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Spots and Activity of Pleiades Stars from Observations with the Kepler Space Telescope (K2)

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Abstract—Observations of the K2 continuation of Kepler Space Telescope program are used to estimate the spot coverage S (the fractional spotted area on the surface of an active star) for stars of the Pleiades cluster. The analysis is based on data on photometric variations of 759 confirmed cluster members, together with their atmospheric parameters, masses, and rotation periods. The relationship between the activity (S) of these Pleiades stars and their effective temperatures shows considerable change in S for stars with temperatures $T_{\rm eff}$ less than 6100 K (this can be considered the limiting value for which spot formation activity begins) and a monotonic increase in S for cooler objects (a change in the slope for stars with $T_{\rm eff} \sim 3700$ K). The scatter in this parameter ΔS about its mean dependence on the $(V-K_s)_0$ color index remains approximately the same over the entire $(V-K_s)_0$ range, including cool, fully convective dwarfs. The computated S values do not indicate differences between slowly rotating and rapidly rotating stars with color indices $1.1 < (V-K_s)_0 < 3.7$. The main results of this study include measurements of the activity of a large number of stars having the same age (759 members of the Pleiades cluster), resulting in the first determination of the relationship between the spot-forming activity and masses of stars. For 27 stars with masses differing from the solar mass by no more than 0.1 $M_\odot$, the mean spot coverage is $S = 0.031 \pm 0.003$, suggesting that the activity of candidate young Suns is more pronounced than that of the present-day Sun. These stars rotate considerably faster than the Sun, with an average rotation period of 4.3^d. The results of this study of cool, low-mass dwarfs of the Pleiades cluster are compared to results from an earlier study of 1570 M stars.

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1. INTRODUCTION

The data with super-high photometric accuracy provided by the Kepler Space Mission archive have enabled qualitatively new approaches to studies of the activity of late-type stars.

The K2 continuation of the Kepler Space Mission has provided wide additional possibilities for studies of many objects in other parts of the sky, apart from the main observation field of the Kepler Space Telescope. Important new scientific problems that can be addressed using the K2 data include studies of the rotation of young low-mass stars. The main field observed by the Kepler Space Telescope contained no star-forming regions or young clusters (with ages less than one billion years). The fields observed in the K2 mission were especially selected to provide possibilities for studies of the light curves of a fairly large number of young objects in stages preceding the main sequence (in Scorpio and Taurus) and the light curves of stars in young clusters (the Pleiades, M35, the Hyades, Praesepe). The resulting data with high photometric accuracy are undoubtedly a unique resource for studies of the rotational evolution of low-mass stars, and appreciably supplement numerous earlier studies aimed at analyzing the evolution of the angular momentum of late-type stars having various ages.

In the series of papers [1–3], K2 observations were used to analyze the light curves of several stars in the Pleiades cluster, in order to study the evolution of their angular momenta and activities. The shapes of the light curves were also analyzed.

It was demonstrated in [3] that the $(V-K_s)_0$ photometric indices of objects belonging to a sequence of slowly rotating stars identified by the authors ranged from 1.1^m to 3.7^m, and their spectral types from F5 to K8. The rotation periods of these stars are between 2 and 11^d. Almost all these objects display considerable

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variations in their light curves on time scales shorter than the duration of the observations (72 days). According to [3], the light curves for virtually all fully convective M dwarfs ($5.0 < (V-K_s)_0 < 6.0$) are stable, demonstrating only small variations due to the surface evolution of spots or an absence of differential rotation.

In total, K2 data were used in [3] to study 775 stars with high probability of Pleiades cluster membership and 51 stars with lower probability of cluster membership, with the total number of studied objects being 826.

The purpose of our current study is to estimate parameters describing the activity of stars in the Pleiades cluster, including the spot coverage S, defined as the fraction of the visible stellar surface covered with spots, and to investigate how S varies with the rotation period, Rossby number Ro, and other characteristics of these objects.

2. DATA AND ANALYSIS

As in our earlier studies (e.g., [4–6] and references therein), we used high-accuracy photometric observations acquired with the Kepler Space Telescope to analyze the properties of active regions (cool spots) on the surfaces of the 759 of the 826 stars considered are cluster members beyond doubt and have rotation periods determined in [3].

As earlier [4], we derived the spot coverage S from photomeric observations using the simple technique proposed in [7, 8]. As was noted above, the parameter S is the ratio of the total area of all spots to the total visible surface area of the star.

It was noted in [4] that this technique essentially indicates only the variation amplitude of S for the star's hemisphere with the maximum spot coverage compared to the opposite hemisphere. Thus, we can only obtain a lower limit to the spot coverage, since we do not know the level of the star's brightness in the absence of surface spots. In addition, to improve the accuracy of the method, we did not employ computations using relations between the surface-brightness parameter and color indices in our realization of this method in [8], and directly applied data based on computations with the Kurucz or Phoenix grids. An obvious advantage of this approach is that it can be applied to fairly large samples of objects for subsequent statistical analysis, aimed at deriving relations of a general character.

In the current study, we applied the technique of [8] to analyze the activity of 759 stars in the Pleiades cluster. We used the data of [3, Table 3] on photometric variations of the studied stars, as well as their atmospheric parameters, masses, radii, and rotation periods.

3. DEPENDENCE OF THE SPOT-COVERAGE PARAMETER ON THE EFFECTIVE TEMPERATURE AND MASS

The upper panel of Fig. 1 shows the dependence of the spot coverage S (which can be considered as an indicator of a star's magnetic activity) on the star's effective temperature $T_{\rm eff}$ for 759 objects from [3]. To facilitate comparison with the results of our earlier study [4], the lower panel of Fig. 1 shows the same relation with a logarithmic vertical scale. The spot coverage for objects with effective temperatures higher than 6000 K does not exceed 0.05. The parameter S increases for objects with lower $T_{\rm eff}$ values, reaching 0.25–0.30 for the coolest stars (with $T_{\rm eff} \sim 3000$ K).

The deficiency of objects with effective temperatures about 3775 K, noted in the results of [4] and visible in Fig. 1, is probably an artifact related to the temperature calibration of the Kepler catalog data (similar issues for objects with $T_{\rm eff}$ values of about 4500 K were discussed in [4]).

When considering Fig. 1 (lower panel), two features attract attention: a considerable change in S for stars with $T_{\rm eff} > 6100$ K and a possible non-monotonic increase in S towards cooler stars (a bend at $T_{\rm eff} \simeq 3700$ K). The red vertical line in this diagram shows the range of variations of S for the Sun in various phases of its activity cycle.

The upper panel of Fig. 2 shows the dependence of S on $(V-K_s)_0$. Diagrams of this kind (for example, relating the stellar rotation periods to $(V-K_s)_0$) are discussed in detail in [3]. In particular, a sequence of slowly rotating stars was detected [3, Fig. 2], which defines an upper envelope for stars of spectral types from F5 to K. This sequence is clearly expressed for stars in older clusters (see the discussion in [3]), and is already well defined for Pleiades stars (with ages of 125 million years). The left and right ends of the sequence of slowly rotating stars correspond to the color indices $(V-K_s)_0 = 1.1$ and 3.7 (solid lines in the upper panel of Fig. 2). The left dashed line is plotted for $(V-K_s)_0 = 2.6$, which corresponds to the location of the bend in the sequence of slowly rotating stars. A similar bend may be present in the dependence of S on $(V-K_s)_0$, but it is not so clearly expressed. Finally, we can conclude from Fig. 2 (upper panel) that the spot coverage is virtually the same for slowly rotating and rapidly rotating stars with $(V-K_s)_0 < 3.7$ (in our figure, these stars do not form obvious sequences like those presented in [3, Fig. 2]). Note that the scatter ΔS about the mean dependence on $(V-K_s)_0$ remains approximately the same for objects over the entire range of $(V-K_s)_0$, including cool, fully convective dwarfs. The considerable scatter ΔS hinders firm conclusions about the

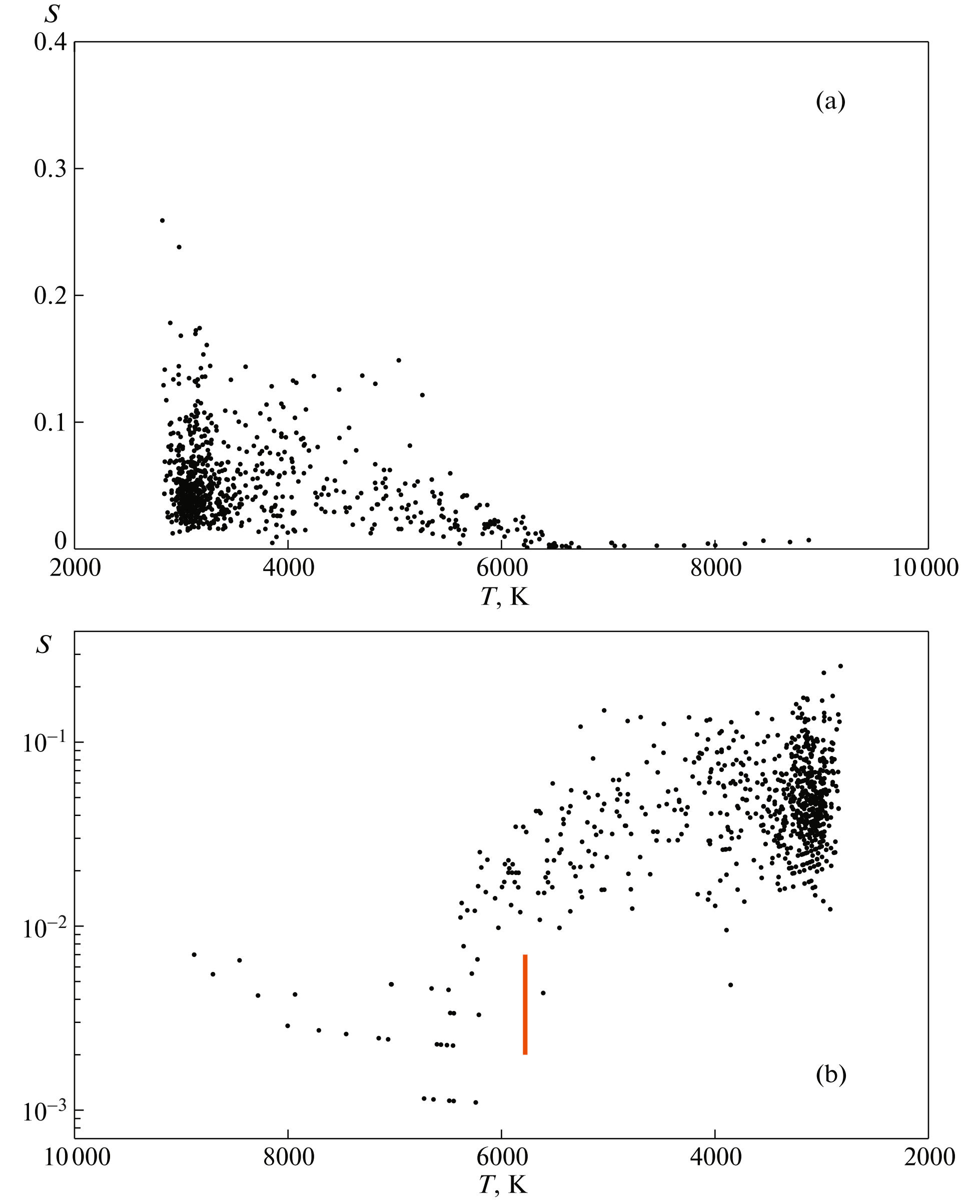

Fig. 1. (a) The spot coverage S for stars in the Pleiades cluster versus their effective temperature $T_{\rm eff}$. The parameter S is expressed as a fraction of the star's total visible surface area. (b) The same diagram plotted with a logarithmic vertical scale. The vertical red line shows the range of variation of S for the Sun during different phases of its activity cycle.

presence or absence of monotonic changes in S or the presence of a jump for objects with $(V-K_s)_0 > 5$.

The mass dependence of the spot coverage S for the 759 objects is shown in Fig. 2 (lower panel). This is the first time that data on variations of spot-forming activity (S) have been presented for such a large number of stars (759) with the same age (all members of the Pleiades cluster). There is no doubt that relations such as that plotted in Fig. 2 (lower panel) will be of considerable importance when verifying models describing the formation of magnetic structures on stars; in future, they may be used to refine parameters characterizing dynamo mechanisms. Similar diagrams plotted for stars from clusters of different ages will make it possible to study the time evolution of the activity of stars of various ages.

No indication of activity related to the formation of cool surface spots was found for stars with masses higher than 1.25 $M_{\odot}$. The parameter S increases from 0.01 to 0.2–0.3 with decreasing mass. The spotted area detected on the surfaces of the highest-mass program stars is considerable, exceeding 1% of the total visible area of the star. The relation shown

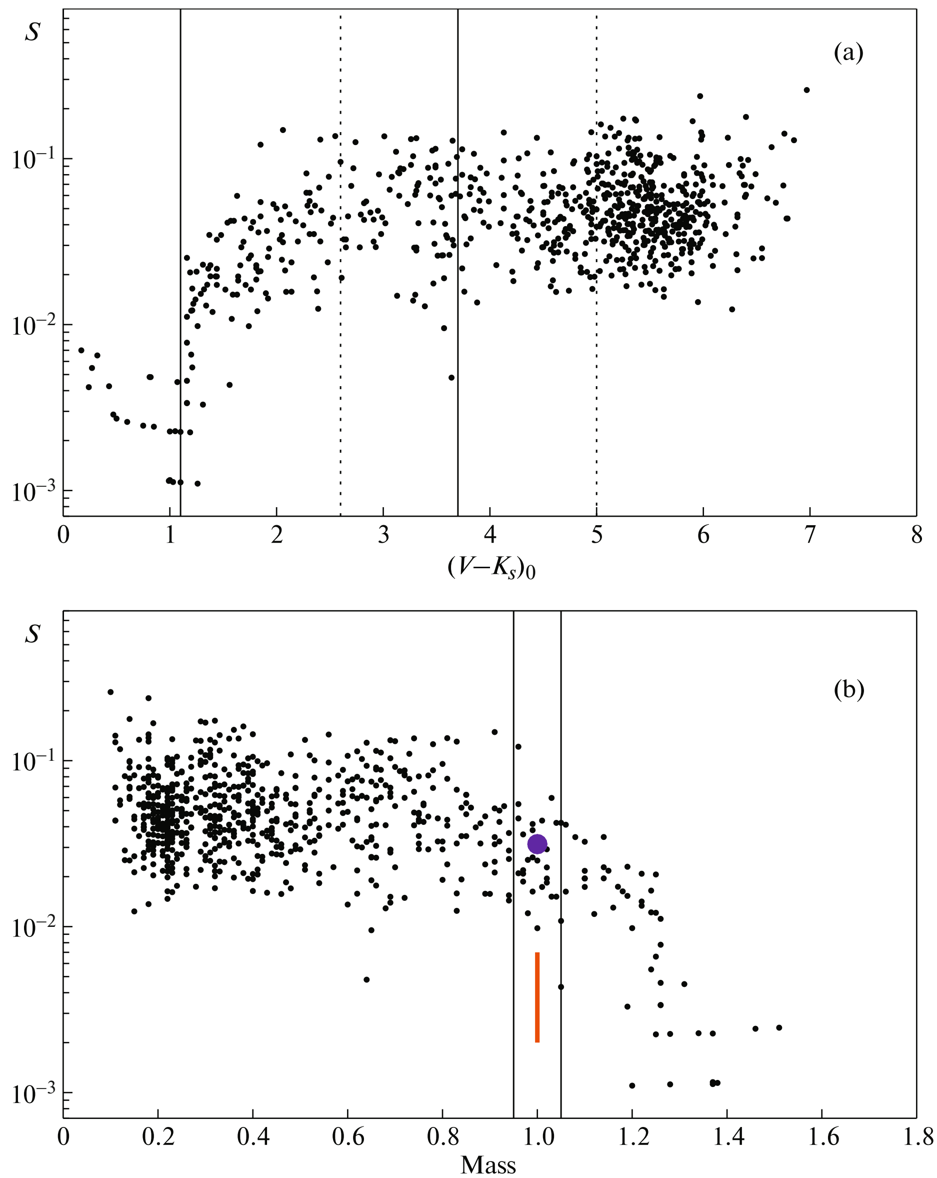

Fig. 2. (a) The spot coverage S versus their $(V-K_s)_0$ color indices. The left and right boundaries of the sequence of slowly rotating stars, plotted as vertical solid lines, correspond to $(V-K_s)_0 = 1.1$ and 3.7. The dashed vertical lines are plotted for $(V-K_s)_0 = 2.6$ (the value corresponding to the bend in the sequence of slowly rotating stars) and $(V-K_s)_0 = 5$ (corresponding to the limiting value for possible bends of the relation for objects with $(V-K_s)_0 > 5$; see the text). (b) Dependence of S on the stellar mass. The vertical red line shows the range of variation of S for the Sun. The solid vertical lines show the boundaries of the area with 27 stars having masses differing from that of the Sun by no more than 0.1 $M_\odot$; the filled blue circle is the mean S value for these objects.

in Fig. 2 (lower panel) may have a bend for stars with masses of (0.5–0.6) $M_\odot$.

4. ANALYSIS OF THE S FOR SOLAR-TYPE STARS AND RED DWARFS IN THE PLEIADES CLUSTER

Among objects in the Pleiades cluster, studies of solar-type stars are of special interest. Studies of the activity of stars with parameters similar to those of the Sun are important for identifying the character of the evolution of the activity of nearest star. This should help us understand how the solar activity has changed with time and how it is related to the properties of younger stars (e.g., Pleiades stars with ages of about 125 million years) with masses close to 1 $M_\odot$. We selected from the complete list of 759 objects 27 stars with masses differing from the solar mass by no more than 0.1 $M_\odot$. The mean S for these objects is 0.031 ±

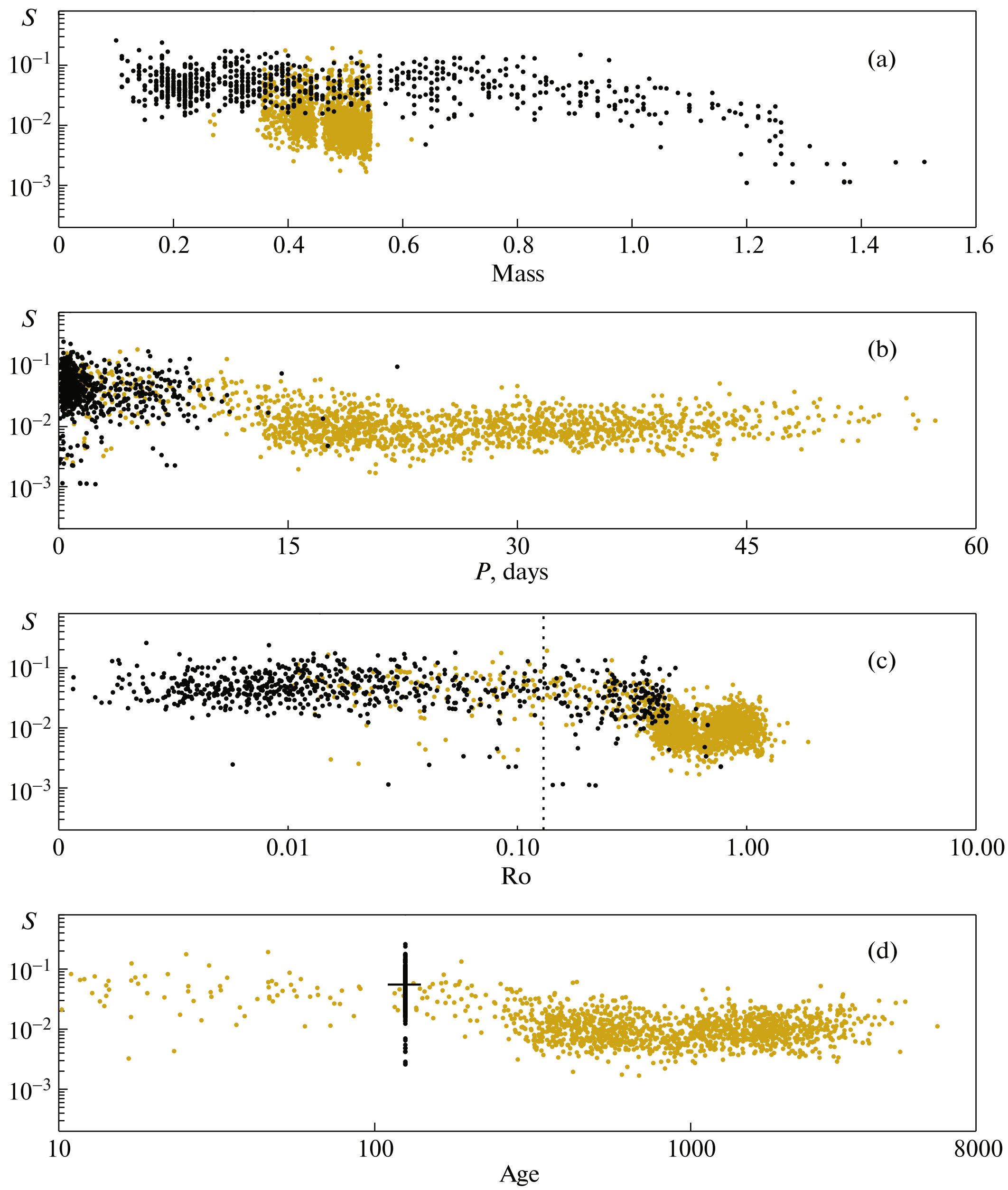

Fig. 3. Dependences of the spot coverage S on the (a) stellar mass, (b) rotation period, (c) Rossby number (the dashed line corresponds to Ro (saturation) = 0.13), and (d) age. The short horizontal line in panel (d) corresponds to the mean S for Pleiades dwarfs. In all the diagrams, the black circles show data for Pleiades objects and the yellow circles data for 1570 objects from [4].

0.003. If we consider these to be candidate young Suns, we can conclude that their activity is more pronounced than for the present-day Sun (Fig. 2, lower panel). These stars rotate considerably more rapidly than the Sun, with a mean rotational period of about 4.3^d.

A considerable fraction of the objects studied in [3] are low-mass dwarfs. The number of stars with masses below 0.6 $M_\odot$ is 530, and the number of dwarfs with masses below 0.3 $M_\odot$ (fully convective stars) is 287 (of the total of 759 objects in the sample). Clearly, the data presented in [3] open unique prospects for studies of the activity of rapidly rotating, low-mass stars.

Earlier, in [4], we used the same method to estimate the spot coverage S for 1570 M dwarfs, based on observations obtained with the Kepler Space Telescope. We studied changes in S with the age and rotational period of the objects. We found that the S–Rossby number (Ro) relation reproduced the classic relationship between the X-ray luminosity of active stars and their Ro values, with the saturation mode in this diagram achieved at the same Ro value, Ro (saturation) = 0.13. We also demonstrated that objects with ages above 100 million years do not form a single sequence (while stars older than 900 million years had surface spot coverages of about 1%).

Figure 3a presents the dependence of S on the mass for stars of the Pleiades cluster, with overplotted data for 1570 objects from [4]. Most objects from [4] have masses between 0.34 and 0.54 $M_{\odot}$. Compared to the data for the Pleiades stars, the S values for these objects are lower, on average, by 0.05–0.06 dex.

Figure 3b relates S to the rotation periods of the stars. All the Pleiades objects rotate fairly rapidly, even taking into account the sequence of slowly rotating stars (see above): generally, the periods P of most objects do not exceed 10^d, with a clearly represented group of stars having periods below $3{-}4^d$. We can conclude from Fig. 3b that the 1570 objects from [4] include fairly many cool (probably older) dwarfs that rotate more (rotation periods up to 60^d), than the Pleiades stars (rotation periods up to 11^d). Earlier, in [4], we identified two groups of objects: those with rotation periods $P < 2^d$ and those with $P \sim 2{-}13^d$. The former group consists of rapidly rotating stars with large spotted areas on their surfaces (S values in the range 0.01–0.30). The stars in the latter group may show a trend for lower spot coverages with increasing rotation period. Note that both trends in the behavior of S detected for field stars in [4] also hold for the Pleiades members: in the region of the most rapidly rotating (young) stars, the typical spot coverages in the samples [3, 4] overlap ($S \sim 0.03{-}0.11$); with increasing rotation period, the spot coverage decreases, reaching a possible jump for objects with $P \sim 13^d$.

The Pleiades stars are mostly in the saturation region in the S–Ro diagram, to the left of the line Ro (saturation) = 0.13 (Fig. 3c).

In our study [4], we used the technique of [9] to compute the ages of the program objects. As in [9], we restricted our consideration to stellar ages established using parameters of the gyrochronologic relation [10]. The relationship between S and the age t for the 1570 objects from [4] and for the Pleiades stars is presented in Fig. 3d. In the corresponding diagram in [4], we identified four groups of objects, with ages $t < 100$ million years, $t \sim 100{-}400$ million years, $t \sim 400{-}900$ million years, and $t \gtrsim 900$ million years–1 billion years. As it was concluded in [4], the first two groups consist of the youngest and most active stars, with very youngest of these (with ages below 100 million years) forming a plateau in the diagram. We noted in [4] that, according to our estimates and the conclusions of [9], the age estimates for stars younger than 100 million years should be treated with caution, since they could contain large uncertainties. The data for the Pleiades cluster members presented in Fig. 3d agree fairly well with the S values for the youngest, rapidly rotating stars from [4] (the mean S value is 0.081, somewhat higher than the value derived in [4] for dwarfs with ages of 100–140 million years).

We can thus conclude that these data for Pleiades stars significantly augment the results of our earlier study of low-mass dwarfs, and are most valuable for the analysis of young objects.

5. CONCLUSIONS

We have applied a technique we had developed earlier to members of the Pleiades cluster, in order to estimate their spot coverages, S, as a way of describing their activity (S is the fractional area of spots on the surface of an active star). We used the published data [3], which contain information on the photometric variations of 759 firm Pleiades cluster members (their atmospheric parameters, masses, and rotation periods are also presented).

We have obtained the following results.

1. Our investigation of changes in activity (S) for the Pleiades stars with their effective temperatures has revealed two characteristic features: considerable changes in S for stars with $T_{\rm eff} > 6100$ K (the limit for which spot-forming activity begins) and a non-monotonic increase in S for cool stars (a bend at $T_{\rm eff} \sim 3700$ K).

2. A sequence of slowly rotating stars was identified in the relation between rotation and the $(V{-}K_s)_0$ color index in [3] (whose left and right boundaries correspond to $(V{-}K_s)_0 = 1.1$ and 3.7). Our calculations of the spot coverages did not indicate differences in S for slowly and rapidly rotating stars in this range of color indices. The scatter ΔS about the mean dependence on $(V{-}K_s)_0$ remains approximately the same for objects over the entire range of variation of $(V{-}K_s)_0$, including cool, fully convective dwarfs. The considerable scatter ΔS hinders firm conclusions about whether there are any monotonic variations in S and whether there is a jump in the transition to objects with $(V{-}K_s)_0 > 5$.

3. One of the main results of our study is that we have presented measurements of the activity (S) for a large number (759) of stars with similar ages (Pleiades cluster members), making it possible, for the first time, to obtain the dependence of the spot-forming activity and the masses of these stars.

4. From the complete list of 759 objects, we selected 27 stars with masses differing from the mass of the Sun by no more than 0.1 $M_\odot$. The mean S value for these objects is 0.031 ± 0.003. Considering the selected stars as candidate young Suns, we conclude that their activity is more strongly expressed than the activity of the present-day Sun. These stars rotate considerably more rapidly than the Sun; their mean rotation period is 4.3^d.

5. We have compared the results of our study of cool low-mass dwarfs in the Pleiades cluster to the results of our earlier study [4] of 1570 M dwarfs in the main field observed by the Kepler Space Telescope. We have studied the variations of S with the mass, age, rotation period, and Rossby number for the combined sample of our program objects.

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