | [2]             |
| Spectral type   | M3.5V           | [3]             |
| $T_{\text{eff}}$ [K] | 3278 ± 51       | [4]             |
| $[Fe/H]$ (dex)  | -0.12 ± 0.16    | [4]             |
| $M_*$ [M$_\odot$] | 0.163 ± 0.022   | [5]             |
| $R_*$ [R$_\odot$] | 0.178 ± 0.011   | [5]             |
| $L_*$ [L$_\odot$] | 0.00329 ± 0.00019 | [5] |
| $\log g$ (cgs) | 5.10 ± 0.07     | [4]             |
| $\log (L_\star/L_{\text{bol}})$ | -5.4            | [6]             |
| $v \sin i$ [km s$^{-1}$] | <3              | [4]             |
| $a_{\text{sec}}$ [m s$^{-1}$ yr$^{-1}$] | 5.15 ± 0.89     | [7]             |
| $\log R'_{HK}$ | -5.82 ± 0.08    | [8]             |
| $P_{\text{rot}}$ [days] | 145 ± 15        | [8]             |
| Long-term activity cycle [days] | 3800 ± 600     | [8]             |

References:
[1] Brown et al. (2018); [2] Koen et al. (2010); [3] Alonso-Floriano et al. (2015); [4] Passegger et al. (2018); [5] Ribas et al. (2018); [6] Kiraga & Stepien (2007); [7] Kürster et al. (2003); [8] This work

| Table 2. Properties of all the spectrographs used in this work. |
|-----------------|-----------------|-----------------|
| Spectrograph    | R               | $\Delta \lambda$ [Å] | $N_{\text{spec}}$ |
| HARPS           | 115 000         | 3780-6910         | 317              |
| HARPS-N         | 115 000         | 3830-6930         | 74               |
| CARMENES        | 90 000          | 5200-17100        | 192              |
| HIRES           | 67 000          | 3700-10000        | 179              |
| UVES            | 130 000         | 3000-11000        | 57               |
| PFS             | 80 000          | 3680-6680         | 43               |
| APF             | 100 000         | 3740-9700         | 95               |

Columns: Name of the spectrograph, resolution, spectral range and number of spectra used in this work.

\textsuperscript{1} source: http://www.exoplanet.eu
(BJD=2458027.5) with an exposure time of 900 s. In the treatment of these data, we performed a separate analysis of the spectra taken before and after May 2015. This is because on that date the vacuum vessel that contains the spectrograph was opened to upgrade the fibre link (Lo Curto et al. 2015), creating a discontinuity in the RV and index values, which necessitates of calculating an offset between the “Pre-2015” and “Post-2015” values. The instrument used for the wavelength calibration was a Thorium-Argon lamp (Lovis & Pepe 2007), which provides a large number of spectral lines distributed in the visible spectral range of HARPS. For the most recent data, we used an ultra-stable Fabry-Perot interferometer (Wildi et al. 2010), which provides the best short-term accuracy in radial velocity determination from the instrument.

HARPS-N is the northern counterpart of HARPS. This instrument was installed in 2012 at the 3.6 m Telescopio Nazionale Galileo (TNG) in Roque de los Muchachos Observatory, Spain (Cosentino et al. 2012). It has the same resolution as HARPS, similar wavelength coverage and is also contained in a vacuum vessel to minimize the temperature and pressure variations that may cause spectral drifts. The spectra used were taken between July 2014 (BJD=2456841.5) and October 2017 (BJD=2458038.4) with the same exposure time used in HARPS. The wavelength calibration was also done using a Th-Ar lamp.

CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs) is a second generation echelle spectrograph installed in 2015 at the 3.5 m telescope in Calar Alto Observatory, Spain (Quirrenbach et al. 2018). This instrument has two different channels that work simultaneously in the visible and near-infrared, and it is mainly focused on searching for low-mass planets in the habitable zones of late-type stars. The spectra we use were acquired between February 2016 (BJD=2457222.7) and October 2017 (BJD=2458032.3). The calibration method is similar to the one used in HARPS, along with simultaneous Fabry-Perot exposures and a daily calibration using Th-Ne, U-Ar and U-Ne lamps (Quirrenbach et al. 2018).

UVES (Ultraviolet-Visual Echelle Spectrograph) is a high-resolution optical spectrograph installed in 2000 at the 8.2 m VLT in Paranal Observatory, Chile (Dekker et al. 2000). The spectra used in this work were taken between April 2003 (BJD=2452743.4) and October 2005 (BJD=2453658.0). These spectra were acquired using an image slicer, with an effective slit width of 0.3 arcsec that gives a resolution of ~130 000. UVES data are calibrated using the standard Th-Ar lamp, and in addition, accurate RVs are extracted thanks to an additional calibration based on an Iodine Cell, which provides many absorption lines on top of the target spectrum in some spectral regions. This makes some parts of the spectra not useful to measure for instance certain chromospheric indexes like the Na I D.

HIRES (High-Resolution Echelle Spectrometer) is a first generation echelle spectrograph installed in 1996 at the 10 m Keck telescope in Mauna Kea Observatory, USA (Vogt et al. 1994). The spectra used were collected between August 2004 (BJD=2453237.9) and September 2014 (BJD=2456908.7). The wavelength calibration was done in a similar way as for the UVES spectra, i.e. inserting the iodine Cell in the light beam with the aim of improving the RV precision.

PFS (Carnegie Planet Finder Spectrograph) is a high-resolution optical echelle spectrograph installed in 2009 at the 6.5 m Magellan II telescope in Las Campanas Observatory, Chile (Crane et al. 2010). The spectra we use were taken between August 2011 (BJD=2455791.6) and August 2016 (BJD=2457615.6). The wavelength calibration method is the same as the one used in UVES and HIRES.

The APF (Automated Planet Finder) consists of a 2.4 m telescope with the Levy Spectrometer commissioned in 2013 at the Lick Observatory, USA (Vogt et al. 2014). The spectra we use were acquired between July 2013 (BJD=2456504.7) and March 2016 (BJD=2457478.0). This instrument has a similar optical configuration to PFS, and also uses an Iodine Cell to make the wavelength calibration.

2.2 Photometric Dataset

For the photometric analysis, we relied on data taken with four different sources. Archival publicly available data come from the ASAS survey, which has a time base of several years:

ASAS (All Sky Automated Survey) consists of two automated observing stations at Las Campanas Observatory, Chile (ASAS-S or ASAS-3), and Haleakalā Observatory, USA (ASAS-N or ASAS-3N) (Pojmanski et al. 1997). These two stations observe simultaneously in the V and I photometric bands with an average accuracy of ~0.05 mag per exposure. They are complemented with the ASAS-SN (All-Sky Automated Survey for Supernovae) project (Shappee et al. 2014), which consists of 20 telescopes distributed around the globe that are automatically surveying the entire available sky every night down to V ~ 17 mag. Data from the ASAS-S and ASAS-SN were retrieved from its public database2, while data from ASAS-N were supplied by M. Kirkaga (priv. comm.), as they have not yet been made public. We thus collect 836 epochs (measurements averaged to one per night) from this survey (coming from ASAS-N, ASAS-S, and ASAS-SN) that were taken between September 2002 (BJD=2452524.6) and October 2017 (BJD=2458032.7).

Our own data comprise the second longest dataset of all, after ASAS, coming from the Four College Automated Photoelectric Telescope (FCAPT) and the Robotically-Controlled Telescope (RCT), with a time span covering 14.5 years:

The FCAPT is a 0.75 m automated telescope installed at the Fairborn Observatory (USA) that provides differential Strömgren uvby, Johnson BV, and Cousins RI photometry of a wide variety of stars (Adelman et al. 2001). RCT is a 1.3 m telescope installed at the Kitt Peak National Observatory (USA) that includes a UBVRi broadband filter set and is focused on observing faint objects such as brown dwarfs (Gelderman 2001). The combined dataset from these two instruments is composed by 348 epochs, acquired in the V Johnson filter, which were taken between May 2003 (BJD=2452764.0) and June 2017 (BJD=2457922.8).

In addition, we orchestrated a joint photometric follow-up campaign for Barnard’s Star, quasi-simultaneous to its

2 http://www.astrowa.edu.pl/asas/
Doppler observations acquired as part of the Red Dots 2017 (RD2017) campaign, designed to search for planet signatures around our closest M dwarf neighbors. The participating observatories were:

The Sierra Nevada Observatory (SNO, Spain), whose data come from the 0.9 m telescope (T90) that is equipped with a CCD camera VersArray 2Kx2K with a 13.2x13.2 arcmin$^2$ field of view. We work with 69 epochs from this telescope that were taken since May 2017 (BJD=2457887.6) until October 2017 (BJD=2458042.3), quasi-simultaneous to the RD2017 campaign. We collected about 30 measurements per night in each in $B$, $V$, and $R$ Johnson filters, accounting for a total of about 2000 observations in each filter.

The Montsec Astronomical Observatory (OAdM, Spain), whose data come from the Joan Oró robotic telescope (TJO) that is equipped with a CCD Andor DV936N-BV camera with a 12.3x12.3 arcmin$^2$ field of view. We work with 72 epochs from this telescope that were taken since June 2017 (BJD=2457920.5) until October 2017 (BJD=2458050.3), quasi-simultaneous to the RD2017 campaign. A minimum of 5 measurements was done per night, to finally obtain a total of about 700 images in two filters ($R$ and $I$). As the majority of photometric data were acquired in the $V$ filter, we do not include the OAdM dataset in the final analysis. Although data in other filters were checked for consistency purposes.

Following the outreach spirit of the Pale Red Dot campaign (Anglada-Escudé et al. 2016), our desire was that the RD2017 campaign involved as many members of the public as possible. Thus, in addition to the setup of the RD2017 website and social media for the campaign, we requested support from the AAVSO (American Association of Variable Stars Observers) and issued an AAVSO alert with a call for support from the AAVSO (USA) and Cerro Tololo Inter-American Observatory (Chile) (Berta et al. 2012). Each array consists of eight identical telescopes with a 0.4 m primary mirror that focuses the light onto a high-grade CCD camera with a broad RG715 nm filter. We work with 161 epochs from this survey that were taken since February 2013 (BJD=2454876.0) until October 2015 (BJD=2457323.6). The large mean error in this dataset indicates that the measurements had a large intra-night scatter, but once consolidated into nightly averages, the scatter of the whole run decreased to 6.5 mmag, indicating that there were not large differences from night to night observations. We did not combine this dataset with the rest of the time-series because it was taken with a filter that did not match the $V$ Johnson filter used in the other datasets.

The properties of all of these photometric sources are shown in Table 3, including the mean error of the averaged nights, which indicates the scatter of the measurements within the night, giving an idea of the quality of the nights; and the RMS of the run, which gives a measure of the night-to-night stability. We mark in boldface the selected datasets that we used for the analysis presented in this paper (using the $V$-filter time-series in each case).

All photometric data (except for ASAS and MEarth) were reduced with standard procedures including bias and/or dark subtraction and flat-field correction. Several apertures were tried to extract the best aperture photometry that maximized the signal-to-noise ratio (SNR). Differential magnitudes were obtained with respect to nearby comparison stars that had previously been checked for stability and, in the case of observations taking place during the RD2017 campaign, agreed upon, so that the different photometric datasets were as uniform and comparable as possible.

3 METHOD

3.1 Determination of Stellar Activity Indicators

In order to measure activity indices, we first correct all the spectra for the blaze function. In the case of HARPS and HARPS-N we use a specific blaze spectrum, and for the other spectrographs we fit a second order polynomial to each order to create an artificial blaze spectrum.

Next, we correct for the pixel size variability in wavelength, which requires to re-binning the spectra to obtain a constant step in wavelength between pixels and also to correct accordingly the flux evaluated in the selected wavelength step (0.01 Å). Then we correct the wavelength for the barycentric velocity of the Earth and the radial velocity of the star. Both velocities are available in the header of the

[^3]: [https://reddots.space/](https://reddots.space/)
Table 3. Properties of the photometric data.

| Observatory/ | Aperture | Filter | Error | RMS   |
|-------------|----------|--------|-------|-------|
| Survey/     | [m]      | [mmag] | [mmag]|
| Telescope   |          |        |       |       |
| ASAS-3      | 0.07     | V      | 10.3  | 17.0  |
| ASAS-3N     | 0.10     | V      | 13.0  | 16.1  |
| ASAS-SN     | 0.14     | V      | 5.2   | 8.3   |
| Combined    |          | V      | 10.4  | 16.8  |
| ASAS        |          |        |       |       |
| FCAPT &     | 0.80, 1.30| V      | 4.9   | 11.2  |
| RCT         | 0.40     | RG715  | 16.5  | 6.5   |
| SNO         | 0.90     | B      | 4.5   | 5.4   |
|             |          | V      | 4.4   | 6.4   |
|             |          | R      | 5.8   | 5.3   |
| OAdM        | 0.80     | R      | 7.2   | 9.6   |
|             |          | I      | 8.4   | 8.8   |
| AAVSO       | Range    | V, BRIHa | 15.1  | 8.9   |
| LCO         | 0.40     | V      | 16.0  | 30.5  |
|             |          | r'     | 31.1  | 45.2  |
|             |          | i'     | 91.4  | 75.6  |
| ASH2        | 0.40     | OIII   | 14.1  | 7.1   |
|             |          | Hα     | 23.9  | 12.5  |
|             |          | [SII]  | 16.8  | 9.5   |

Columns: Observatory, survey or telescope; telescope aperture; filters; mean error of the nights and RMS of the run (see the text for details).

HARPS, HARPS-N, and CARMENES spectra. In the case of HIRES, APF, PFS, and UVES, we calculate the barycentric velocity using the equatorial coordinates (RA and Dec) and the Julian day (BJD), and we use an estimated value of -110.25 km/s for the radial velocity (obtained by averaging the HARPS and HARPS-N header values). Finally, we build an average spectrum and use the individual spectra to calculate the weights of each echelle order involved in the index.

Once all the spectra have passed through this process, we can measure the three activity indices. The first one is the Hα index, which we define as:

$$Hα = \frac{A}{L + R}$$  \hspace{1cm} (1)

where $A$ is a rectangular passband centered at the core of the Hα line (6562.808 Å) with a width of 1.6 Å, and $L$ and $R$ are the continuum bands centered at 6550.870 and 6580.310 Å respectively, with a width of 8.75 Å (Gomes da Silva et al. 2011). Fig. 1 shows this spectral region for the seven spectrographs in which it is possible to measure this index.

The second one is similar to the S-index related to the CaII H & K lines (Noyes et al. 1984), that we call CaHK index and define as:

$$S = \frac{H + K}{R + V}$$  \hspace{1cm} (2)

where $H$ and $K$ are triangular passbands for the core of the lines (centered at 3968.470 and 3933.664 Å, respectively) with a full width at half maximum (FWHM) of 1.09 Å. In this work we have shifted the continuum filters of $R$ and $V$ from 4001.070 and 3901.070 Å, to 3976.5 and 3925.5 Å, respectively, and also modified the width of both filters from 20 to 3 Å, in order to use narrower spectral regions near the core of the lines located in the same echelle orders as those lines. These continuum bands allow us to avoid the overlap between different echelle orders in all of the spectrographs. Fig. 2 shows this spectral region for the four spectrographs in which it is possible to measure this index.
Figure 3. Normalized one-dimensional spectra taken with five spectrographs. The Na I D$_1$ and D$_2$ bands are marked in pink and green respectively, the continuum passbands are marked in yellow and violet and the continuum region used for the index error is marked in grey.

The last activity indicator is the Na I D index (Díaz et al. 2007), which we define as:

$$N = \frac{D_1 + D_2}{L + R}$$

where $D_1$ and $D_2$ are rectangular passbands for the core of the sodium doublet lines (centered at 5895.92 and 5889.95 Å, respectively) with a width of 1 Å. $L$ and $R$ are the continuum bands that are usually centered at 5805.0 and 6090.0 Å, with a width of 10 and 20 Å, respectively, but in this work we shifted them to 5881.5 and 5902.5 Å. We also modified their widths to 12 Å for the same reason as the one used for the CaHK index. Fig. 3 shows this spectral region for the five spectrographs in which it is possible to measure this index.

The uncertainties of the three indices were determined through error propagation (Taylor 1982), using the RMS in the error region marked in grey in Fig. 1, 2 and 3 as the error for the bands $A$, $L$, $R$, $H$, $K$, $V$, $D_1$ and $D_2$.

We also used the cross-correlation function (CCF) computed by the HARPS, HARPS-N, and CARMENES pipelines to estimate the FWHM as an additional activity indicator. We computed an average CCF as we did with the spectra, using individual weights for each echelle order. Then we cut the CCF to a width of 25 pixels and used a Gaussian+second-order-polynomial fit to obtain the FWHM. In Fig. 4 four CCF fits are shown, one per spectrograph, along with their residuals.

Once we had the measurements from all the spectra, we computed the weighted average per night, discarding those values that are beyond 2σ from the median index. We also discarded values with errors beyond 3σ from the median error. In some cases, we made these two conditions more restrictive to remove outliers. These outliers may be associated in some cases with flares, a phenomenon already detected in Barnard’s Star (Paulson et al. 2006), though occurring rarely due to its advanced age. We also applied this treatment to the photometric data, in which we already had a set of magnitudes measured with different instruments. This process gave the final number of datapoints shown in Table 4 for the four spectroscopic indices and the photometric magnitudes.

The relative offsets between instruments were calculated for each index separately. We divided the spectroscopic data into two separate blocks: the first one included HIRES, HARPS-Pre2015, PFS, APF, and UVES; and the second one included HARPS-Post2015, HARPS-N, and CARMENES. We used time windows of 10 days for spectrographs of the same block, and 30 days for spectrographs of different blocks. We determined the difference between the values contained in these windows and averaged all of them to obtain the offset. For the photometric data, we only used one block of instruments due to the long-time coverage of surveys like ASAS. These offsets are shown in Table 5.

After applying these offsets we get the time-series (of each spectroscopic index and photometric magnitude) shown in Fig. 5.

Table 4. Number of measurements used for every index after the selection criteria were applied.

| Instrument        | $H$ | $N_{\text{meas}}$ | $NaD$ | FWHM | $m_V$ |
|-------------------|-----|------------------|-------|------|-------|
| HARPS-Pre2015     | 109 | 110              | 115   | 115  | ...   |
| HARPS-Post2015    | 66  | 66               | 63    | 60   | ...   |
| HARPS-N           | 40  | 39               | 39    | 38   | ...   |
| CARMENES          | 182 |                  | 161   | 174  | ...   |
| HIRES             | 123 | 123              |       |      | ...   |
| APF               | 44  | 46               | 42    |      | ...   |
| PFS               | 33  |                  | 28    |      | ...   |
| UVES              | 21  |                  |       |      | ...   |
| ASAS              |     |                  |       |      | 830   |
| FCAPT-RCT         |     |                  |       |      | 344   |
| AAVSO             |     |                  |       |      | 148   |
| SNO               |     |                  |       |      | 68    |
| Combined          | 618 | 384              | 448   | 387  | 1390  |

Figure 4. CCFs obtained for a single observation of three different spectrographs along with their respective residuals.
Table 5. Offsets between spectral and photometric indices datasets from different instruments.

| Instruments             | Hα Offset   | CaHK Offset | NaD Offset | FWHM Offset [km/s] | $m_V$ Offset [mag] |
|-------------------------|-------------|-------------|------------|-------------------|-------------------|
| HIRES-HARPSpre         | 0.00188 ± 0.00004 | 0.924 ± 0.003 | ...        | ...               | ...               |
| HIRES-PFS              | 0.01357 ± 0.00005 | ...         | ...        | ...               | ...               |
| HIRES-APF              | -0.0245 ± 0.0008  | -1.86 ± 0.09 | ...        | ...               | ...               |
| HIRES-UVES             | 0.05624 ± 0.00006 | ...         | ...        | ...               | ...               |
| CARMENES-HARPSpost     | -0.00154 ± 0.00002 | ...        | -0.00634 ± 0.00004 | 0.13034 ± 0.00001 | ...               |
| CARMENES-HARPSN        | -0.03556 ± 0.00003 | ...        | -0.00354 ± 0.00004 | 0.20647 ± 0.00001 | ...               |
| HARPSpre-HARPSN        | ...          | -0.514 ± 0.004 | ...        | ...               | ...               |
| HARPSpre-PFS           | ...          | ...         | 0.0250 ± 0.0002 | ...               | ...               |
| HARPSpre-APF           | ...          | ...         | -0.075 ± 0.002 | ...               | ...               |
| ASAS-FCAPT+RCT         | ...          | ...         | ...        | -0.00870 ± 0.00002 | ...               |
| ASAS-AAVSO             | ...          | ...         | ...        | -0.01531 ± 0.00002 | ...               |
| ASAS-SNO               | ...          | ...         | ...        | -0.011340 ± 0.000007 | ...               |

Figure 5. Time series of the four spectroscopic indexes and the $V$ photometry with their respective offsets applied. The NaD plot contains a legend with all the spectrographs and the FWHM plot contains a legend with the instruments used for the photometry analysis.

3.2 Time Series Analysis

We carry out a time-series analysis of the three spectroscopic activity indicators, the CCF FWHM and the $V$-band photometry using the Lomb-Scargle periodogram (Lomb 1976) in its generalized form (Zechmeister & Kürster 2009), in which each value has an independent error. We also analyze
The double sinusoidal fit is defined as:

\[ z(\omega) = \frac{N - 3}{2} \cdot \rho(\omega) = \frac{N - 3}{2} \cdot \frac{\chi^2(\omega) - \chi^2}{\chi^2} \]  

(4)

where \( N \) are the degrees of freedom and \( \chi^2 \) is the squared difference between the data and the model for a certain frequency \( \omega \), calculated as:

\[ \chi^2 = \sum_{i=1}^{N} \frac{(y_i - y(t_i))^2}{\sigma_i^2} \]  

(5)

The False Alarm Probability Alarm (FAP) (Horne & Baliunas 1986) associated with every point in the periodogram is calculated with the following expression (Cumming 2004):

\[ FAP = 1 - [1 - P(z > z_o)]^M = 1 - [1 - e^{-z_o}]^M \]  

(6)

where \( z \) is the real power of a point in the periodogram, \( z_o \) is the measured power, \( M \) is the number of independent frequencies used in the periodogram, and \( P(z > z_o) \) measures the probability of \( z \) being greater than \( z_o \). Using Eq. (6) we established a first approximation of the 10%, 1% and 0.1% levels of FAP for the periodograms. To obtain more precise values of these levels we applied a bootstrapping method (Endl et al. 2001). This method implies re-arranging the time order of the indices values 10000 times, searching for the period with the highest significance in every iteration to determine which values are obtained 10%, 1% and 0.1% of the times.

In Fig. 6 we show the periodograms for the four spectroscopic indexes and the V magnitude using the time-series from Fig. 5 (which includes all the instruments used with their respective offsets, except in the case of the photometric time-series, where we did not use the FCAPT-RCT dataset for reasons that will be discussed later) with the FAP Levels from bootstrapping.

We first carried out a pre-whitening process for a single instrument. We started calculating the periodogram with the FAP levels from bootstrapping. We selected a signal from the periodogram (usually the most significant one) and modelled it with a double sinusoidal fit to subtract that signal and, thus, recompute the periodogram (Boisse et al. 2011). The double sinusoidal fit is defined as:

\[ y(t) = A_1 \cdot \sin(\omega_1 + \phi_1) + A_2 \cdot \sin(\omega_2 + \phi_2) + A_3 \]  

(7)

where \( \omega_2 = 2 \omega_1 = 2 \pi f / P \). We left \( A_1, A_2, A_3, \phi_1, \phi_2 \) and \( P \) as free parameters, restricting the value of \( P \) in a 15% from the original period in the periodogram. The reason for using this double sinusoidal model is to account for the asymmetry of some signals (Berdyugina & Järvinen 2005) with the MPFIT routine (Markwardt 2009). After subtracting this first signal, we repeated the process until we had no more significant signals in the periodogram.

Then we isolated each individual signal from the rest of signals that we subtracted along the pre-whitening process. We selected one at a time and used the frequencies from the rest to make a model. The subtraction of this model gave us an isolated periodogram, where we can check that the original period was not caused by effects of the other signals. We obtain this isolated periodogram for every single signal that was detected along the pre-whitening process.

Once we carried out this process for one single instrument, we added a second instrument with its respective offset and repeated the modeling-subtraction-isolation method, because the information provided by a single instrument may not be enough in terms of time-span or sampling. The addition of instruments follows the order shown in Table 6. When we combined two different blocks of instruments, we needed to estimate an additional offset using a wider time window (30 days). These offsets are also shown in Table 6.

4 ANALYSIS

4.1 Hα index

This method was applied to each individual index. In the case of Hα we obtained 618 measurements, characterized by an average of 0.48, mean error of 0.001, and RMS of 0.01. We began analyzing the HIRES dataset (in the HIRES-Red configuration), and then added individually HARPS-Pre2015, PFS, APF, and UVES. After every addition, we used the
Stellar activity analysis of Barnard’s Star

Table 6. Addition order of spectrographs for each individual index and offsets between spectral indices datasets from different blocks of spectrographs.

| Index  | Block | Spectrograph                   | Offset       |
|--------|-------|--------------------------------|--------------|
| Hα     | 1     | HIRES-HARPSpre-PFS-APF-UVES    | 0.0143 ± 0.0002 |
|        | 2     | CARMENES-HARPSpost-HARPSN      |              |
| CaHK   | 1     | HIRES-HARPSpre-APF             | 1.03 ± 0.09  |
|        | 2     | HARPSpost-HARPSN               |              |
| NaD    | 1     | HARPSpre-PFS-APF               | 0.1033 ± 0.0008 |
|        | 2     | CARMENES-HARPSpost-HARPSN      |              |
| FWHM   | 1     | HARPSpre                       | -0.153371 ± 0.000006 |
|        | 2     | CARMENES-HARPSpost-HARPSN      |              |

Figure 7. **Top:** Periodograms of the time-series of Hα for HARPS+HARPSN+CARMENES+HIRES+APF+PFS+UVES spectra after the trend correction. **Bottom:** Periodogram of the residuals after the subtraction of the 143 days period signal.

modeling-subtraction technique to see which signals are hidden behind the main ones. We repeated this treatment for the second block of instruments, beginning with HARPS-Pre2015 and adding HARPS-N and CARMENES in that particular order. When we combined the two blocks, the periodogram of the data gives a 7692 days signal as the second most significant peak after the ∼140-150 days peak (see the first periodogram of Fig. 6). To see if this signal was caused by any instrumental effect, we applied a trend correction to the whole dataset, and this signal disappeared, as it is shown in the top of Fig. 7.

After the trend correction, the most significant peak is at 143 days, which is close to the rotation period predicted by Suárez Mascareño et al. (2015). This signal is surrounded by multiple peaks between 130 and 177 days with low FAP. We note that the baseline of the observations is much longer than the expected lifetime of spots and plages on the surface of the star. These magnetic phenomena can occur at different stellar latitudes, favoring these multiple peaks around the rotation signal (see Section 5). In the second periodogram of Fig. 7, the second signal detected, after the subtraction of the 143 days signal (modeled by a double sinusoidal), has a 149 days period with a FAP between the 10% and 1%

Figure 8. **Top:** Periodogram of the time-series of Hα index after the subtraction of the 149 days period signal. **Bottom:** Phase-folded curve of the Hα time-series using the 143 days period. Each spectrograph has been represented with a different color, following the legend in Fig. 5. The green line represents the best double-sinusoidal fit found by the MPFIT routine.

To complement this analysis, we introduce one jitter term for every single spectrograph in the double sinusoidal model and we change the independent term ($A_3$) for a linear trend term ($A_3 + A_4 \cdot t$), which leads to a very similar pre-whitening process shown in the Fig. 9. In this case, the second signal to be detected is at 177 days with a FAP close to the 10% level, and may also be related with differential rotation. The forest of peaks around the rotation period in the residuals is similar to the one shown in the bottom panel of Fig. 7, giving us a rotation range between 130 and 180 days.

4.2 Ca II HK index

In the time-series of the CaII HK index, the blue arm spectra of UVES, where the calcium lines are located, was not available. The CARMENES wavelength coverage did nei-
ther include the Ca II H&K spectral range, and therefore it was not used. We also omitted PFS due to the high noise in that wavelength range. Therefore, we had 384 measurements of this index coming from HARPS, HARPS-N, HIRES and APF, with an average of 4.63, mean error of 0.06, and RMS of 0.6. Owing to the new continuum filters introduced in this work, we did not use the Mount Wilson calibration (Vaughan et al. 1978) for this index. Using the four time-series with their respective offsets and without any calibration, we first detected a 3225.8-day signal that remains stable after the trend subtraction, as it is shown in Fig. 10. This long-period signal may be related to a long-term activity cycle in the star. It has a FAP level above the 0.1% and its fitted by the double sinusoidal shown in Fig. 11 that includes jitter terms and has an amplitude of $0.7 \pm 0.2$. When we subtract this model, we obtain a 84-day period signal with low significance that seems to be dependent on the model that we used to subtract the long-term signal. For different models, we obtain different peaks in the range of $\sim 80$ to 200 days, so we could not ensure that any of the signals are indeed stellar activity signals. We also could not find a clear signal associated with the expected rotation in the analysis of the CaHK index.

4.3 Na I D index

The time-series measurements of the Na I D index do not include HIRES data because we could not get a reliable wavelength calibration for the echelle orders that contains the core lines and the continuum regions. We also avoid using UVES due to the lower SN ratio in those orders. This leaves 448 measurements with an average of 0.19, mean error of 0.01, and RMS of 0.02. When we treat this time-series and combine the two blocks of instruments we obtain the first periodogram shown in Fig. 12. We found a signal at 164 days surrounded by a forest of peaks similar to the one found in Hα that could be associated with the rotation of the star. The difference in period with respect to the detected signal in the Hα index suggests that this signal could be caused by differential rotation. In the Sun, for instance, the rotation period can vary from the equator (25 days) to the pole (35 days) in 40%. From a sample of more than 24 000 active Kepler stars, Reinhold et al. (2013) found evidences of differential rotation within the 30% of the equatorial rotation period in 77 % of the sample. In this case, the variation from the original period measured in Hα to the one measured in Na I D is only 15%. This signal has an amplitude of $0.008 \pm 0.001$ and its FAP grows near the 0.1%. When we subtract this signal with the double sinusoidal model shown in Fig. 13, the rest of the peaks remains between the 0.1% and 10% level of FAP, and they may be caused by the offsets between spectrographs, so no more clear information was extracted from this index.
4.4 Full width half maximum

Finally, the time-series of the FWHM, consists of 387 measurements, with an average of 4.52 km/s, mean error of 0.00005 km/s, and RMS of 0.006 km/s. We first apply a trend correction to the HARPS-Pre2015 values due to a focus drift problem. We also noticed a highest dispersion in the CARMENES values (see Fig. 5) that may be related with the lack of weights per order in this spectrograph (the CCFs that we have used were already built as a one average function). The combination of the three spectrographs for which we have a CCF leads to a tentative detection of the rotation period at 150 days with a FAP level close to the 0.1%, as it is shown in Fig. 14. In this case, the signal its fitted by the double sinusoidal shown in Fig. 11 with an amplitude of 0.00355 ± 0.00006 km/s. After subtracting this first peak with a double sinusoidal including jitter terms and a global trend, the remaining peaks do not exceed the 10% level of FAP, making it difficult to establish a clear origin for them.

4.5 Photometry

We complement our spectroscopic analysis using the time-series of V-band photometric measurements. A higher number of data points are available (1390) compared to the spectroscopic dataset (618 as maximum), with an average of 9.5 mag, mean error of 9.2 mmag, and RMS of 15.4 mmag. We begin by analysing the largest dataset (ASAS), combining the ASAS-S and ASAS-N time-series.

As it is shown the top panel in Fig. 16, we find the first signal at 3703.7 days, which may be related to a long-
term activity cycle in the star. After the subtraction of this signal with a very high amplitude (0.012 ± 0.004 mag), the rest of the peaks in the periodogram remain under the 10% level of FAP, with the rotation period at 141 days being the second signal in amplitude. The addition of the ASAS-SN dataset produces a shift in the peak of the long-period signal to 3846 days, increasing its amplitude, and also producing an increase in the FAP levels from the bootstrapping.

When we add the rest of the datasets (except FCAPT-RCT) and determine the offsets using ASAS as reference, we recover the long-term activity cycle signal at 3846 days signal present in the complete ASAS dataset as it shows the first periodogram of Fig. 17, where the bootstrapping process to obtain the FAP levels was done omitting the ASAS-SN data. The double sinusoidal model that includes jitter terms and a linear trend presents an amplitude of 0.012 ± 0.006 mag, and its subtraction produces the periodogram shown in the bottom panel of Fig. 17, where the peak with the highest amplitude is a signal at 438.6 days with very low significance.

The addition of the FCAPT-RCT dataset (see Fig. 18) creates a broad and signal at 204.5 days as the most significant one. After the subtraction of this first signal, we recover the long-term activity cycle signal at 3846.2 days obtained in previous time-series with an amplitude of 0.009 ± 0.008 mag. This signal is shown in Fig. 18, where the periodicity of the cycle is even more clear than in the time-series of the CaHK index due to the higher number of points. The FAP values come from the bootstrapping process carried out omitting the ASAS-SN and FCAPT-RCT values.

The problem with the FCAPT-RCT dataset is the high amplitude of the noisy 204.5 days period signal, which produces high FAP values from the bootstrapping process that can make the long-term activity cycle signal be confused with noise because it does not reach the 10% level of FAP. This signal and these high FAP values may be caused by the offset between the FCAPT and RCT datasets, which are also separated in time by ~ 8 years. The same happens between the ASAS-S+ASAS-N and ASAS-SN dataset, with a gap of more than 1 year between them, but in this case the increment is not so remarkable. We maintain the ASAS-SN time-series in the analysis because is needed to obtain the offset values using the time windows methodology and the FCAPT-RCT time-series because it increases the $m_V$ amplitude of the long-term activity cycle signal.

In the separate analysis of Montsec and MEarth timeseries, we do not detect any significant signal that could be attributed to rotation or a long-term activity cycle, although MEarth has proven to be capable of detecting rotation period Newton et al. (2016).

4.6 Chromatic index and Bisector span

We also did an additional analysis using the time-series of the chromatic index (CRX) that contains 216 measurements.
taken by CARMENES in a 2-year time span. This activity indicator was defined by Zechmeister et al. (2018) and it serves to measure the RV-wavelength dependence. The CARMENES pipeline correlates these two quantities along all the echelle orders and then fits a first-order-polynomial whose slope is taken as a measurement of the CRX.

In the time-series of this index, we first did a trend correction to get rid of an artificial 10000 day-signal. After the correction, the FAP of the most significant signal is above 10%, so we could not find anything relevant in this time-series.

We also analyzed the bisector span time-series (BIS), an index that comes from the slope of the polynomial that fits the centroid of the CCF at different heights Queiroz et al. (2001). The BIS time-series is composed by 116 measurements of HARPS-N, 31 of HARPS-N and 186 of CARMENES. This index measures the distortion of the CCF under the presence of stellar spots and plages. This distortion is lower in fast rotators and low activity stars. As for the CRX index, we could not find any significant signal in the analysis of the BIS time-series.

5 DISCUSSION

Combining the rotation period from Hα, FWHM time-series we obtain a final average value of 145 ± 15 days. We establish a 10% error due to the uncertainty in the latitude of the active regions that are producing the 145-day signal. The differential rotation may be responsible for the different signals found in between 130 to 180 days, as a consequence of the presence of active regions at different latitudes of the stellar surface. This means that Barnard’s Star is one of the main sequence stars with the lowest rotation known to date, below the M-stars average periods (Suárez Mascareño et al. 2018b).

We detected two similar long period signals, in the Ca II H&K and m\text{v} time-series. The two signals show similar periodicities, both compatible with the length of a solar-like cycle. When we compare the two series side by side (see Fig. 19) we can see even more similarities. Not only their periodicities, both compatible with the length of a solar-like cyclic nature. We can interpret this variability as the foot-print of a magnetic cycle of 10 ± 2 years, which is not expected for a completely convective star like Barnard’s Star (Chabrier & Kürster 2006; Wargelin et al. 2017).

It is interesting to note that the position of the maximum emission phase coincides with the position of the faintest phase of the star and the minimum emission phase coincides with the brightest phase of the light-curve. Given the low level of chromospheric and X-ray emission of Barnard’s Star (Passegger et al. 2018), this behaviour is opposite to the solar case, and to most old FGK stars (Radick et al. 1998). It would be compatible with a spot-dominated stellar surface, typical of active FGK stars. In active stars, spots dominate the brightness changes, while plages would dominate chromospheric and X-ray emission. The situation is similar to what Wargelin et al. (2017) found for the case of Proxima, when comparing V-band photometry to X-ray and UV emission. Despite being old, Proxima remains quite active (Pavlenko et al. 2017), which made it natural to put in on the “active stars” category. The case of Barnard is quite different, as the star shows very low levels of chromospheric and X-ray emission. This could hint at late M-dwarfs keeping the “active star” behaviour, and remaining spot dominated, even after their chromospheric and X-ray emission reach extremely low levels.

Given our short baseline, the exact period and long-term behaviour are still complicated to assess. Further monitoring spectroscopic and photometric would be needed to better characterize it.

Applying the Mount Wilson calibration to the S-index of all spectrographs by the following expression:

\[ S_{\text{mv}} = \alpha \cdot S + \beta \]  

where \( \alpha = 1.111 \), \( \beta = 0.0153 \) (Lovis et al. 2011) and \( S \) is calculated with the original passbands, we can use its mean value \( < S_{\text{mv}} > \) to calculate the level of chromospheric activity \( \log_{10}(R'_{\text{HK}}) \) as (Noyes et al. 1984):

\[ \log_{10}(R'_{\text{HK}}) = \log_{10} \left( 1.34 \cdot 10^{-4} \cdot C_{cf} \cdot < S_{\text{mv}} > - R_{\text{phot}} \right) \]  

where \( C_{cf} \) is a conversion factor to correct the flux variations in the continuum passbands and also to normalize to the bolometric luminosity, that is defined as (Suárez Mascareño et al. 2015):

\[ \log_{10}(C_{cf}) = -0.443 - 0.645(B-V) - 1.270(B-V)^2 + 0.668(B-V)^3 \] 

and \( R_{\text{phot}} \) is the photospheric contribution to the calcium.
we get an induced semi-amplitude of $K$ amplitude found by (Suárez Mascareño et al. 2017, 2018b), between the chromospheric activity level and induced RV semi-amplitude from the literature. If we use the relation between the X-ray emission and the rotation rate of stars. Using the relation found by Wright et al. (2011, 2016, 2018a,b) and Astudillo-Defru et al. (2017), to investigate the relation between the X-ray emission and the rotation period of a large sample of stars (see e.g. McQuillan et al. 2014; Newton et al. 2016; Díez-Alonso et al. 2018). We have selected a sample from Suárez Mascareño et al. (2015, 2016, 2018a,b) and Astudillo-Defru et al. (2017), to see how the values of the rotation period and the level of chromospheric activity obtained for Barnard’s Star fit into the relation found by Suárez Mascareño et al. (2016):

$$\log_{10}(R_{\text{phot}}) = (1.48 \cdot 10^{-4}) \cdot e^{-4.3658 \cdot (B-V)}$$

Eq. (9) gives a chromospheric activity level of $\log_{10}(R'_{\text{HK}})=-5.82 \pm 0.08$ using our $S_{\text{inv}}$ measurements of GJ 699 that is in good agreement with the values of -5.69 (Astudillo-Defru et al. 2017) and -5.86 (Suárez Mascareño et al. 2015) from the literature. If we use the relation between the chromospheric activity level and induced RV semi-amplitude found by (Suárez Mascareño et al. 2017, 2018b), we get an induced semi-amplitude of $K = 0.67^{+0.20}_{-0.28}$ m/s, which give us an upper limit of 0.95 m/s that marginally falls on the detection limit for most of the current instrumentation dedicated to RV searches (Pepe et al. 2014).

In the last years, several groups have studied the rotation periods of a large sample of stars (see e.g. McQuillan et al. 2014; Newton et al. 2016; Díez-Alonso et al. 2018). We have analyzed the time variability of several spectroscopic indexes (Hα, CaII H&K, NaI D, and CCF’s FWHM) in a sample of 964 spectra of Barnard’s Star taken with seven different spectrographs (HARPS, HARPS-N, CARMENES, HIRES, APF, PFS and UVES) in a time-span of 14.5 years. We also have used the available photometric time series of the star that forms a sample of 1390 measurements of photometric magnitudes coming from four different instruments (AAVSO, FCAPT-RCT, ASAS, and T90@SNO) in a time-span of 15.1 years.

We have detected the rotation period signal in the Hα and FWHM time-series at 143 and 150 days respectively, along with differential rotation between 130 and 180 days seeing also in the NaD time-series. We have also detected this signal in the $m_V$ time-series at 141 days, although with a higher level of FAP. We determine the rotation period to be $145 \pm 15$ days for Barnard’s Star. We also calculate a chromospheric activity level of $\log_{10}(R'_{\text{HK}})=-5.82$ that indicates a very low stellar activity. Using an activity-rotation relation, we obtain an expected rotation period that is in good agreement with our determination, and an upper limit to the activity induced RV signal associated to rotation of 1 m/s. Also, the low X-ray activity of the star supports our determination of the stellar rotation period.

In the CaHK and $m_V$ time-series we find evidence of a long-term activity cycle in 3226 days and 3846 days respectively, which is consistent with previous estimates of magnetic cycles from photometric time-series in other M stars with similar activity levels. We then derive a long-term activity cycle of 3800 ± 600 days for Barnard’s Star.

### Table 7. Semi-amplitude of the isolated signals from the four spectroscopic indexes and the photometric magnitude.

| Index | $P$ [days] | Semi-amplitude |
|-------|------------|----------------|
| Hα    | 143.68     | $0.00555 \pm 0.00007$ |
| CaK   | 149.25     | $0.0033 \pm 0.0001$  |
| NaD   | 322.58     | $0.7 \pm 0.2$       |
| FWHM  | 164.20     | $0.008 \pm 0.001$   |
| $m_V$ | 150.15     | $0.00355 \pm 0.00006$ km/s |

6 CONCLUSIONS

We have analyzed the time variability of several spectroscopic indexes (Hα, CaII H&K, NaD, and CCF’s FWHM) in a sample of 964 spectra of Barnard’s Star taken with seven different spectrographs (HARPS, HARPS-N, CARMENES, HIRES, APF, PFS and UVES) in a time-span of 14.5 years.

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We also have used the available photometric time series of the star that forms a sample of 1390 measurements of photometric magnitudes coming from four different instruments (AAVSO, FCAPT-RCT, ASAS, and T90@SNO) in a time-span of 15.1 years.

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In the CaHK and $m_V$ time-series we find evidence of a long-term activity cycle in 3226 days and 3846 days respectively, which is consistent with previous estimates of magnetic cycles from photometric time-series in other M stars with similar activity levels. We then derive a long-term activity cycle of 3800 ± 600 days for Barnard’s Star.
We found no evidence that the signals detected in the chromospheric activity indicators are causing the RV signal detected by Ribas et al. (2018).

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MNRRAS 000, 1–16 (2018)
### Table 8. AAVSO contributions.

| Observer code | Name            | Country | Filters | N\textsubscript{exposures} | N\textsubscript{epochs} |
|---------------|-----------------|---------|---------|-----------------------------|-------------------------|
| BJFB          | John Briol      | USA     | V       | 334                         | 13                      |
| BLOC          | Lorenzo Barbieri| IT      | V, H\(\alpha\) | 523, 59 (9)                |                         |
| CIVA          | Ivaldo Cervini  | CH      | V, H\(\alpha\) | 161, 70 (12)               |                         |
| DLM           | Marc Deldem     | FR      | V       | 2015                        | 28                      |
| DUBF          | Franky Dubois   | BE      | BVRI    | 210, 233, 188, 124 (31)     |                         |
| HBB           | Barbara Harris  | USA     | V       | 463                         | 4                       |
| HMB           | Franz-Josef Hamsch |       | BE      | 2753                        | 111                     |
| KCLA          | Clifford Kotnik  | USA     | V, H\(\alpha\) | 867, 83 (8)                |                         |
| LJBE          | Jean-Marie Lopez| FR      | V       | 446                         | 6                       |
| MMAE          | Michael McNeely | USA     | V       | 2                           | (2)                     |
| OYE           | Yenal Ogmen     | CY      | V       | 416                         | 1                       |
| PLFA          | Luis Pérez      | ES      | V       | 65                          | 1                       |
| RZD           | Diego Rodríguez | ES      | V       | 1                           | (1)                     |
| SFGA          | Fabián Sánchez Urquijo | ES | V       | 2                           | (2)                     |

**Columns:** Observer initials and name, country code (USA=United States of America; IT=Italy; CH=Switzerland; FR=France; BE=Belgium; CY=Cyprus; ES=Spain; EC=Ecuador), filters, number of exposures and number of epochs. The parenthesis in the last column indicates that the datasets were not included in the final analysis due to high scattering or insufficient number of observations.

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