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Spots and Activity of the M Dwarf KIC 1572802

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Abstract—The photometric variability of the M dwarf KIC 1572802 has been studied using the most complete observational data, obtained by the Kepler Space Telescope. Power spectra constructed from 59 488 single brightness measurements over 1460 days (∼4 yr) show complex brightness variations. It is suggested that two peaks corresponding to the periods $P = 0.37088^d$ and $P = 0.37100^d$ are related to the presence of active regions at different latitudes on the differentially rotating star. Maps of the surface temperature inhomogeneities are used to derive the positions of these active regions. Analysis of these maps suggests that a switch in the active latitudes occurred 590 days after the beginning of the observations. The variations of the positions of the active regions are also analyzed. These high-temporal-resolution observations revealed a short time-scale change in the active latitudes lasting about 7^d, followed by a "flip-flop," for the first time. The fraction of the surface of KIC 1572802 covered by spots is $S \sim 7\%$. Comparison with literature data indicate that this S value for KIC 1572802 is substantially higher than the average spottedness of stars with temperatures of 3500–4500 K. This may indicate enhanced activity of KIC 1572802. The parameters of the differential rotation of the star are estimated; the inferred rotational velocity, $\Omega = 0.0056 \pm 0.0010$, is substantially lower than the solar value, but comparable to Ω for the cool dwarfs HK Aqr and EY Dra. The value of the Rossby number Ro = 0.011 suggests that KIC 1572802 is in the saturation region of the diagram of Ro vs. X-ray luminosity. If the Ro value for KIC 1572802 is this low, this implies that its magnetic field is of the order of tens or even hundreds of Gauss.

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1. INTRODUCTION

Ultra-high-precision photometric data obtained by the Kepler Space Telescope (whose main aim is the survey and study of exoplanets) have made it possible to develop qualitatively new approaches to studies of the activity of late dwarf stars.

The results of one of the most unique studies of this type are presented by McQuillan et al. [1], who analyzed the rotation periods of 2483 cool stars with masses ranging from 0.3 to 0.55 $M_\odot$. Precise values of the rotation periods P were found for 1570 of these objects (63% of the total sample). It was found that the P values lie in the range 0.37–69.7^d, and that the amplitudes of the brightness variations due to rotational modulation are 1–141 mmag. McQuillan et al. [1] interpreted the inferred bimodal distribution of the rotation periods with the maxima close to 19 and 33^d as a manifestation of two waves of star formation.

Rappaport et al. [2] studied the light curves of about 3900 M dwarfs with the aim of determining their rotation periods. Particular attention was paid to rapidly-rotating objects. Among the stars studied in [2], 178 objects with rotation periods shorter than 2 days and 110 with periods shorter than one day were found. One of the most interesting results of [2] is the identification of two or more independent periods for 30 of these 178 objects. If these data indicate that these stars are components of young binary or multiple systems, this offers opportunities for the detection and study of young hierarchical systems containing late-type dwarfs. One example of such a study of two active M5 dwarfs (GJ 1245 A and B) is presented in [3]; this system probably also contains a third component that is an M8 star.

The first two of these studies contain data for the M dwarf KIC 1572802 (rotation period ∼0.37^d [1, 2], variability amplitude 74.8 mmag [1]), which we analyze in detail in the current paper. This study of KIC 1572802 was carried out using the maximum volume of available material. Using archival data from the Kepler Space Telescope, we managed to trace the continuous evolution of active regions on the surface

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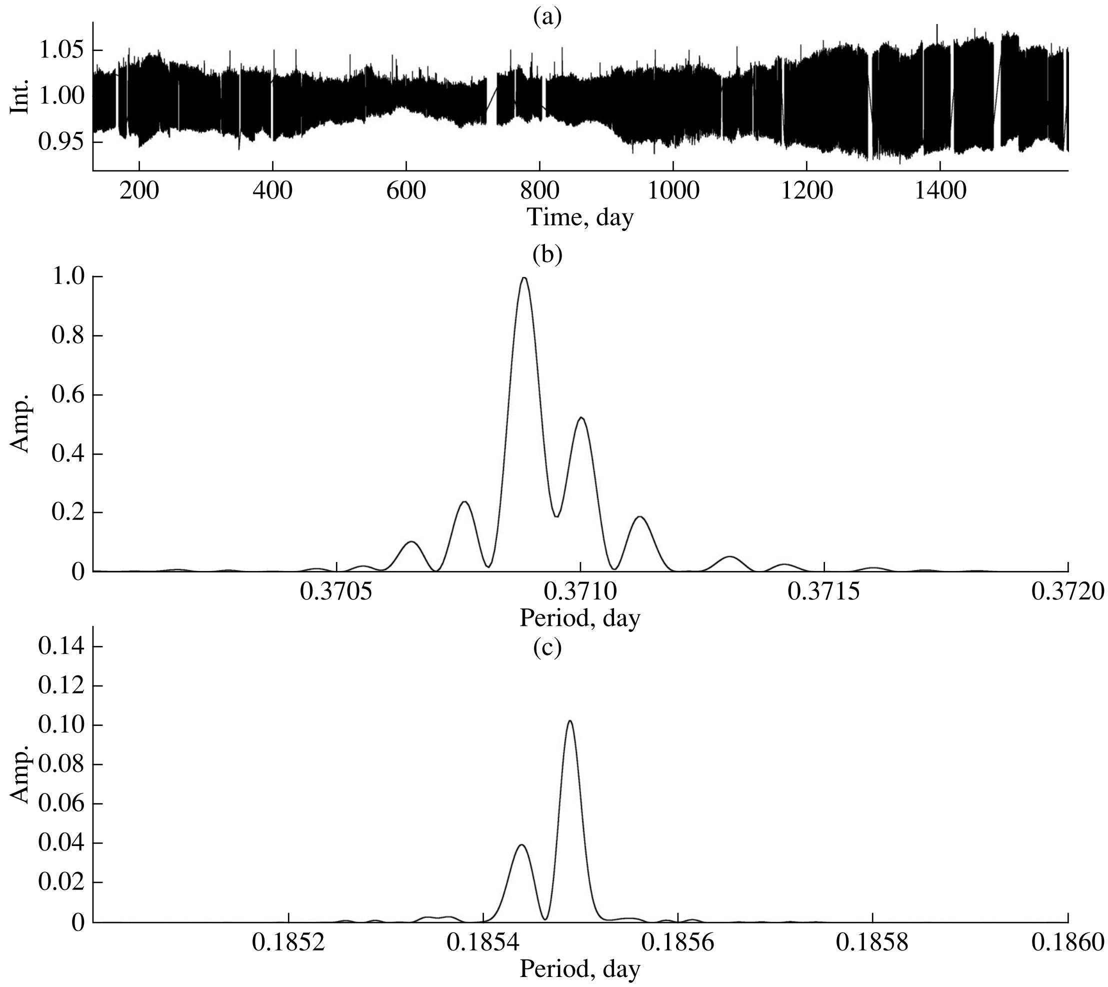

Fig. 1. (a) Normalized light curve of KIC 1572802 for 17 sets of observations from the archive of the Kepler Space Telescope. (b) Amplitude power spectra for the time intervals corresponding to the photometric period of the stellar rotation ($\sim 0.37^d$, in the center). (c) Amplitude power spectra corresponding to half the photometric period of the stellar rotation, $\sim 0.18^d$ (see the text).

of this star over a considerable interval of about four years.

2. OBSERVATIONAL DATA

We examined 17 sets of observations of KIC 1572802 available in the archive of the Kepler Space Telescope. The resulting light curves are presented in the upper panel of Fig. 1. The method used to process the data was similar to the method we applied in our earlier studies [4, 5]. We used the latest version of the program for the correction of the light curves for instrumental effects available in the archive. We selected 59 488 single brightness measurements for further analysis. These observations started on HJD 2454833, and the duration of the observation interval was 1460 day ($\sim$4 yr). The brightness of KIC 1572802 in Kepler system is $K = 15.329^m$, and in the Johnson K filter $K = 12.281^m$.

3. ANALYSIS OF BRIGHTNESS VARIABILITY

The calculated power spectra (Figs. 1b, 1c) suggest fairly complex variations of the star's brightness. Two peaks are observed in the power spectrum, corresponding to the periods $P = 0.37088^d$ and 0.37100^d (which we will refer to as $P_{\rm min}$ and $P_{\rm max}$, respectively). One possible origin for these two periods could be the presence of spots (or groups of spots) located at different latitudes on the surface of the differentially rotating star [6, 7]. In this case, changes in the brightness variability periods may match not only changes in the positions of the spots in latitude, but also the evolution of active regions located at different latitudes on the stellar surface (their appearance and disappearance). Based on the estimated half-widths of the peaks of the amplitude spectra, the estimated accuracy of our derived periods is 0.00010^d. Finally, we emphasize that there are two peaks with amplitudes obeying the relationship $\mathrm{AMP}(P_{\min}) < \mathrm{AMP}(P_{\max})$ in the power spectrum of KIC 1572802 in the range corresponding to half the photometric rotation period of the star ($\sim 0.18^d$), while the opposite relation is valid in the range corresponding to the main peaks: $\mathrm{AMP}(P_{\min}) > \mathrm{AMP}(P_{\max})$.

According to [8], this can most reasonably be interpreted as an indication of differential rotation resembling the solar behavior, with polar regions rotating slower than equatorial regions. Our derived rotation periods for KIC 1572802, 0.37088^d and 0.37100^d, differ from the mean periods found earlier: $P = 0.3680^d$ [1] and $P = 0.3711^d$ [2]. The reason for this is probably both differences in the methods used to determine the periods (using power spectra in our case and applying an autocorrelation analysis in [1]) and differences in the volume of data considered (e.g., McQuillan et al. [1] analyzed the Kepler data from Release 14 for Q1–Q4, covering only 310 days, while our study was based on data from 17 sets of observations covering about 4 yr).

Despite this difference in the P values, it remains justified to conclude that KIC 1572802 is the most rapidly rotating M dwarf studied in [1]. Unfortunately, the study [8] aimed at determining periods of rotation and parameters of the differential rotation for more than 12 300 dwarfs using Kepler data does not contain KIC 1572802, since only objects with periods in the range $P = 0.5–60^d$ were considered. We carried out our subsequent analysis of the photometric variability of KIC 1572802 using the mean photometric period 0.37088^d. A similar approach was used earlier in the analysis of the activity of HD 199178 [9], the K dwarf KIC 8429280 (TYC 3146–35–1) [10], and other stars. The full observational data was divided into 3551 subsets, each covering sequentially one stellar rotation period. Each full single set of observations includes, on average, 17–18 photometric estimates. We did not consider incomplete data sets, since they could not be used to estimate the positions of active longitudes (see below).

4. TEMPERATURE MAPS

As in our previous studies of late dwarfs [9, 11], we analyzed each individual light curve using the iPH-code [11, 12]. This program solves for the reconstruction of the temperature inhomogeneities on the stellar surface using a two-temperature approximation for the light curve. In other words, the intensity of the radiation from each area element on the stellar surface is approximated using two components: the photosphere and a cool spot. A full description of the program and test carried out using it are presented in [11]. Details of the analysis can be found in our earlier paper [9].

The photospheric temperature of KIC 1572802 was taken to be 3990 K [13] and $\log g$ to be 4.484, in accordance with the data of the KIC catalog (see also information in the headers of the MAST data archive). As before, we assumed that the temperature of the spots was 700 K lower than the temperature of the photosphere [14]. In our methodology, we determined the filling factor f for each $6° \times 6°$ area element on the stellar surface, which represents the fraction of the area element occupied by spots. Figure 2 shows an example of a reconstruction of temperature inhomogeneities on the surface of KIC 1572802 for a number of sets of observations. This figure also presents the observed light curves and the theoretical light curves based on the reconstructed model. Because the entire observational data was split into a fairly large number of subsets (3551), we did not inspect each light curve visually, and the analysis of the positions of the longitudes corresponding to the maximum values of f (darker areas in the figures) was performed using the software. If the surface maps contained spots at two longitudes, their values were automatically recorded by the program as two independent active longitudes. Obviously, the accuracy of this automatic detection is somewhat lower than that of a manual detection, but this approach makes it possible to analyze large arrays of photometric observations obtained over long time intervals. The uncertainty in the active longitudes is about $10°–12°$ on the stellar surface (about 0.04 in phase units). Since we do not know the precise inclination i of the stellar rotation axis to the line of sight, we initially performed the calculations for $i = 60°$. The computations of the temperature-map reconstructions for our 3551 sets of observations took several days. For this reason, although we also performed computations for $i = 30°$ and $i = 90°$, which can be regarded as limiting values, this was not done for the entire data set, but instead for the first thousand sets of observations only. The differences in the maps for the three i values do not change our main conclusions about the position and evolution of the active regions on the surface of KIC 1572802.

5. POSITIONS OF ACTIVE LONGITUDES AND FLIP-FLOP

As in [11], we analyzed the dependence of the filling factors f on time and longitude on the stellar surface (see Fig. 3, where the third panel from the top shows a diagram corresponding to the stellar surface, repeated with a vertical offset three times for clarity). The positions of two active longitudes separated by about 180° are clearly traced in Fig. 3, as well as a switch in their positions that took place

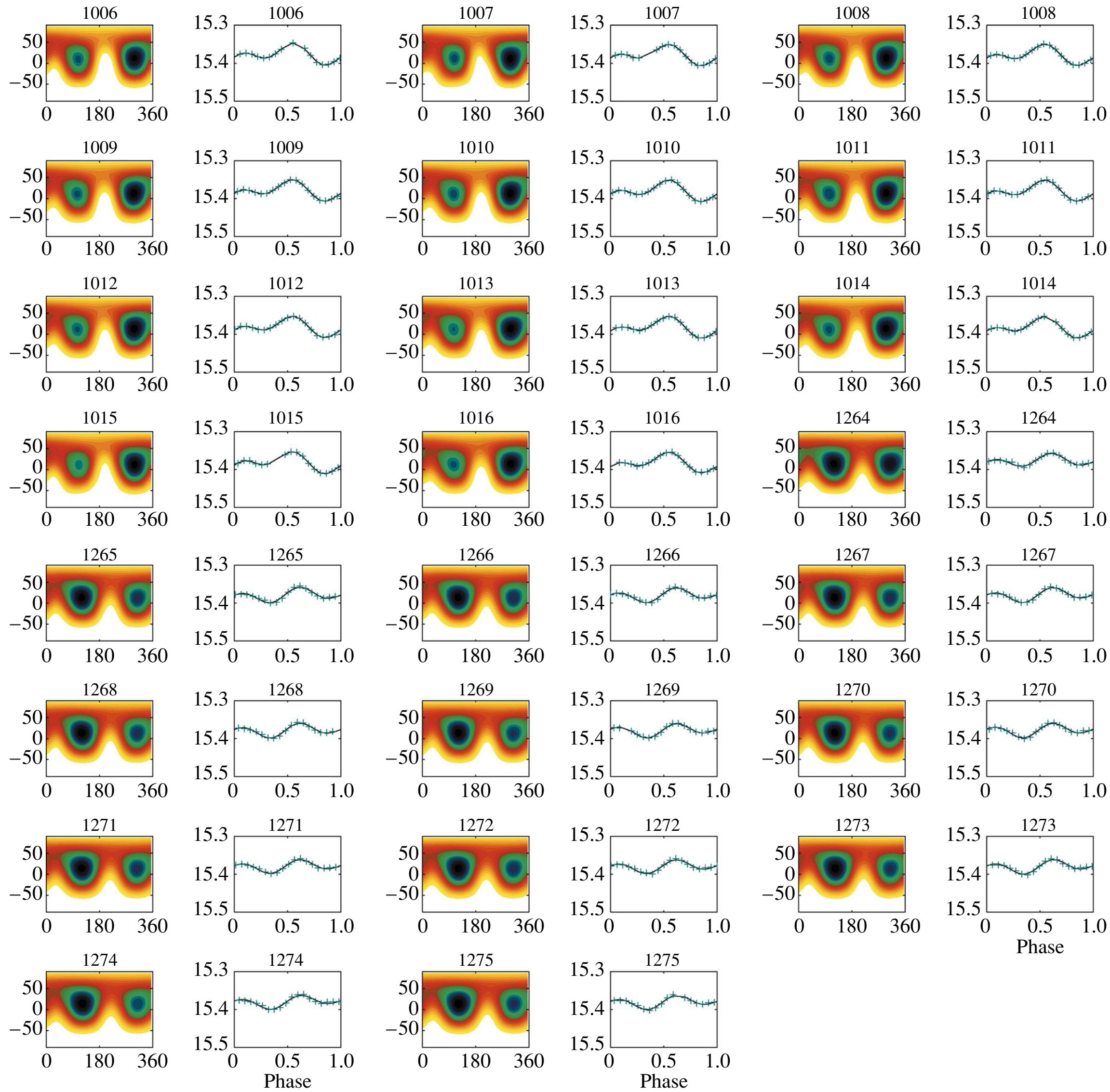

Fig. 2. Examples of reconstructions of the temperature inhomogeneities on the surface of KIC 1572802 for selected sets of observations preceding (sets 1006–1016) and following (sets 1264–1275) the flip-flop. The maps are presented on the same scale, with darker regions corresponding to higher filling factors f. The observed and theoretical light-curves constructed using reconstructed model are also shown.

590 days after the beginning of the observations at $t_0 = \text{HJD } 2455423$ (shown by the bold vertical line). Recall that we adopted the value 0.37088^d (a mean photometric period) for the rotation period of the star. With this period, the positions of both active regions undergo appreciable migration. According to our computations, both areas move, and experience a continuous diplacement, generally in the direction opposite to the stellar rotation. Only at times close to $t = 230^d$ and $t = 770^d$ and after $t = 1300^d$ did the direction of the displacement of the spots occur in the direction of the stellar rotation. In most cases, this movement had a piecewise-smooth character with small deviations, for example, near 220^d and 310^d. The scatter in the longitudes at times close to $930–1040^d$ and $1200–1340^d$ is due to uncertainties caused by the limited quality of the light curves.

Two active regions were almost always present on the stellar surface (Fig. 3). The longitude distance between them was, on average, $D \sim 0.58P$, varying at some epochs within the phase range from 0.4 to 0.6. The group of points with $D \sim 0.4$ can be neglected, as this was due to inaccurate measurement of the longitudes for the less active region; in some cases, it was determined with higher uncertainty, and less active region essentially disappeared at 170–

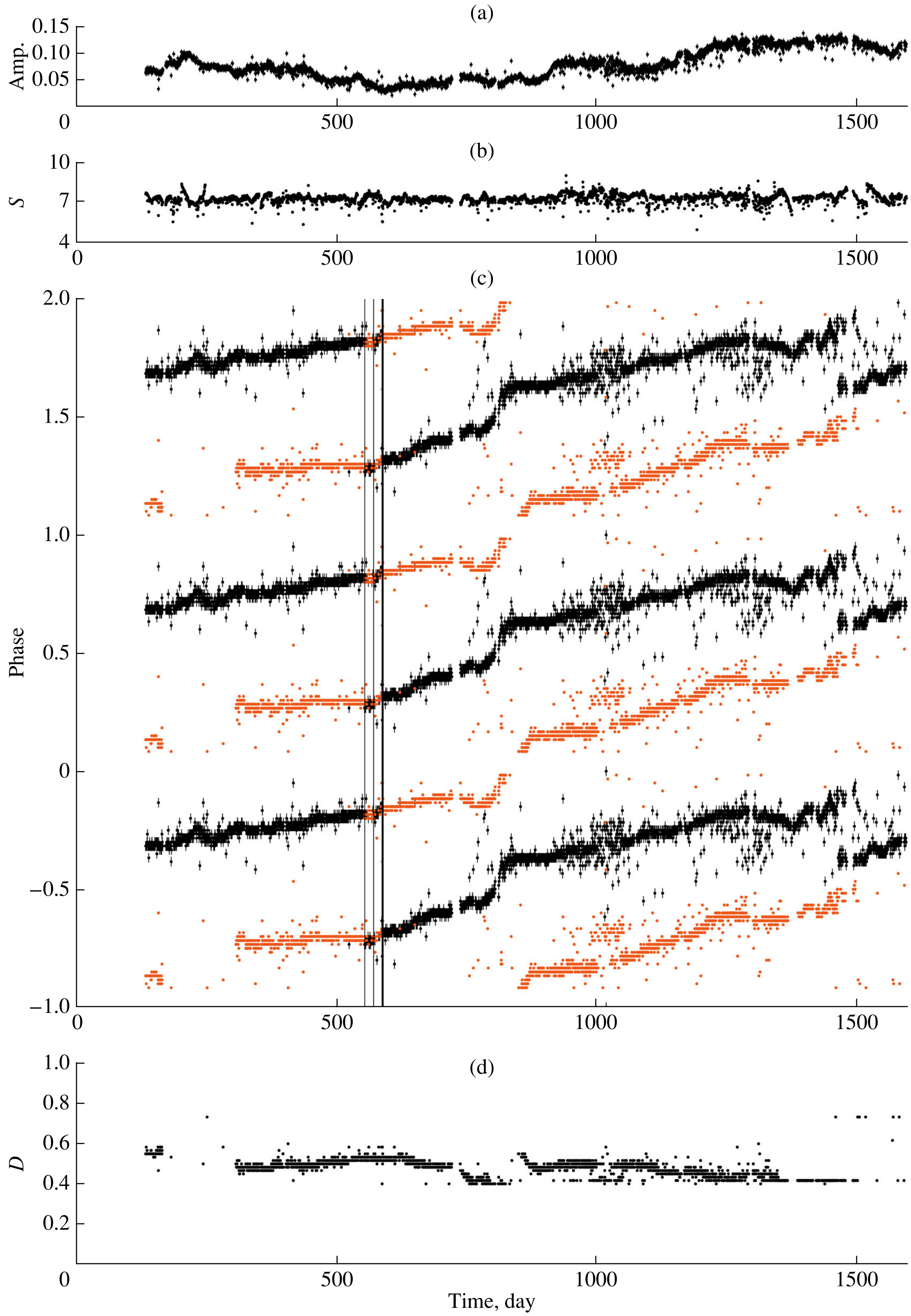

Fig. 3. (a) Change in the brightness variability amplitude with time in fractions of the normalized intensity of KIC 1572802. (b) Change in the spottedness S of the surface of KIC 1572802, with S defined as the ratio of the area all spots on the surface to the area of the visible surface of the star. (c) Positions of more active (filled symbols) and less active (open symbols) areas on the surface of KIC 1572802. The errors are indicated for the active region only, and are approximately a factor of two higher for less active regions. A short-term change in longitude lasting $\sim 7^d$ followed by the main flip-flop is marked by vertical lines. The bold vertical line corresponds to the exchange in the positions of the active regions in longitude (the flip-flop). For clarity, the diagram corresponding to the stellar surface is repeated three times with a vertical offset. (d) Distance between the active regions D, expressed in phase fractions (see text for details).

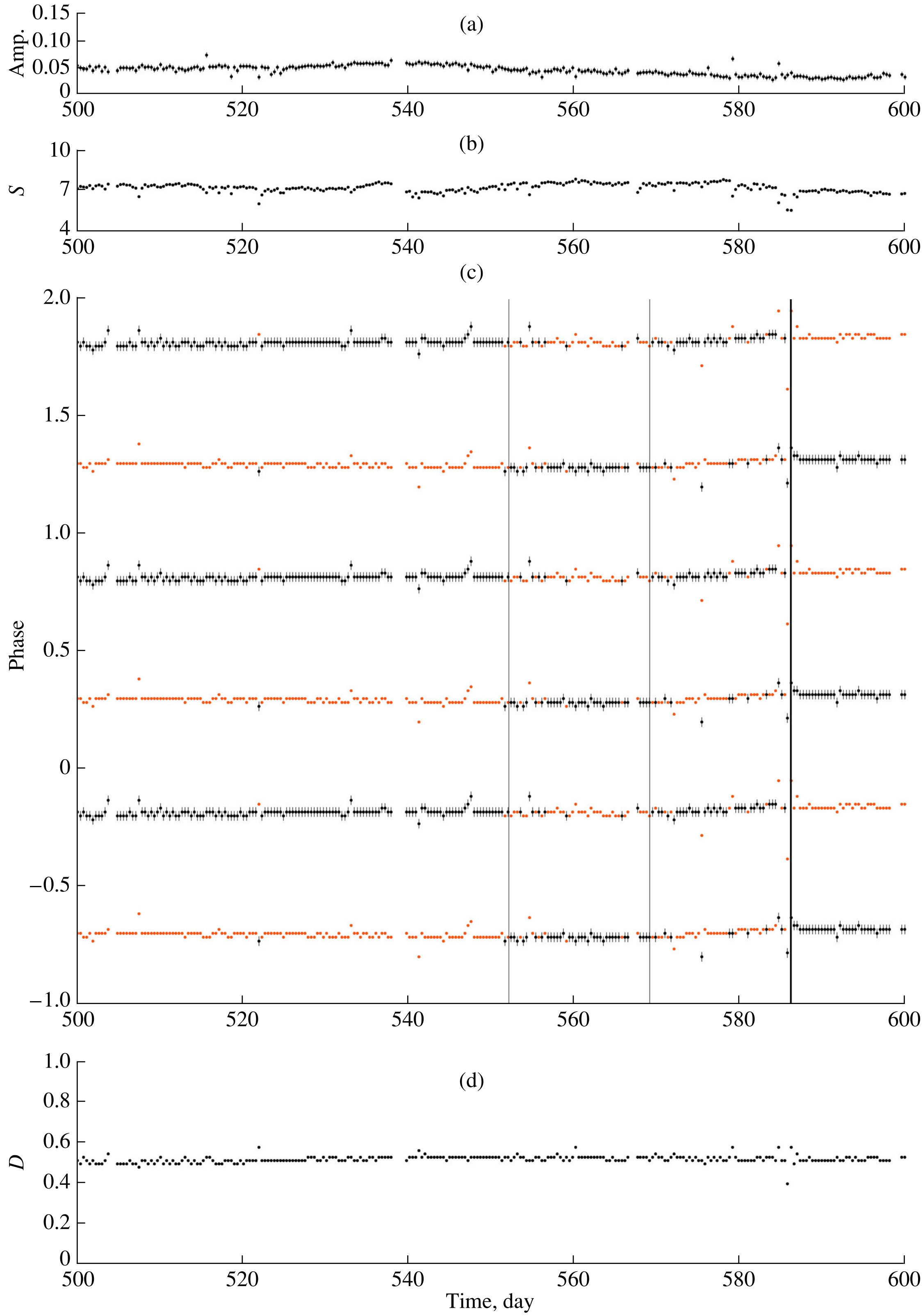

Fig. 4. Same as Fig. 3 for the time range $500–600^d$, encompassing the exchange in the positions of the active regions in longitude (the flip-flop, shown by the bold vertical line) and the short-term exchange in the longitudes lasting $\sim 7^d$ that preceded the main flip-flop (thin vertical lines).

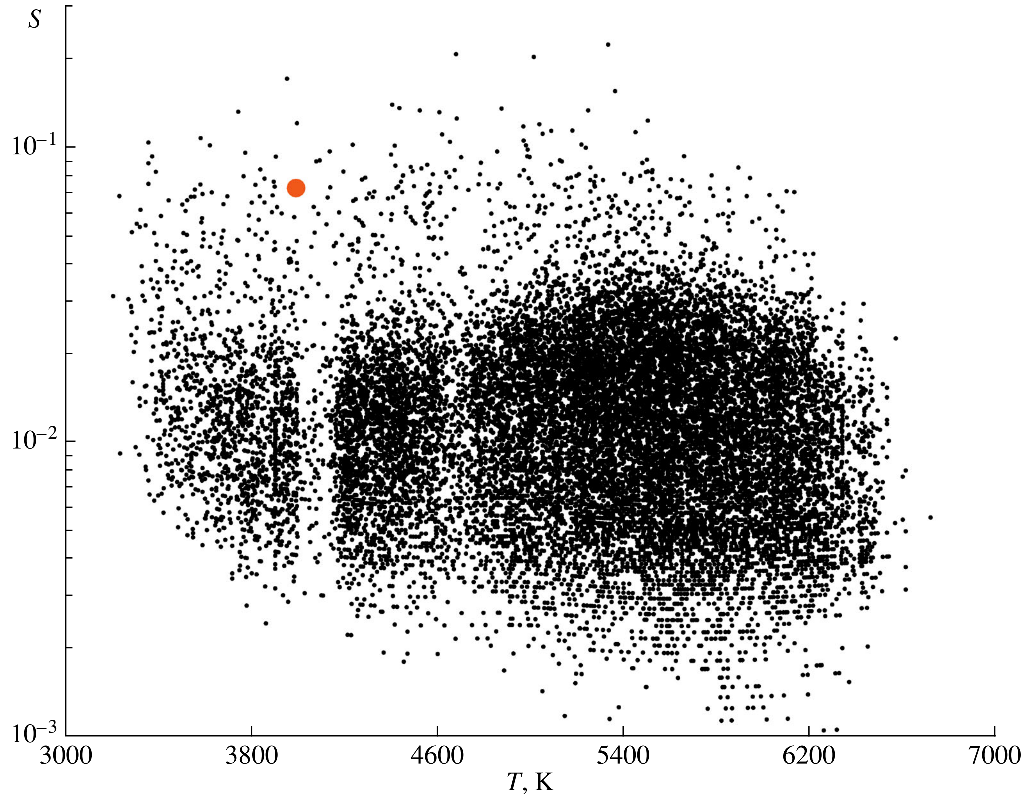

Fig. 5. Dependence of the spottedness S of stars on their effective temperature. The points show data taken from [6]. The data for KIC 1572802 are shown by the larger point.

300^d and closer to the end of the full range of observations ($1470-1550^d$).

At 586^d, an exchange in the longitudes of the active regions occurred—a so-called flip-flop [14] (bold vertical line in Fig. 3). This was preceded by a similar short-term event lasting for $\sim 7^d$ (shown in Fig. 4 in more detail), which was followed by the main flip-flop (vertical lines in Figs. 3 and 4). The flip-flop itself was not accompanied by a changes in the spottedness of the star or the distance between the active longitudes. However, one may suspect that the flip-flop corresponded to changes in the amplitude of the brightness variations due to rotational modulation, so that the exchange of the active longitudes was accompanied by a minimum in the brightness-variability amplitude. We first encountered this phenomenon in our very first study of the active star HD 291095 (V1355 Ori) [11]. We emphasize that such detailed study of the rare flip-flop phenomenon became possible only with the availability of high-precision continuous observations by the Kepler Space Telescope.

6. THE SPOT AREA AND DIFFERENTIAL ROTATION OF THE STAR

The fraction of the surface of KIC 1572802 that is covered by spots is $S = 7.3\%$, and varies slightly in the range of 7–8% (Fig. 3a). There is no periodicity in the variation of S. We compared the S value we found for KIC 1572802 with the spottedness of other stars derive in [6]. We showed earlier [15] that the method suggested in [16] and modified in [17] can be applied to fairly large samples of objects and, most importantly, provides homogeneous data that can be used for statistical estimates and the identification of common dependences. On this basis, we applied our technique to analyze the activity of 18 500 stars from [6], using the data from Table 2 of [6], which contains information about the photometric variability of these stars. The final comparison showed that the estimated S value for KIC 1572802 is significantly higher than the mean S value for spotted stars with temperatures 3500–4500 K (Fig. 5). This can be regarded as evidence for enhanced activity in KIC 1572802.

Using the procedure applied in [6] to determine the differential-rotation parameters of 12 300 stars based on Kepler and our derived $P_{\min}$ and $P_{\max}$ values

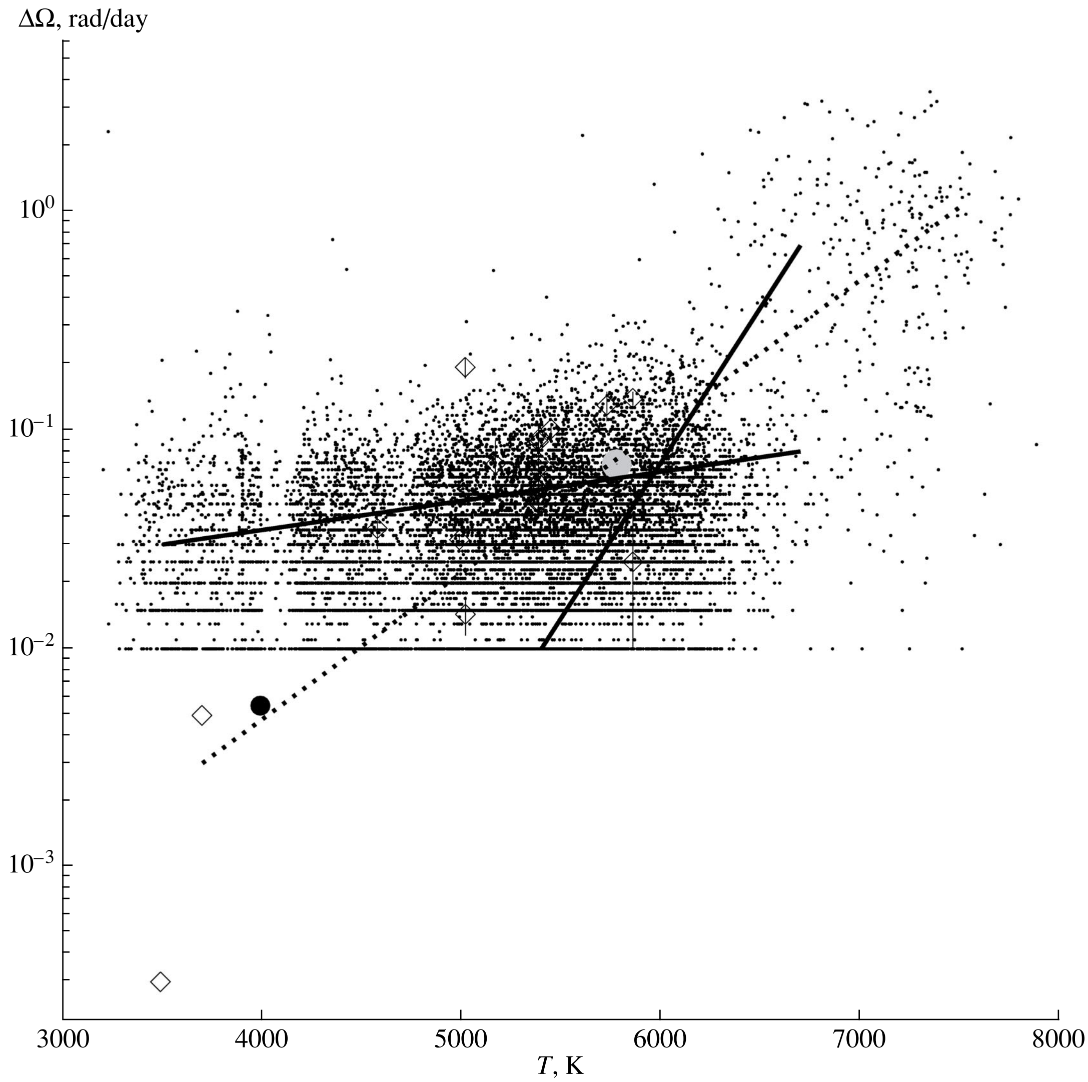

Fig. 6. Dependence of the differential-rotation parameter $\Delta\Omega$ on the effective temperature. The points show data taken from [6] and the diamonds data from [18]. The position of KIC 1572802 is shown by the filled circle and the position of the Sun by the open circle. The solid lines show theoretical predictions from [19], and the dashed line the empirical dependence from [18].

(0.37088^d and 0.37100^d), we estimated the parameters $\Delta\Omega$ (the difference in the angular velocities at the equator and the pole) and α (the relative parameter in the differential-rotation law). It is generally accepted that differential rotation is described by an equation of the form $\Omega(\theta) = \Omega(\mathrm{eq})(1 - \alpha \sin^2 \theta)$, where θ is the latitude. Thus, according to our estimate, KIC 1572802 has $\Delta\Omega = 0.0056 \pm 0.0010$, significantly lower than the solar value. This value of $\Delta\Omega$ is also lower than was assumed in [6] as the detection limit (Fig. 6). However, we note that our estimate of $\Delta\Omega$ for KIC 1572802 is comparable in magnitude to the results of [18] for the two cool dwarfs HK Aqr(M0 Ve) and EY Dra (dM1.5e; the data of [18] are shown by diamonds in Fig. 6). The symbols representing the data for these two stars and for KIC 1572802 are located considerably below the theoretical predictions of [19] (solid lines), although the $\Delta\Omega$ value for KIC 1572802 is in agreement with the empirical dependence of [18]. Our estimate of α is 0.00032. All of these parameter values are estimates, and can be considered limits, since we do not know the latitudes where the active areas giving rise to the rotational modulation of the stellar brightness are located.

We also derived the time delay between one of the active regions on the equator and an active region that lags or leads it at another latitude, and found this to be $\sim 1140^d$. We also found the Rossby number for KIC 1572802 using the mass estimate for the star ($M \simeq 0.54\ M_\odot$ [1]) from the calibration [20] for stars with masses from 0.09 to 1.36 $M_\odot$. The resulting value, Ro $= 0.011$, is comparable to the values listed in [21, Table 1] for a number of M dwarfs with the lowest values of this parameter. No estimates of the X-ray luminosity of KIC 1572802 are available, but it is expected that the star should be in the saturation regon in a diagram relating Ro and the X-ray luminosity if Ro $= 0.011$ (saturation occurs at Ro < 0.1 [21]). In addition, with such a small Ro value, it is expected that the mean surface magnetic field of KIC 1572802 should be of the order of several tens, or even hundreds, of Gauss, according to [21, Table 1]. This makes this star an interesting candidate for observations aiming at Zeeman–Doppler mapping.

7. CONCLUSIONS

We have studied the photometric variability of the M dwarf KIC 1572802 based on the most complete set of observational data for this star obtained by the Kepler Space Telescope. Our analysis was based on 59 488 individual brightness measurements over 1460^d ($\sim$4 yr).

The calculated power spectra indicate fairly complex brightness variations of this star. The two peaks in the power spectrum, corresponding to periods of 0.37088^d and 0.37100^d, are probably associated with the presence of active regions at different latitudes on the surface of the differentially rotating star. The overall observational data set was split into 3551 subsets, each sequentially covering one rotation period of the star.

For every data subset, we obtained a solution for the reconstruction of the temperature inhomogeneities on the stellar surface from the light curve of the star, and used this to derive maps of surface-temperature inhomogeneities (filling factors f). We then used these maps to determine the positions of active regions.

Our analysis of the distribution of filling factors f indicated a switch in the positions of the active longitudes occurring on day 590 of the observations. In general, the positions of both active regions migrated appreciably, as a rule, continually drifting opposite to the direction of the stellar rotation, and only occasionally moving in the direction of rotation. In most cases, this motion had a piecewise-smooth character.

For the first time, we observed a short-term longitude switch lasting about 7 days, followed by the main flip-flop event. The flip-flops itself was not accompanied by any changes in spottedness of the star or the distance between the active longitudes, but was accompanied by variations in the amplitude of the brightness variability

The fraction of the surface of KIC 1572802 covered by spots is about $S = 7\%$. A comparison with data from the literature indicates that this value significantly exceeds the average S for dwarfs with temperatures of 3500–4500 K. This suggests the presence of enhanced activity in KIC 1572802.

We estimated the parameters of the star's differential rotation $\Delta\Omega$ (the difference in the angular velocities at the equator and the pole) and α (the relative parameter of the differential-rotation law). We estimate for KIC 1572802 $\Delta\Omega = 0.0056 \pm 0.0010$; this is significantly lower than the solar value, but is comparable to the $\Delta\Omega$ values for the two cool dwarfs HK Aqr and EY Dra [18].

The Rossby number for KIC 1572802, Ro $=$ 0.011, suggests that the star is located in the saturation region in a diagram relating Ro and the X-ray luminosity. This low Ro value suggests that the star has a magnetic field of the order of several tens, or even hundreds, of Gauss.

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