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Activity of Young Dwarfs with Planetary Systems: EPIC 211901114 and K2−33

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Abstract—The results of an analysis of the activity of the young stars with planetary systems EPIC 211901114 and K2−33 based on observational data obtained over 70 days with the Kepler Space Telescope are presented. The rotation periods of EPIC 211901114 (8.56 ± 0.60^d) and K2−33 (6.29 ± 0.50^d) have been found. Maps of temperature inhomogeneities on the surfaces of EPIC 211901114 and K2−33 have been constructed. No relative displacements of the active regions on the stellar surface have been foundfor EPIC 211901114. The differential-rotation parameter has been estimated for K2−33, $\Delta\Omega = 0.0039 \pm (0.0020{-}0.0012)$ rad/day. The fractional spotted area S on the surface of EPIC 211901114 reaches about 5% of its total visible surface. For K2−33, S is 3.8% of its total visible surface, on average. On the whole, the positions of EPIC 211901114 and K2−33 on S−age, S−rotation period, and S−Rossby number diagrams match the general character of the dependence found earlier for M dwarfs. The flare activity of EPIC 211901114 and K2−33 has been studied, based on 32 flares of EPIC 211901114 and 7 flares of K2−33. The flare frequencies and amplitudes for EPIC 211901114 and K2−33 have been estimated, together with the time scales for their rise and decay. The flare energies have also been estimated, $10^{32.1-33.4}$ and $10^{32.2-33.3}$ erg for EPIC 211901114 and K2−33, respectively.

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1. INTRODUCTION

The analysis of observational data from the Kepler Space Telescope archive and the follow-up mission K2 has made possible high-precision photometric studies of the activity of stars with planetary systems in young clusters (with ages below 1 Gyr). In such young systems, the physical and chemical properties of the planets formed are appreciably influenced by both the ongoing infall of planetesimals and the magnetic activity of the central young star (its excess UV and X-ray emission and coronal ejections), which can alter the physical properties of the atmospheres of nearby planets, and even destroy these atmospheres.

Rizzuto et al. [1] published a review of the results of a search for young planetary systems. Objects in the Pleiades, Hyades, Praesepe, and Sco-Cen association (Upper Scorpius subgroup) were considered. The use of a specially developed technique made possible the detection of new planetary systems belonging to members of these clusters.

For instance, Mann et al. [2] reported the discovery and analysis of a Neptune-like planet in the system of the M dwarf EPIC 210490365 (K2−25, 2MASS J04130560+1514520) in the Hyades cluster (650−800 Myr). The star has an effective temperature of 3180 ± 60 K, a mass of 0.294 $M_\odot$, and a radius of 0.295 $R_\odot$. Mann et al. [2] classify the star as an M4.5 dwarf. We presented the results of our analysis of the activity of K2−25 based on data obtained by the Kepler Space Telescope in [3]. We traced the continuous evolution of active regions on the stellar surface over 70 days, and established that the stellar brightness variations had a fairly stable character. The rotation period of K2−25 is 1.878 ± 0.030^d. For 37 sets of observations, we constructed maps of the temperature inhomogeneities on the surface of K2−25. Spots with various sizes are preasent on all these maps. The total spotted area S on K2−25 is, on average, 2.6% of the total visible surface of the star. We estimated the star's differential-rotation parameter to be $\Delta\Omega = 0.0071 \pm 0.002$ rad/day. Our analysis of the positions of K2−25 on S−age, S−rotation period, and S−Rossby number diagrams showed that they match

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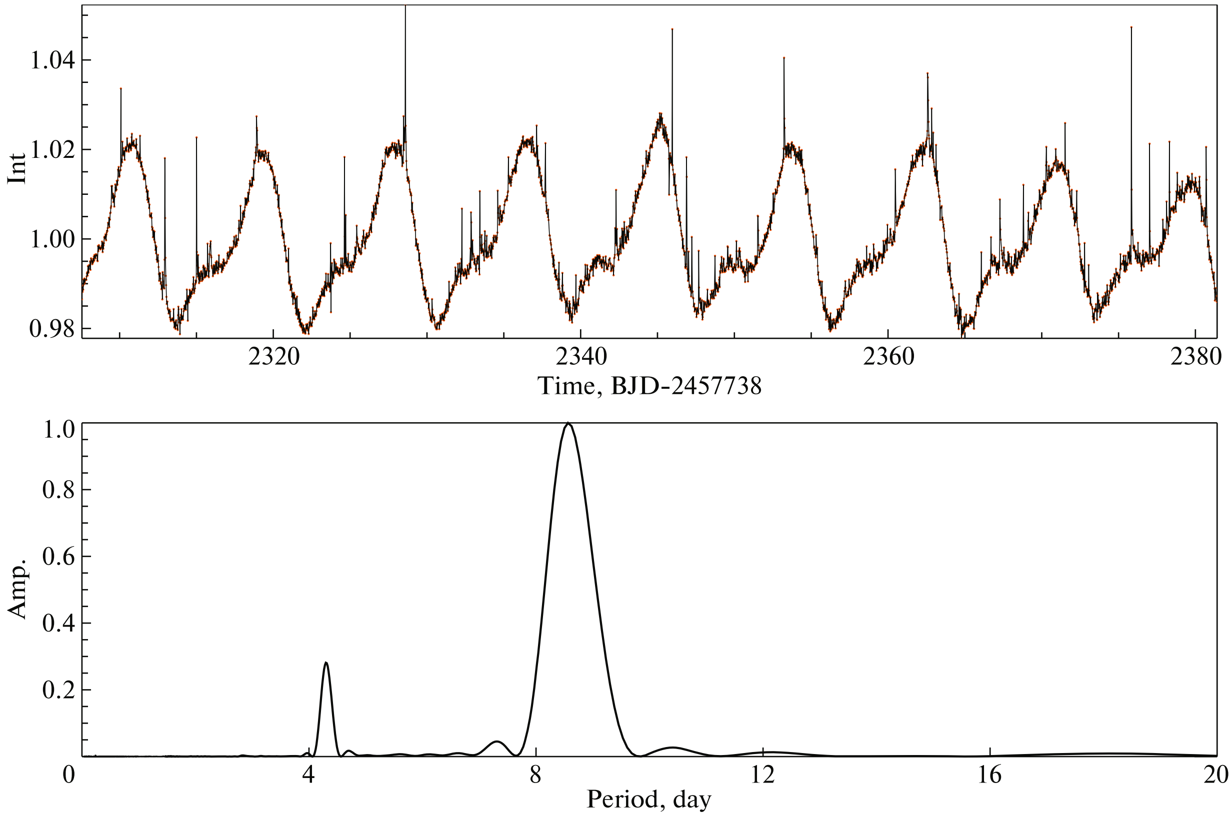

Fig. 1. Light curve of EPIC 211901114 (upper) and normalized power spectrum for the star's brightness variations in the period interval 2–20^d (lower).

the general character of the dependences found by us earlier for M dwarfs.

We have chosen two objects for further studies of young stars with planetary systems: EPIC 211901114 (2MASS J08413569+1844350) from the Praesepe cluster and EPIC 205117205 (K2–33, 2MASS J16101473-1919095) from the Upper Scorpius subgroup of the Sco-Cen association. The main data for these stars can be found in [4, 5].

We have investigated EPIC 211901114 and K2–33 based on data available from the Kepler Space Telescope archive, using light curves processed applying the technique [6]. We were able to trace the continuous evolution of active regions on their surfaces over a time span of about 70 days.

2. OBSERVATIONAL DATA AND ANALYSIS

The light curves of these two objects are presented in the upper panels of Figs. 1 and 2. The data reduction was similar to the procedures applied by us earlier to data for late-type dwarfs [7, 8]. We selected in all 3403 and 3341 brightness measurements for EPIC 211901114 and K2–33, respectively, for our subsequent analysis. When examining the light curves, we noted some features that were interpreted as flares (see below). In the Kepler Telescope system, the brightnesses of EPIC 211901114 and K2–33 are $K(\mathrm{mag}) = 16.024$ and 14.357^m, respectively. Their masses and radii are 0.46, 0.56 $M_\odot$ and 0.46, 1.05 $R_\odot$, respectively [4, 5].

The calculated power spectra (Figs. 1 and 2, lower panels) indicate the fairly stable character of the brightness variations of these two stars. There are peaks corresponding to 8.56 ± 0.60^d and 6.29 ± 0.50^d in the power spectra for EPIC 211901114 and K2–33. Both power spectra have peaks in the range corresponding to half the star's photometric rotation period. This most likely suggests the presence of two active regions separated by approximately 180° on the stellar surface. Mann et al. [4, 5] give the results of an independent determination of the stars' rotation periods, which agree with our own values (8.61^d and 6.29^d for EPIC 211901114 and K2–33, respectively).

We divided all the observational data for EPIC 211901114 and K2–33 into 8 and 12 data sets, respectively, each successively covering one rotation period of the star. The technique used in our analysis has been described in earlier publications (see, e.g., [7, 8]), and we present only its main features below.

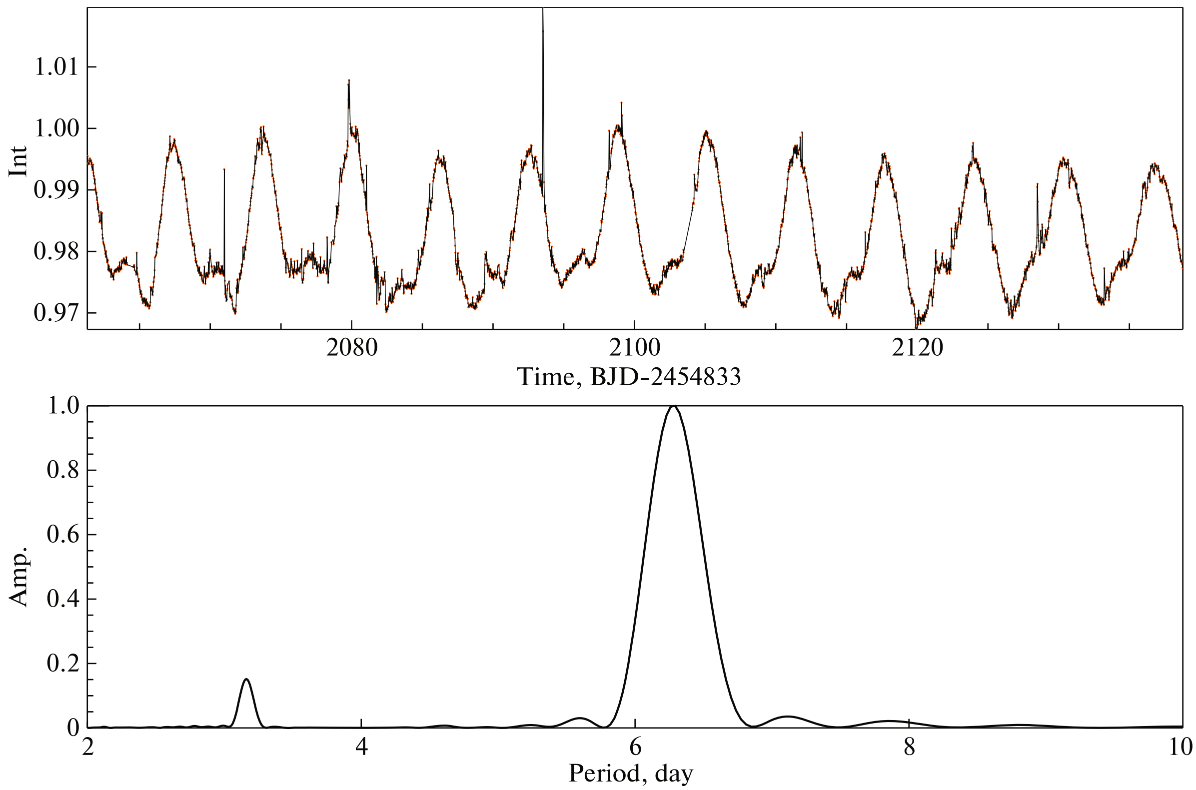

Fig. 2. Light curve of K2–33 (upper) and normalized power spectrum for the star's brightness variations in the period interval 2–10^d (lower).

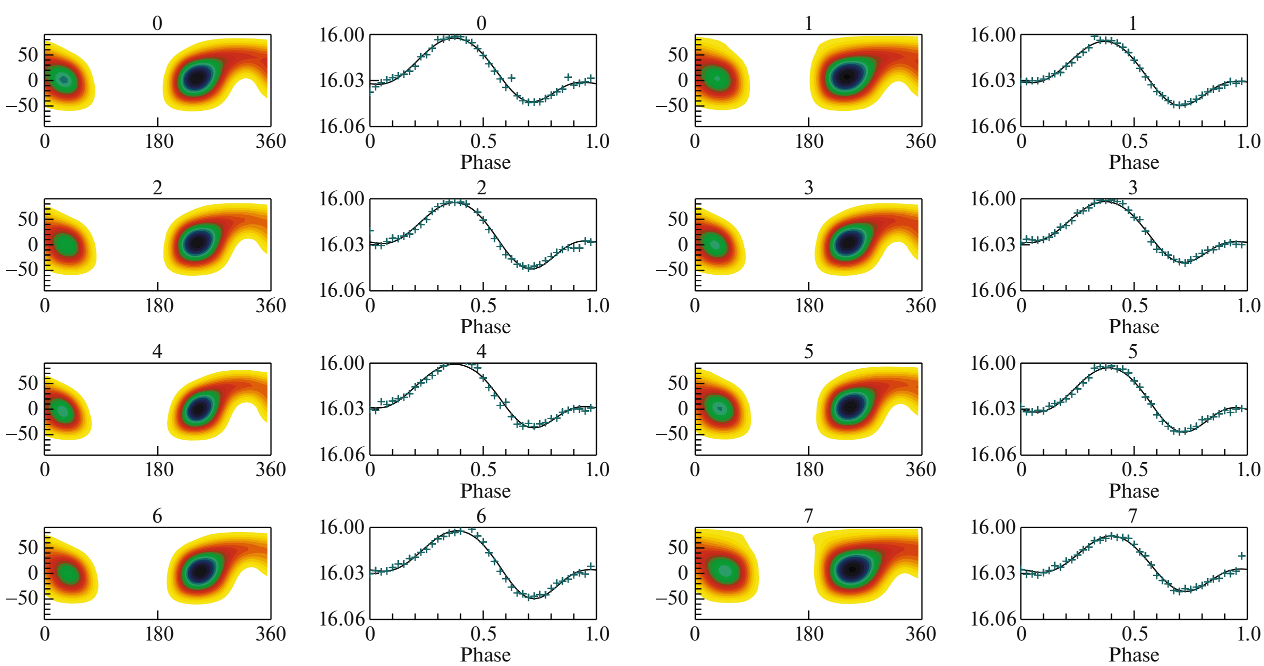

Fig. 3. Reconstructed maps of temperature inhomogeneities on the surface of EPIC 211901114. The maps are all presented on the same scale, with darker areas corresponding to higher filling factors f. The observed light curves are also given together with theoretical light curves constructed using the reconstructed model.

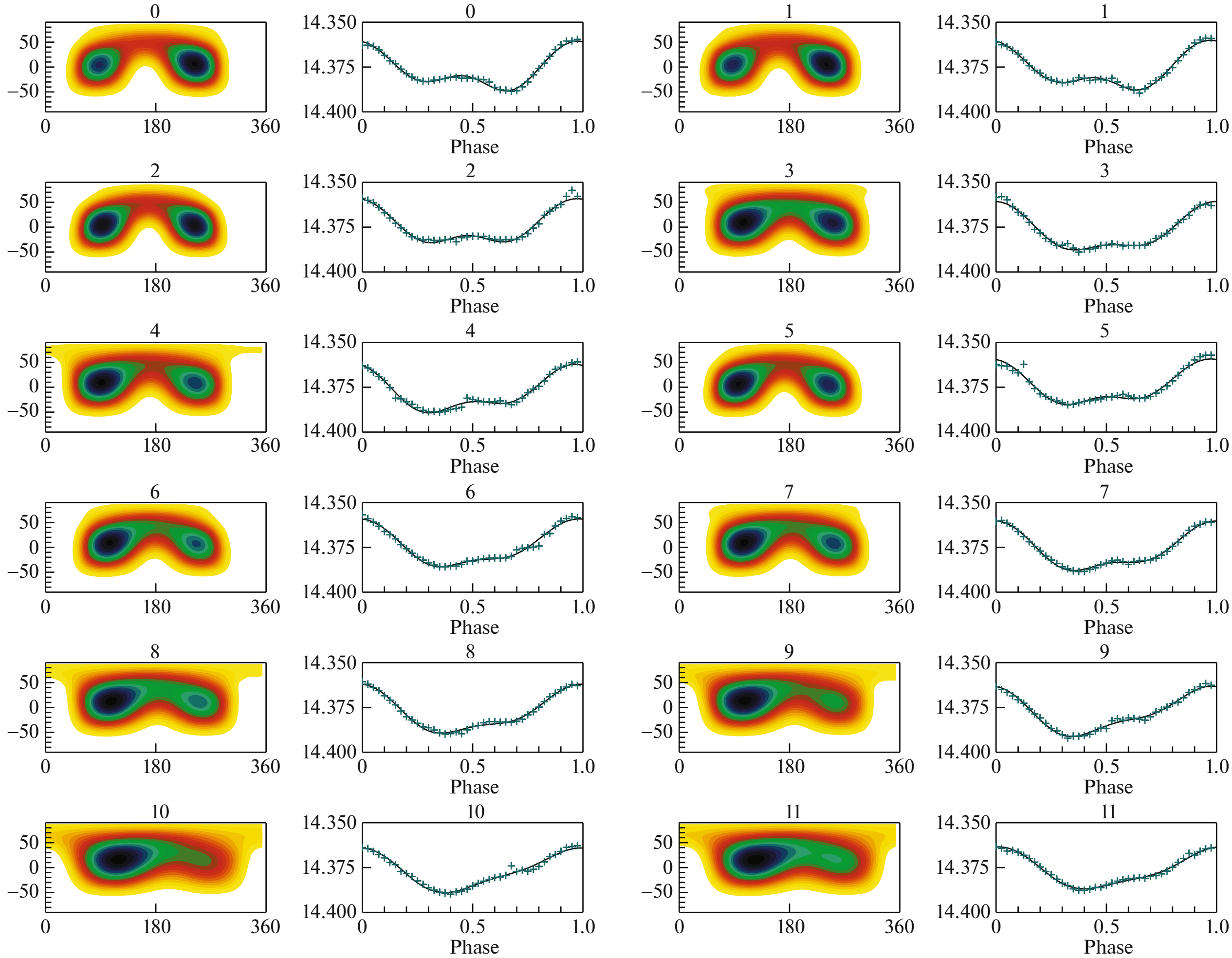

Fig. 4. Reconstructed maps of temperature inhomogeneities on the surface of K2−33. Notation is the same as in Fig. 3.

We analyzed each individual light curve using the iPH software [9], which solves for the reconstruction of the surface temperature inhomogeneities based on the light curve in a two-temperature approximation. In the modeling, we divided the stellar surface into area elements $6^\circ \times 6^\circ$ in size, for each of which we determined the filling factors f.

In accordance with the results of [4], we adopted 3440 K for the photospheric temperature of EPIC 211901114 and 3200 K for the temperature of the surface spots. For K2−33, we adopted the values 3540 and 3300 K, respectively [5]. Our calculations were carried out using data from the PHOENIX grid of models.

We reconstructed maps of the surface temperature inhomogeneities for EPIC 211901114 and K2−33 assuming inclinations of the stellar rotation axes to the line of sight of $i = 63^\circ$ and 64°, respectively; these values were adopted as estimates in [4, 5].

We used the resulting maps to determine the longitudes corresponding to the maximum values of f (darker regions in Figs. 3 and 4). All the surface maps display spot clusters at two longitudes, which we recorded as two independent active regions (active longitudes). We found that the areas of the two regions were different. For both EPIC 211901114 and K2−33, distance D between the active regions is $\sim$180° in the longitude (0.58 in phase for EPIC 211901114, Fig. 5, and 0.4−0.45 in phase for K2−33, Fig. 6). In both cases, the accuracy of the active-longitude positions is about 6° on the stellar surface (or 0.02 in phase units).

We found no relative displacements of the active-region positions on the surface of EPIC 211901114 (Fig. 5). Analysis of the maps of the surface temperature inhomogeneities for K2−33 suggested the presence of systematic displacements of the active regions and switches (flip−flops) in the position of the more active region. The distance D between the active regions decreased by about 0.06 in phase during the observed interval (Fig. 6). We interpret this as time variability in the positions of the active

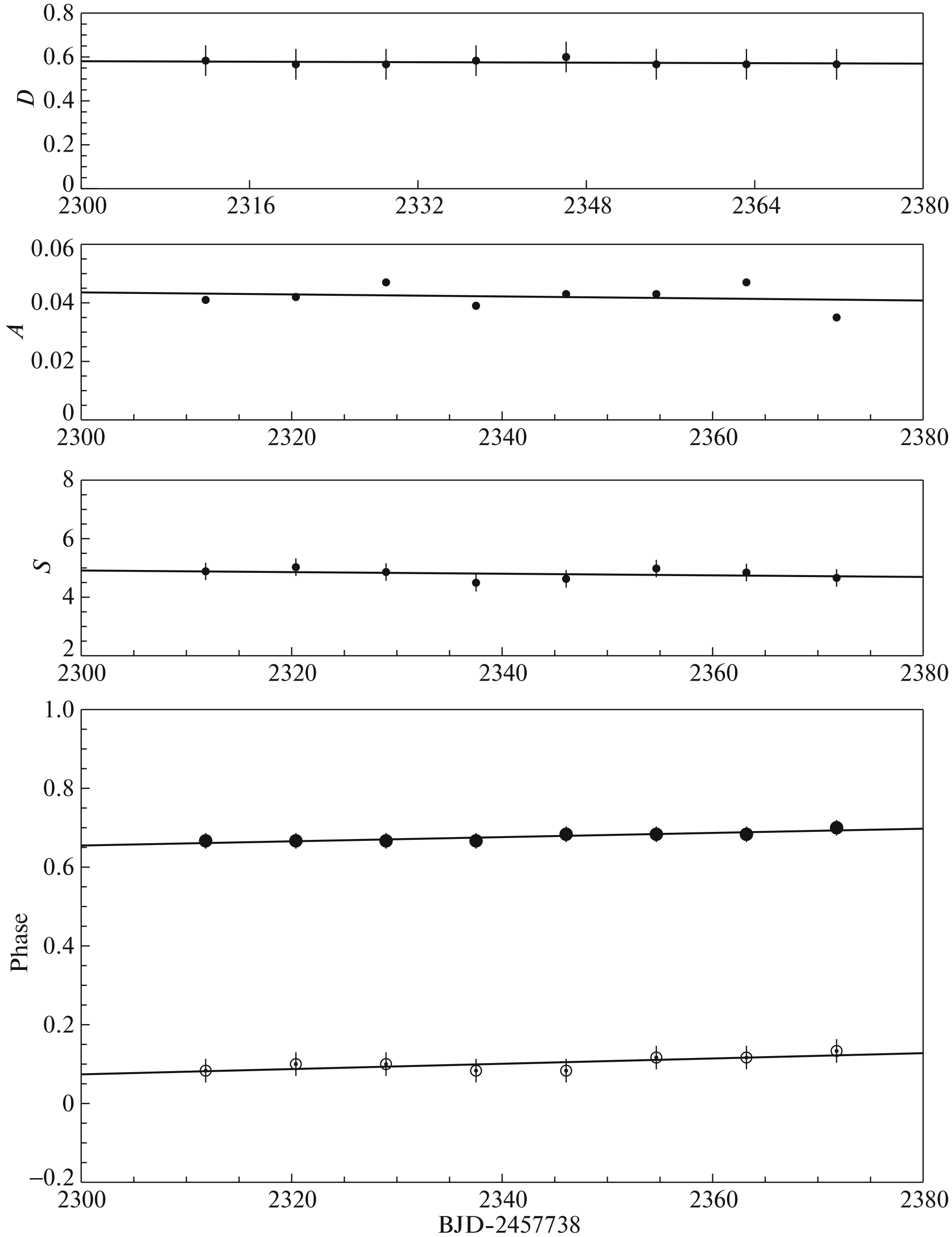

Fig. 5. The time dependences of the following parameters for EPIC 211901114, from top to bottom: distance D between active regions on the stellar surface in fractions of the phase; change in brightness variation amplitude A (in fractions of the normalized intensity); variation of the surface spottedness S; positions of the two systems of active regions on the stellar surface ($Phase$), shown by dark and light symbols for the more and less active region, respectively. The uncertainties in the active region positions are given (see text).

regions on the surface of a star displaying differential rotation. We estimated the differential-rotation parameter (the difference in the angular rotation rates at the equator and the pole) to be $\Delta\Omega = 0.0039 \pm (0.0020-0.0012)$ rad/day.

For EPIC 211901114, the spotted area of the stellar surface S is about 5% of the total visible surface of the star. The brightness-variation amplitude A is 4%. In the case of K2−33, $S = 3.8\%$ of the total visible surface of the star, on average, and the amplitude A of the star's brightness variations was approximately constant ($\sim$2.6%).

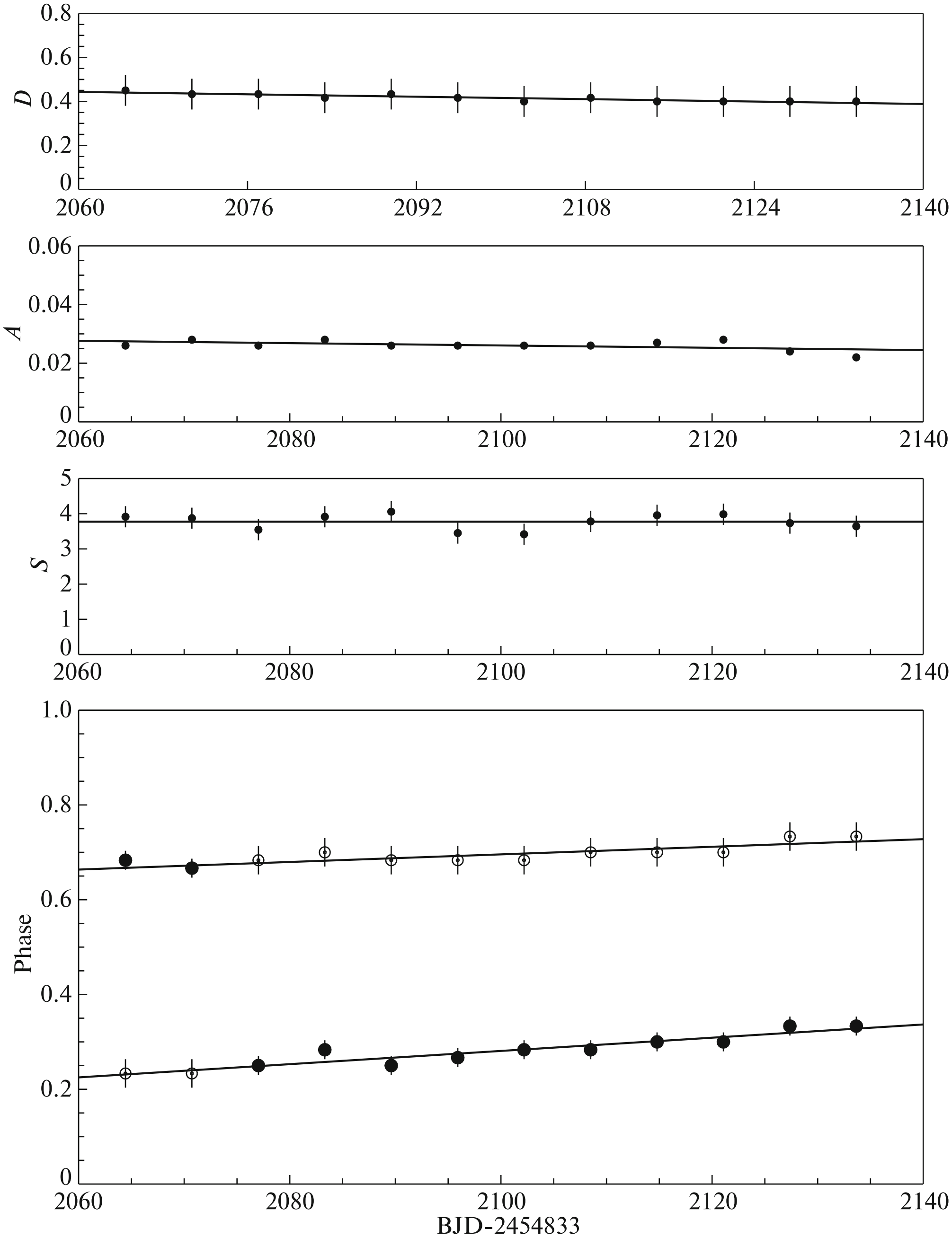

Fig. 6. Same as Fig. 5, for K2–33 (see text).

3. RELATIONSHIP OF SPOTTEDNESS TO ROTATION AND AGE

Earlier in [10], we applied the technique for estimating the spottedness parameter S (the fractional area of spots on the surface of an active star) developed by us in [11] to analyze the activity of 1570 M dwarfs based on data on their photometric variability, atmospheric parameters, masses, and rotation periods [12].

In the absence of data on the chromospheric activity (e.g., R'_{HK} indices), the quantity $Rvar$ characterizing the amplitude of the brightness variations (see [10, 12]) or the spottedness parameter S can be used as indicators of activity. First and foremost, we studied variations in the activity of M dwarfs with their ages, calculated using equations for the gyrochronological dependence, as in [13].

The relationship between the spottedness parameters of the objects S and their age t is presented in Fig. 7 (top panel). We discussed the properties of groups of objects in this diagram in [10].

The position of the previously studied star K2–25

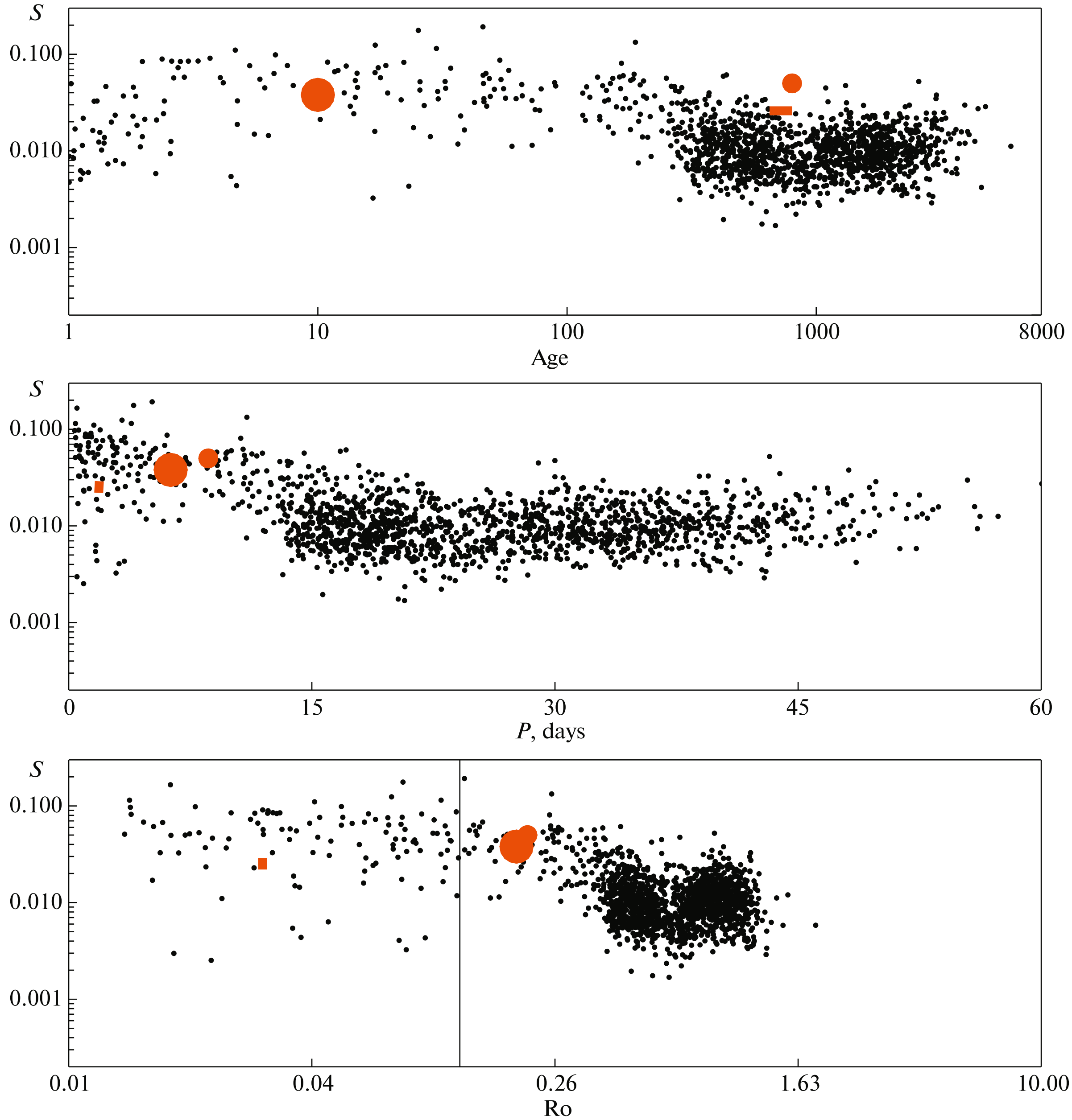

Fig. 7. Spottedness parameter S for M dwarfs as a function of their age t in millions of years (top), rotation periods P (center), and Rossby numbers Ro (bottom). The vertical line corresponds to Ro (saturation) = 0.13. In all the diagrams, the position of K2–25 is marked by a line segment. The large filled circle shows the data for K2–33, and the smaller filled circle the data for EPIC 211901114.

in the the Hyades cluster is shown by a horizontal line segment (the age of the Hyades cluster is about 650–800 Myr). The large and small filled circles correspond to K2–33 and EPIC 211901114. According to [5], the age of the very young dwarf K2–33 in the Upper Sco association is estimated as 9.3 ± 1.1 Myr. The age of EPIC 211901114 in the Praesepe cluster is 800 Myr (see [4]).

Given that the S value for K2–33 is about 4%, its position on the spottedness–age diagram corresponds to the general dependence found for very young stars from [10]. However, among stars with ages of 800–900 Myr, K2–25 and EPIC 211901114 are distinguished by their high values of S.

Let us now consider the dependence of S on the stellar rotation period (Fig. 7, middle panel). We can tentatively identify a group of rapidly-rotating stars with rotation periods shorter than 10–12 days in this diagram. These stars are characterized by high S values. All three stars we have considered fall into

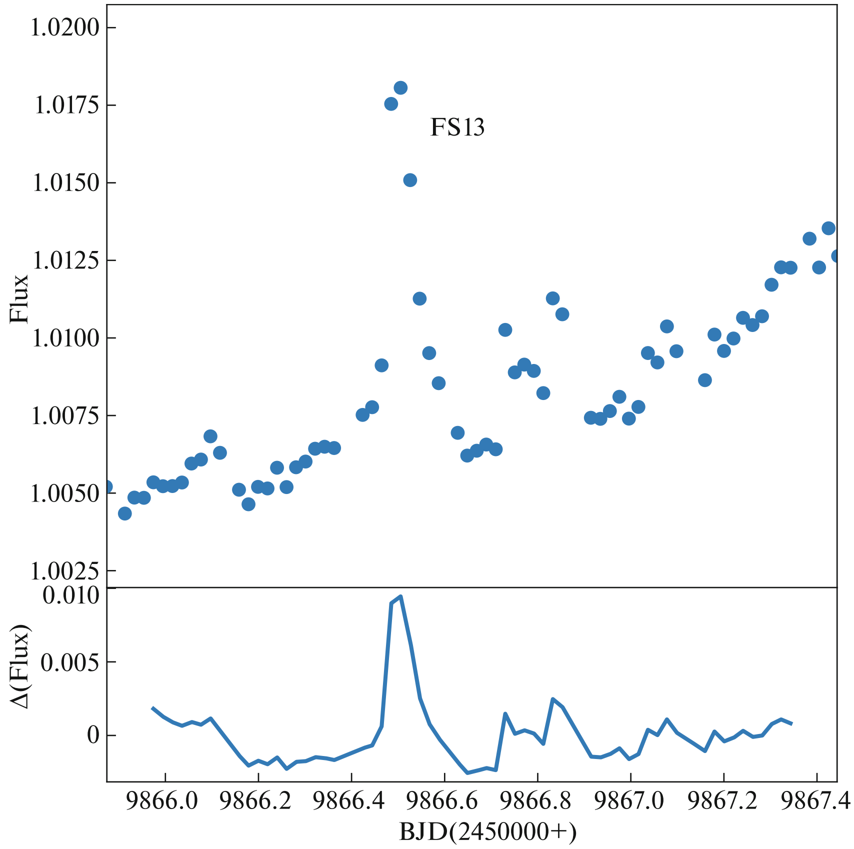

Fig. 8. A flare of EPIC 211901114. The light curve segment including the flare (upper) and the normalized light curve (lower) are shown.

this group, and fit reasonably well into the average dependence for M dwarfs with similar rotation periods (K2–25 may have a somewhat lower activity).

In [10], we compared the spottedness S and the Rossby numbers Ro for the stars studied, and showed that the relationship between S and Ro mimics the classical dependence of the X-ray luminosities of active stars on the Rossby number, with the saturation regime achieved at the same value, Ro (saturation) = 0.13. It is most likely that objects having Rossby numbers greater than Ro (saturation) do not form a unified sequence. For the Rossby numbers found for K2–33 and EPIC 211901114, 0.20 and 0.22, respectively, their positions on the S–Ro diagram testifies to the possible applicability of the estimates of [14]. According to the relationships of [14, 15], we would expect the X-ray luminosities of K2–33 and EPIC 211901114 to correspond to $\log R_x$ values ($R_x = L_x/L_{\mathrm{bol}}$) of −3.99 and −4.01, respectively, which are considerably higher than the solar value, $\log R_x = -6.24$ [15].

The Rossby number for K2–25 is 0.03. This star is in the saturation region on the S–Ro diagram.

4. FLARE ACTIVITY

We carried out an additional analysis of the light curves of EPIC 211901114 and K2–33 to study their flare activity. In the preliminary processing of the data, our attention was drawn to multiple features in the light curves (Figs. 1 and 2) that could be interpreted as flares [16]. Figures 8 and 9 present examples of such flares. There is an extensive literature on studies of flare activity based on observations with the Kepler Space Telescope, including studies of active late-type dwarfs (see, e.g., the review [17]). The technique used to estimate the flare energy is standard, and is described in detail in the literature (see, e.g., the review [17]). Since we analyzed only two light curves, each containing about 3300–3400 measurements, we carried out a visual analysis of the potential flares. Our technique was the same as those used by other researchers. In the light curves corrected for rotational modulation, we considered only episodes that included no fewer than three measurements that differed from those corresponding to the brightness of the unperturbed photosphere by more than 3σ.

As a result of this analysis, we noted 32 flares for EPIC 211901114 and 7 flares for K2–33. In addition, we noted eight flare candidates for EPIC 211901114

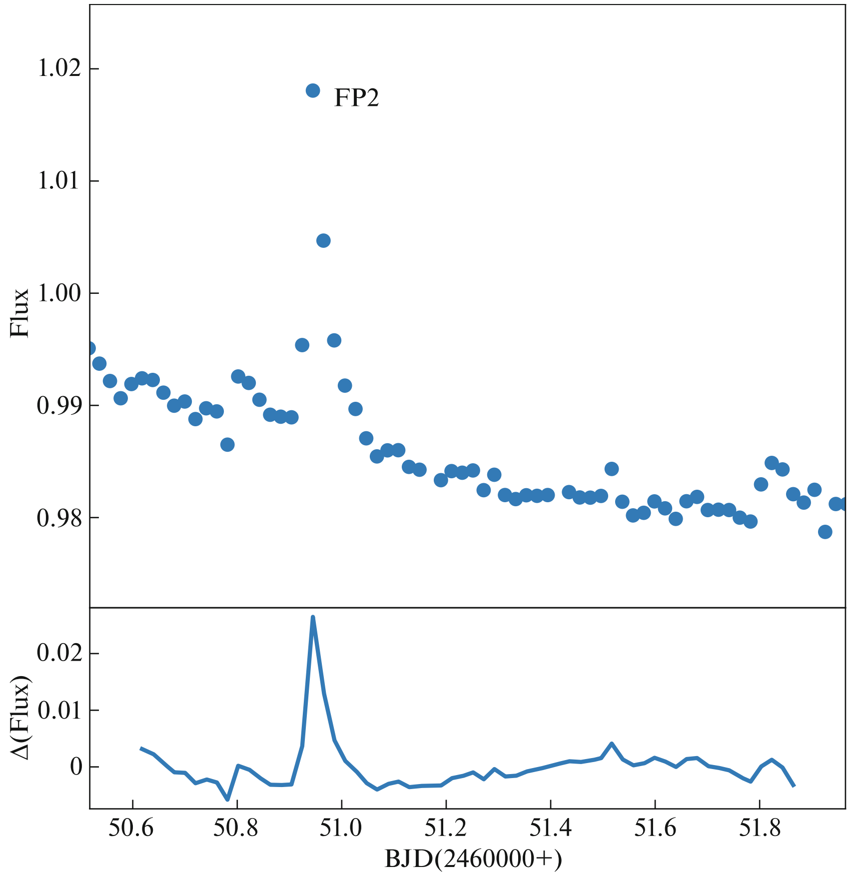

Fig. 9. A flare of K2–33. The light curve segment including the flare (upper) and the normalized light curve (lower) are shown.

and three for K2–33. These flare candidates had structures typical of flares, but the local noise level was too high for the 3σ condition to be satisfied. In addition, 20 flare events having only one measurement (no structure) were recorded for EPIC 211901114 and three for K2–33. Since the data considered were obtained with 30-min exposures, these phenomena may be either artifacts or flares of shorter durations. However, due to their uncertain origin, we did not consider these events to be flares.

As a result, we established that the flare rate for EPIC 211901114 is ~1 flare per 2 days, or 4.6 flares per rotation period. The flare rate for K2–33 is ~1 flare per 8 days, or one flare per ~1.2 period.

The flare amplitudes for EPIC 211901114 and K2–33 are in the range 0.001–0.051 and 0.002–0.011, with median values of 0.010 and 0.005, respectively. The rise and decay time scales of the flares are 0.04–3 hours and 0.27–2.9 hours for EPIC 211901114, 0.1–4.7 hours and 0.2–9.3 hours for K2–33.

We used the estimated excess radiation flux released during the flare $F_e(t)$ to derive the energy characteristics of the flares. We adopted distances of 117 pc and 129 pc for EPIC 211901114 and K2–33 [1], respectively, when finding the flare energies. Our estimates yielded $10^{32.1-33.4}$ erg for EPIC 211901114 and $10^{32.2-33.3}$ erg for K2–33. These energies are somewhat higher than those observed in solar flares, but lower than those recorded by us for a number of rapidly rotating dwarfs, such as LO Peg [18].

Assuming that the energy emitted by the star during a flare must not exceed the energy stored in spot-associated magnetic regions (i.e., $E_{\rm flare} \leq E_{\rm mag}$), we can estimate the minimum magnetic field strength B: $E_{\rm mag} \sim B^2 l^3$. Adopting a loop length l for a typical flare on the surface of an M dwarf to be 10^{10} cm, we obtain magnetic-field estimates of 0.3–1.4 kG and 0.3–1.3 kG for EPIC 211901114 and K2–33, respectively.

5. CONCLUSIONS

Our study of the stars EPIC 211901114 and K2–33 provides a unique opportunity to investigate young planetary systems. For example, it was concluded in [5] that the star K2–33 is a member of the Sco-Cen association (Upper Scorpius subgroup), whose estimated age is only $(9.3 \pm 1.1) \times 10^6$ years. This is probably one of the youngest planetary systems detected using transit measurements.

We have obtained the following results.

(1) We have traced the continuous evolution of active regions on the surfaces of EPIC 211901114 and K2–33 over a time span of 70 days. The brightness variations of these two stars are fairly stable. We have found the rotation periods of both EPIC 211901114 (8.56 ± 0.60^d) and K2–33 (6.29 ± 0.50^d).

(2) We have constructed maps of the temperature inhomogeneities on the surfaces of EPIC 211901114 and K2–33. All these maps contain clusters of spots at two longitudes, which we took to represent two independent active regions (active longitudes). For EPIC 211901114, we saw no relative variations of the active regions' positions on the surface of the star. We did find such variations for K2–33, and estimated the star's differential-rotation parameter to be $\Delta\Omega = 0.0039 \pm (0.0020-0.0012)$ rad/day.

(3) The fractional spotted area S on the surfaces of the stars are about 5% of the total visible surface area for EPIC 211901114 and 3.8%, on average, for K2–33.

(4) The positions of EPIC 211901114 and K2–33 on the S–age, S–rotation period, and S–Rossby number diagrams overall matches the general character of the dependence found by us earlier for M dwarfs.

(5) We have studied the flare activity of EPIC 211901114 and K2–33, based on 32 flares of EPIC 211901114 and 7 flares of K2–33. The flare rate for EPIC 211901114 is ∼1 flare per 2 days, or 4.6 flares per rotation period. the flare rate for K2–33 is ∼1 flare per 8 days, or ∼0.8 flares per rotation period. We have estimated the flare amplitudes for EPIC 211901114 and K2–33 together with the time scales for the rise and decay of the flares. We have estimated the flare energies to be $10^{32.1-33.4}$ erg and $10^{32.2-33.3}$ erg for EPIC 211901114 and K2–33, respectively.

ACKNOWLEDGMENTS

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