A&A 600, A120 (2017)
DOI: 10.1051/0004-6361/201629429

Astronomy & Astrophysics

Further evidence for a sub-year magnetic chromospheric activity cycle and activity phase jumps in the planet host τ Boötis

J. H. M. M. Schmitt and M. Mittag

Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany
e-mail: jschmitt@hs.uni-hamburg.de

Received 29 July 2016 / Accepted 4 October 2016

ABSTRACT

We examine the S-index data, obtained in the context of the Mount Wilson H&K project for the nearby F-type star τ Boo, for the presence of possible cyclic variations on timescales below one year and "phase jump" episodes in the observed S-index activity levels, to determine whether such features are persistent properties of the chromospheric activity of τ Boo and possibly other late-type stars. Within the Mount Wilson H&K project τ Boo was observed during 1278 individual nights, albeit with a very inhomogeneous coverage ranging from 2 to 137 observations per year. Our analysis shows that periodical variations with timescales on the order of 110–120 days are a persistent feature of the Mount Wilson data set. Furthermore we provide further examples of "phase jump" episodes, when the observed S-index activity drops from maximum to minimum levels on timescales of one to two weeks, hence such features also appear to occur on a more or less regular basis in τ Boo.

Key words. stars: activity – stars: chromospheres – stars: late-type

1. Introduction

Recently the data obtained in the context of the so-called Mount Wilson H&K project have been publicly released and become available to the astronomical community at large. The hitherto most complete description of this Mount Wilson monitoring data set has been presented by Baliunas et al. (1995), who discuss the S-index "light" curves of 112 stars; one of these is τ Boo (=HD 120136), which shows, according to Baliunas et al. (1995), a chromospheric cycle of 11.6 ± 0.5 yr. τ Boo is a bright (m_V = 4.5 mag) star of spectral type F7 with an M2 type companion, which was observed several thousand times during the Mount Wilson program. In addition to the 11.6 yr cycle described by Baliunas et al. (1995) there is evidence for cyclic variability on substantially shorter timescales.

τ Boo is now one of the brightest known planet hosts. τ Boo b, a so-called hot Jupiter, was discovered by Butler et al. (1997) with an orbit period of 3.3 days, which is very close to the rotation period of τ Boo A. For these reasons and its substantial magnetic activity, the τ Boo system is very interesting also from the point of view of star-planet-interaction (SPI). Lanza (2013) describes a theoretical framework linking a magnetic interaction between star and planet and shows that such effects could significantly enhance evaporative effects due to EUV and X-ray radiation from the host. As far as τ Boo is concerned, Shkolnik et al. (2008) present Ca II K data and argue that these data may indicate SPI, however, it is probably fair to say that actual observational clear-cut demonstrations of SPI are still very elusive.

Mittag et al. (2017) describe an S-index variability of τ Boo with a timescale of about 120 days observed in the years 2013–2016 with the TIGRE facility (Schmitt et al. 2014) and show that the same period is also consistent with cyclic variability at X-ray wavelengths. Similarly, Mengel et al. (2016), using their S-index time series taken with the NARVAL instrument in the years 2007–2015, deduce a 117-day period; we identify this period with the 116-day period previously mentioned, but not described by Baliunas et al. (1997). Furthermore, based on spectropolarimetric observations with ESPaDOnS and NARVAL, subsequent Zeeman Doppler Imaging by Donati et al. (2008) provides evidence for magnetic field reversals on τ Boo; further observations of polarity changes with the same instrumental setup have been reported by Fares et al. (2009), Fares et al. (2013), and by Mengel et al. (2016), and the observed field reversals suggest a possible magnetic cycle of 240 or 740 days.

Using their TIGRE monitoring data, Mittag et al. (2017) show that the maxima of the S-index data might well be associated with polarity reversals of τ Boo as is observed for the Sun, so that the "magnetic" cycle period would be twice as large. Finally, Mittag et al. (2017) report a "phase jump" of the activity cycle of τ Boo, i.e., an episode in the spring of 2016, when the activity more or less suddenly dropped from maximum to minimum values. The purpose of this research note is to investigate to what extent similar phenomena are present in the Mount Wilson time series of τ Boo.

2. Observations and data analysis

2.1. Mount Wilson data

As already mentioned, the data obtained in the context of the Mount Wilson Project have recently been publicly released and can be downloaded[1]. A detailed description of the data is also provided at this web site. The available data specifically include the star identification; the calibrated S index, which we use in

[1] From ftp://solis.nso.edu/MountWilson_HK/

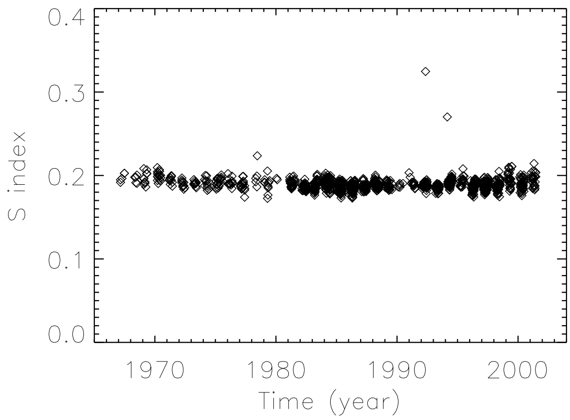

Fig. 1. Mount Wilson S-index time series of τ Boo.

this paper as the basis for our analysis; an instrument code indicating with which instrument the data was taken; and the date of the observation as well as other material.

Naturally, it suggests itself to investigate whether the star τ Boo also shows similar phenomena as observed in recent years and reported by Mittag et al. (2017) in the Mount Wilson time series. In the context of the Mount Wilson Program, τ Boo has been intensively observed for more than 30 yr and the data base lists more than 4000 entries of individual observations. However, a closer inspection of these data shows that, normally, τ Boo was observed three times per night, in a few cases even more often, and in one single night more than 100 observations had been obtained. On the other hand, especially in the early years, there is typically only one observation per night available. All observations available within a single night were averaged to obtain a more homogeneous data set and so we end up in this fashion with observations of τ Boo in 1278 individual nights spread over the years 1967–2001. In Table 1 we provide a list with the number of nights per year when τ Boo was observed. In every year between 1967 and 2001 H&K observations of τ Boo have been carried out, the number of nights varies from 2 (in 1980) to 137 (in 1984). The "light curve" produced from this data is shown in Fig. 1. One recognizes a few outliers with S-index values above 0.25, which are ignored in our subsequent analysis.

2.2. Discrete autocorrelation function

One of the methods to determine recurrent structures and periods in light curves is autocorrelation analysis. Normally one assumes data with equidistant temporal spacing, in which case the calculation of the autocorrelation for a given time lag τ is straightforward and described in every text book. In data collected in the context of ground-based astronomy (or geophysics for that matter) the recorded time series are usually irregularly sampled and hence the computation of, for example, an autocorrelation function becomes a bit more cumbersome.

While it is possible to resample a given light curve onto a regularly spaced time grid, in our opinion any application of such methods is precluded by the way astronomical data are usually sampled (for example, seasonal variations). In the context of AGN work, Edelson & Krolik (1988) introduced the so-called discrete correlation function as a method to compute cross- or autocorrelations without the need to interpolate any data. Briefly, their method works as follows: we let $s(t)$ be some function that is sampled at some (nonequidistant) times t_i, $i = 1, N$ with values

Table 1. Overview of available τ Boo Ca II H&K observations obtained in the Mount Wilson (MW) and TIGRE programs.

Year	Number of nights	Program
1967	4	MW
1968	5	MW
1969	11	MW
1970	17	MW
1971	10	MW
1972	11	MW
1973	12	MW
1974	12	MW
1975	19	MW
1976	14	MW
1977	20	MW
1978	5	MW
1979	12	MW
1980	2	MW
1981	36	MW
1982	69	MW
1983	63	MW
1984	137	MW
1985	83	MW
1986	88	MW
1987	46	MW
1988	62	MW
1989	33	MW
1990	6	MW
1991	14	MW
1992	52	MW
1993	35	MW
1994	79	MW
1995	22	MW
1996	58	MW
1997	81	MW
1998	50	MW
1999	34	MW
2000	47	MW
2001	29	MW
2014	77	TIGRE
2015	73	TIGRE
2016	88	TIGRE

$s_i = s(t_i)$. We can then consider all pairs of data points, which are characterized by some pairwise lag $\Delta t_{i,j} = t_i - t_j$; since we are dealing with autocorrelation functions (rather than crosscorrelation functions) we need to consider only positive lags (i.e., $i > j$). We let $\overline{s}$ and σ_s denote the first two moments of the distribution function of the function $s(t)$, the unbinned discrete autocorrelation function UBAF is defined as

$$\mathrm{UBAF}_{i,j} = \frac{(s_i - \overline{s}) * (s_j - \overline{s})}{\sigma_s^2}. \quad (1)$$

Edelson & Krolik (1988) point out that in the case of data with significant errors the denominator in Eq. (1) has to be modified to $\sigma_2^2 - e_s^2$, where e_s is a typical error; since in our case the intrinsic scatter of the data is much larger than the measurement errors, we use Eq. (1) as is. Each time lag pair contributes toward the estimate of the discrete autocorrelation function (DAF), which can be constructed (in binned form) as follows: to determine DAF at some lag τ, we identify all time lag pairs, satisfying $\tau - \Delta\tau/2 < \Delta t_{i,j} < \tau + \Delta\tau/2$, where $\Delta\tau$ is the spacing of the time lags where the DAF is calculated. We let there be M such pairs, then

$$\mathrm{DAF}(\tau) = \frac{\langle \mathrm{UBAF}_{i,j} \rangle}{M}. \quad (2)$$

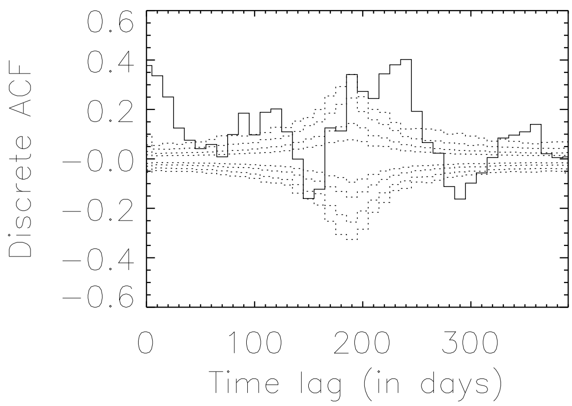

Fig. 2. Discrete autocorrelation function of Mount Wilson S-index time series (solid histogram). The dashed histograms denote the maximum values of the autocorrelation functions at the 0.67%, 90%, 99%, and 99.9% level; see text for details.

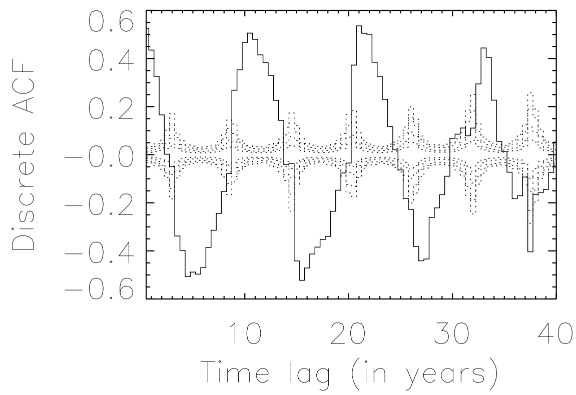

Fig. 3. Same as Fig. 2, but for solar sun spot record.

Edelson & Krolik (1988) proceed with providing some error estimates for the so-constructed function DAF(τ). We compute errors by bootstrapping the data using permuted data sets with the same temporal sampling as the original data. Performing these calculations on the Mount Wilson data of τ Boo (shown in Fig. 1), we obtain the DAF shown in Fig. 2 (solid histogram); the dashed histograms show the extent of the 10 000 bootstrapped realizations comprising 67.5%, 90%, 99%, and 99.9% of the autocorrelation values at each time lag considered. As is clear from Fig. 2, there are highly significant autocorrelations in the DAF of the Mount Wilson τ Boo data. We recognize a peak at small time lags, while periods of ≈50 days have no measurable autocorrelation. For periods of ≈120 days and ≈240 days, however, we find a non-zero autocorrelation at a significance of more than 99.99%. The autocorrelation error distribution is asymmetric and attains maximal values at about 190 days or half a year. This can be attributed to the observing pattern of τ Boo, which can be observed well from about January to August.

As a sanity check, we perform the same computations as carried out for τ Boo for the daily solar Sun spot record, available online[2]. That Sun spot record dates back to 1818, prior to that date the available daily observations are too sparse. We further note that the 198 yr since then comprise about 18 solar cycles, while the approximately 36 yr of Mount Wilson monitoring of τ Boo correspond to about 144 cycles. In order to simulate the seasonal Mount Wilson sampling we sample the solar data with the same sampling pattern as encountered for τ Boo and obtain the DACF for the Sun spot record shown in Fig. 3, which clearly shows the solar 11-yr cycle and its harmonics. So clearly, the DACF retrieves the known solar cycle from the daily sun spot data when observed with a typical astronomical sampling pattern.

2.3. Lomb Scargle analysis

In order to characterize any periodicities in the activity of τ Boo further and to identify possible changes in the periodicity pattern, we investigate the changes on shorter timescales as follows. Since τ Boo disappears behind the Sun for a few months, it is natural to group the available data into observation seasons. Following our TIGRE approach, we then consider three adjacent seasons and up in this fashion with a total of 11 periods each comprising three observation seasons. We list the dates of these observational periods and the number of nights with observations of τ Boo in Table 2. Since we are interested only in variations on short timescales, we rectified the data for each season by subtracting the respective mean for that season.

Table 2. LS period analysis in Mount Wilson data.

Time span	Number of nights	Period	Probability
1967–1970	37	too few data	n.a.
1971–1973	33	too few data	n.a.
1974–1976	45	115 day	<0.999
1977–1979	37	too few data	n.a.
1980–1982	107	114 day	>0.9999
1983–1985	283	85,112 day	>0.9999
1986–1988	196	87 day, 120 day	>0.9999
1989–1991	53	110 day	<0.997
1992–1994	166	90, 118 day	>0.9999
1995–1997	161	123 day	>0.9999
1998–2000	131	90, 121 day	>0.9999

Notes. We list the observing seasons, the total number of available nights, the identified periods and an estimate of their significance.

Zechmeister & Kürster (2009) derive a generalized Lomb-Scargle (LS) periodogram and show that the normalized power spectrum $p(\omega)$ at some frequency ω is given by the expression

$$p(\omega) = \frac{\chi_0^2 - \chi^2(\omega)}{\chi_0^2}, \tag{3}$$

where χ_0^2 and $\chi^2(\omega)$ are the values of the χ^2 statistics at frequency values of zero and ω, respectively. Given some observed data o_i ($i = 1...N$) at times t_i with errors σ_i the χ^2 statistics is calculated as usual through

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{m_i - o_i}{\sigma_i} \right)^2, \tag{4}$$

and the model values m_i at times t_i are given by

$$m_i = m(t_i) = A \sin(\omega t_i) + B \cos(\omega t_i) + C, \tag{5}$$

and Zechmeister & Kürster (2009) present an analytical solution for the best-fit coefficients A–C and, hence, the normalized power $p(\omega)$.

For the calculation of the significance of the power recorded at some frequency, we do not follow the approach by Zechmeister & Kürster (2009); rather we perform repeated permutations of the measurements while keeping the observed times

[2] For example, at the web site http://www.sidc.be/silso/datafiles

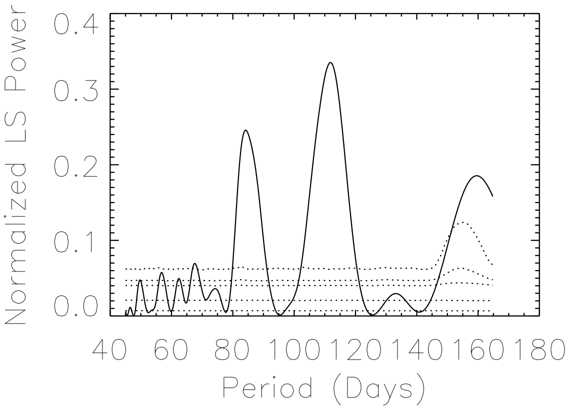

Fig. 4. Lomb Scargle diagram for the Mount Wilson τ Boo data taken between 1983–1985 (solid line); we also indicate the confidence levels of 0.675, 0.954, 0.9973, 0.999, and 0.9999, respectively.

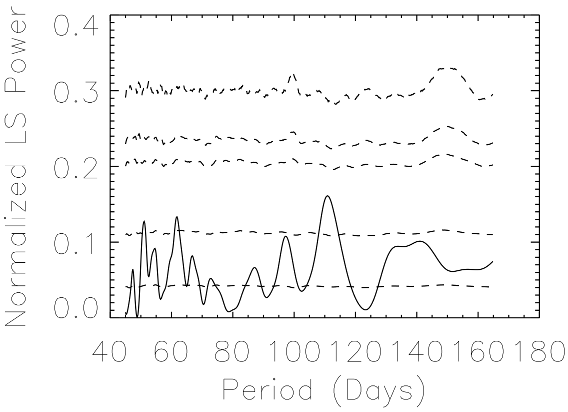

Fig. 5. Lomb Scargle diagram for the Mount Wilson τ Boo data taken between 1989–1991 (solid line); confidence levels are given as in Fig. 4.

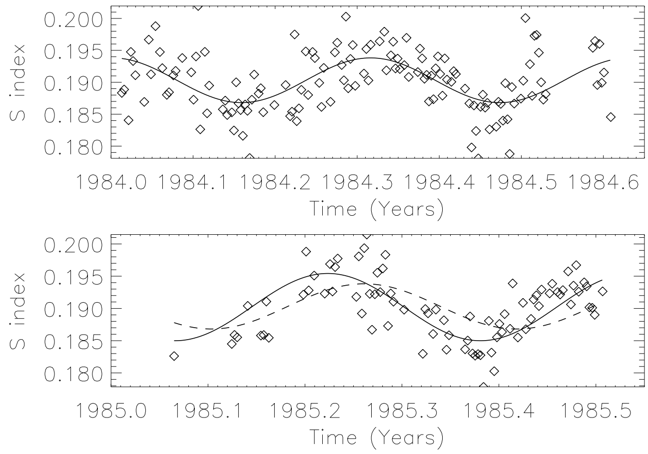

Fig. 6. Mount Wilson S-index time series in observing season 1984 (*upper panel*) and 1985 (*lower panel*). The solid lines denote best-fit sine waves; the dashed line in the *lower panel* denotes the extrapolation of the 1984 best-fit solution into 1985; see text for details.

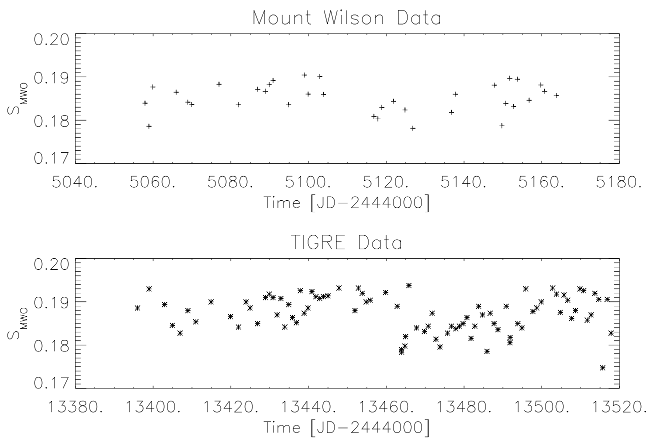

Fig. 7. Mount Wilson S-index time series in the year 1993 (*upper panel*) and TIGRE S-index time series in the year 2006 (*lower panel*); see text for details.

the same and carry out a LS analysis of the so-permuted data sets. In this fashion all biases introduced by the temporal sampling pattern of the observations are maintained for the error analysis. To compute the significance we therefore compute predetermined percentiles of the computed normalized power distributions of the permutation at each frequency under investigation.

In Figs. 4 and 5 we show two examples of our analysis. In each case we performed 1 000 000 random permutations to compute confidence levels of the derived periods. In Fig. 4 one clearly sees a highly significant signal at a period of about four months in addition to a signal at around 85 days, both of which are highly significant well above the 99.99% level. On the other hand, the peak near 160 days is probably a feature introduced by the data sampling, since also the bootstrapped periodograms show a peak near that period. In Fig. 5 again a signal near a period of about four months is apparent, however, the significance is below the formal “3σ” level. The periodogram in Fig. 4 was computed from 283 data points and that in Fig. 5 was computed from 53 data points, indicating the need for dense sampling to reach reliable conclusions on the presence of periodicities in the data.

2.4. Phase jumps

A “phase jump” episode was recorded in the TIGRE S index. In the spring of 2016 the cycle changed its phase by almost 180 degrees, jumping almost from maximum to minimum levels and thereupon rising again. It is obvious to check whether in the Mount Wilson time series there are also signatures of such phase jumps. Clearly, phase jumps can be recognized only in rather densely sampled time series. In the Mount Wilson series these are the years 1983–1986, with a particularly dense sampling available for the year 1984 with 137 different nights. The available data (in 1984) cover six months from January to June and hence cover almost two of the τ Boo activity cycles. In Fig. 6 we show a close-up view of the Mount Wilson data for the observing season 1984 (upper panel) and 1985 (lower panel); for each season we removed the trends and brought all data to the same mean value per season. For each observing season we fit a sine wave with a period of 120 days (solid lines in Fig. 6) to the data, we also propagated the best fit from observing season 1984 into observing season 1985 (dashed line in lower panel of Fig. 6). It appears that some time in the second half of 1984 a “phase jump episode” occurred that was very similar to that observed in the spring of 2016.

A second possible “phase jump episode” is visible in the Mount Wilson data taken in 1993. In upper panel of Fig. 7 we plot the Mount Wilson τ Boo S-index time series; it appears that between days 5105 and 5115, i.e., a ten-day period for which there is unfortunately no data, a jump from close to maximum to close to minimum values occurred. For comparison, in the lower panel we show the TIGRE light curve from 2016 (taken from Mittag et al. 2017), where a similar phase jump between day 13 460 and day 13 465 occurred. Therefore activity phase jumps appear to occur on τ Boo, however, the available data coverage precludes us from determining a frequency or occurrence pattern of such events.

3. Discussion and conclusion

We have inspected the data obtained for τ Boo in the context of the Mount Wilson monitoring program for the occurrence of shorter term periodicities. Specifically we investigated to what extent evidence for the four-month cycle recently described by Mittag et al. (2017) can be found in this data series. Using both the technique of discrete autocorrelation functions and the technique of Lomb Scargle periodograms, we find strong evidence for the occurrence of periodicities at a period of about 120 days or four months in these data; other shorter periods, especially at 90 days, may also be present in the data. Therefore a cycle with a period of about 120 days seems to be consistently present in τ Boo between at least 1967, when the Mount Wilson observations started and 2016 with the TIGRE observations reported by Mittag et al. (2017). These 49 yr in the life of τ Boo correspond to approximately 147 cycles; in the case of the Sun this number would correspond to more than 1600 yr of continuous cyclic activity. The Mount Wilson time series also provides evidence for phase jumps in the observed Ca activity, however, in general, the temporal sampling of the data is usually too coarse for definite conclusions. There is, naturally, substantial scatter in the data and almost nightly sampling is required to distinguish the intrinsic scatter from deterministic variations in the data. It is obvious that the dense monitoring of the Mount Wilson S index is a good and observationally very simple method to study the activity cycle of a star such as τ Boo. It would clearly be interesting to accompany these measurements with simultaneous magnetic field measurements and Zeeman Doppler images and check to what extent magnetic topologies change during phase jumps of the activity cycle.

Acknowledgements. The HK_Project_v1995_NSO data derive from the Mount Wilson Observatory HK Project, which was supported by both public and private funds through the Carnegie Observatories, the Mount Wilson Institute, and the Harvard-Smithsonian Center for Astrophysics starting in 1966 and continuing for over 36 yr. These data are the result of the dedicated work of O. Wilson, A. Vaughan, G. Preston, D. Duncan, S. Baliunas, and many others.

References

Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269
Baliunas, S. L., Henry, G. W., Donahue, R. A., Fekel, F. C., & Soon, W. H. 1997, ApJ, 474, L119
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Donati, J.-F., Moutou, C., Farès, R., et al. 2008, MNRAS, 385, 1179
Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646
Fares, R., Donati, J.-F., Moutou, C., et al. 2009, MNRAS, 398, 1383
Fares, R., Moutou, C., Donati, J.-F., et al. 2013, MNRAS, 435, 1451
Lanza, A. F. 2013, A&A, 557, A31
Mengel, M. W., Fares, R., Marsden, S. C., et al. 2016, MNRAS, 459, 4325
Mittag, M., Robrade, J., Schmitt, J. H. M. M., et al. 2017, A&A, 600, A119
Schmitt, J. H. M. M., Schröder, K.-P., Rauw, G., et al. 2014, Astron. Nachr., 335, 787
Shkolnik, E., Bohlender, D. A., Walker, G. A. H., & Collier Cameron, A. 2008, ApJ, 676, 628
Zechmeister, M., & Kürster, M. 2009, A&A, 496, 577