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 $T_{\text{eff}}$ 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 $T_{\text{eff}} \sim 3700$ K). The scatter in this parameter $\Delta S$ 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 computed $S$ 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 days. 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 to 3.7, and their spectral types from F5 to K8. The rotation periods of these stars are between 2 and 11 days. 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 $R_\text{o}$, 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 photometric 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 $T_{\text{eff}}$ 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 $T_{\text{eff}}$ values, reaching 0.25–0.30 for the coolest stars (with $T_{\text{eff}} \sim 3000$ 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 $T_{\text{eff}}$ 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 $T_{\text{eff}} > 6100$ K and a possible non-monotonic increase in $S$ towards cooler stars (a bend at $T_{\text{eff}} \simeq 3700$ 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 $\Delta S$ 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 $\Delta S$ hinders firm conclusions about the