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COMPARATIVE ANALYSIS OF THE ACTIVITY CYCLES OF THE ATMOSPHERES OF THE SUN AND OF STARS OF THE SOLAR-TYPE

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The atmospheric activity of the sun and of stars of the solar-type is analyzed using observations from the HK-project at the Mount Wilson Observatory, California, and the Carnegie Planet Search Program at the Keck and Lick Observatories, as well as from the Magellan Planet Search Program at the Las Campanas Observatory. It is shown that a cyclical activity of the stars that is analogous to the 11-year solar activity cycle occurs in stars of spectral classes F, G, and K and is more pronounced in stars of class K. A comparative analysis of the solar-type stars with different levels of chromospheric and coronal activity confirms that the sun is one of the stars with a comparatively low level of atmospheric activity and that these stars have a minimal level of coronal emission and minimal variations in the fluxes of photospheric radiation.

Keywords: *Sun: atmosphere: stars of solar type: activity cycles: stars: HK-project*

1. Introduction

The magnetic activity of the sun and of stars of the solar-type is evidence of complex electromagnetic and hydrodynamic processes in their atmospheres. It is known that the variations in the total flux and in the flux in individual lines are cyclical processes for the sun and for stars [1-4]. Although the average solar activity cycle lasts

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about 11 years, cycles lasting from 9 to 14 years do occur. The average values have also varied over the centuries. Thus, in the 20th century the average length of the cycle was 10.2 years [5,6].

Based on observations of stars that are analogous to the sun as part of the HK-project at the Mount Wilson Observatory activity cycles have been reliably detected in other stars. The durations of the chromospheric activity cycles determined for 50 stars of spectral classes F, G, and K range from 7 to 20 years. The HK-project, begun by O. Wilson in 1956, is still under way. It is one of the most effective programs for study of solar-type activity in stars [1,7]. Currently, there are several data bases covering thousands of stars with measured fluxes in chromospheric CaII lines [8-12], but the periods of the magnetic activity cycles are known for only a few dozen stars [1,3,7,10].

In this paper we analyze data from three programs for observing stars of the solar-type with known values of the S-index, a parameter characterizing the level of chromospheric activity in stars:

1. The HK-project is a program of the Mount Wilson Observatory that determines the S-index, which has become the standard characteristic of the level of chromospheric activity [1,7]. These values of the S-index are compared with and used to calibrate the subsequent programs for observation of stars with active chromospheres.

2. The California program and the Carnegie Planet Search Program, which include observations of about 1000 stars at the Keck and Lick Observatories in the CaII H and K chromospheric emission lines. The S-indices of these stars were determined in the Mount Wilson system [8]. Based on these measurements and using general parametric models, the median activity levels, age, and rotation periods for 1228 stars were determined. The S-indices of ~1000 of these stars had not been published previously.

3. The Magellan Planet Search Program at the Las Campanas Observatory. This includes measurements of chromospheric activity of 670 main sequence stars in spectral classes F, G, K, and M observed in the southern hemisphere. The S-indices of these stars were also given in the Mount Wilson system [9].

The purpose of this paper is:

(1) to study the place of the sun among stars of the solar-type with different levels of chromospheric and coronal activity, and

(2) to make a comparative analysis of the chromospheric, coronal, and cyclical activity of the sun and of stars of the solar-type.

2. The place of the sun among stars of the solar-type with different levels of chromospheric and coronal activity

The sun and the stars from the different samples are shown on a Hertzsprung-Russell diagram in Fig. 1. Approximately 1000 stars of the solar-type from Ref. 8 observed as part of the California and Carnegie Planet Search Program (hollow circles), 600 stars from Ref. 9 as part of the Magellan Planet Search Program (asterisks), 110 stars and the sun from Ref. 1 as part of the Mount Wilson HK-project (shaded circles) are shown. The smooth curve corresponds to the initial main sequence (ZAMS) on the Hertzsprung-Russell absolute stellar magnitude-color index diagram.

The stars close to the ZAMS in Fig. 1 are the youngest of all the stars shown here, with an age of 10^8-$10^{8.5}$

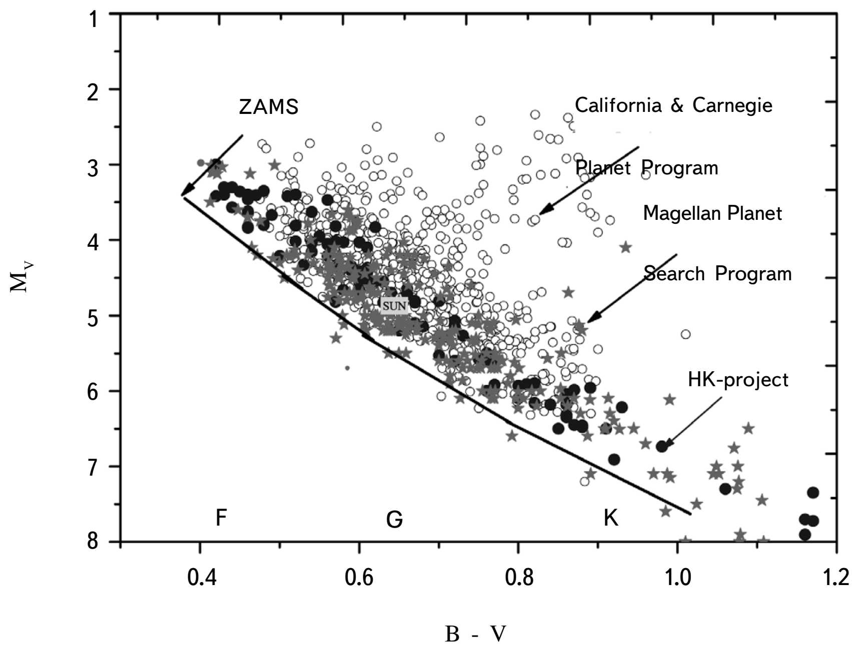


Fig. 1. The sun among stars of the solar-type from different observation programs plotted on a Hertzsprung-Russell diagram.

years. The older stars lie higher above that curve. The ages of the stars shown in Fig. 1 range from 10^9 to 10^{10} years. A significant deviation of some of the stars from the main sequence can also be seen in Fig. 1; this is because a number of subgiants with large values of M_V were included in the search program. We have neglected the subgiants in our analysis of chromospheric and coronal activity.

Convective motions in the subphotospheric layers of the sun excited different kinds of hydrodynamic waves in the atmosphere. The energy flux of these waves falls off with height relatively slowly, and the combination of a rapid drop in the density of matter and a slow decrease in the energy flux of the waves that are efficiently absorbed by this matter leads to a rise in temperature. As a result, in the sun there is a comparatively narrow region in height, about 100 km, with a temperature minimum, above which the chromosphere begins. The emission lines found in spectra of bright stars of the solar-type originate at different levels of their atmospheres, from the lower chromosphere to the transition zone between the chromosphere and the corona. An analysis of these lines showed that stars of the solar-type (F, G, K) have essentially the same type of atmosphere as the sun, while the chromosphere of active red dwarfs (M) is substantially more powerful than that of the sun [13]. The systematic changes in the predominant solar activity phenomena along the main sequence arise from different activity phenomena. Thus, for F and some G stars, activity that is higher, but less regular, than that of the sun predominates. G and K stars are characterized by stable cycles, while red M-dwarfs have irregular flares [14].

Figure 2 shows how stars with different levels of chromospheric activity are distributed over the spectral classes. It is clear that the S-indices characterizing the chromospheric activity of the star differ greatly. For stars

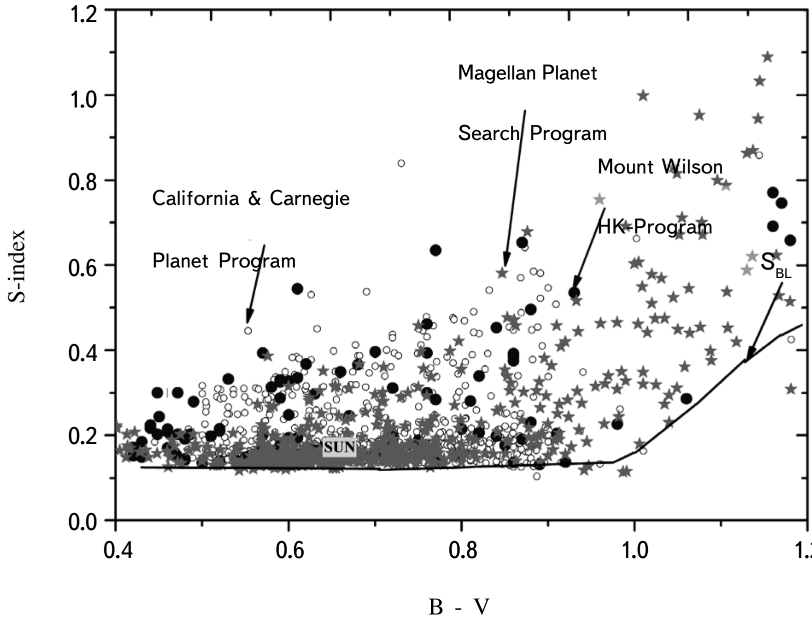


Fig. 2. Chromospheric activity of stars in spectral classes F, G, K, and M according to data from the three observation programs.

in spectral class F, the S-index ranges from 0.13 to 0.3, for class G, from 0.13-1.5, and for class K, from 0.13 to 0.6-0.7. According to Ref. 10, the average levels of chromospheric activity (corresponding to the Mount Wilson S-index) are higher for stars in spectral class F than for G-stars. On the other hand, for stars in spectral classes K and M, the average levels of chromospheric activity are also higher than for G-stars.

A lower envelope for the chromospheric activity, the basic level *S*-index S_{BL}, as a function of the color index (*B-V*) and a polynomial approximation for it have been determined for the large sample of 2600 stars from the California Planet Search Program [10]. S_{BL} is indicated by the smooth curve in Fig. 2. For stars with color indices $0.4 < B - V < 1.0$ is essentially constant (roughly equal to 0.13) and for stars with $1.0 < B - V < 1.6$ begins to rise gradually from 0.13 to 0.6. It was assumed [10] that this increase in S_{BL} is related to a reduction in the continuum flux for redder stars, since the *S*-index is defined as the ratio of the CaII H and K emission to the nearby continuum. From the location of the sun in Fig. 2, it is clear that the level of the sun's chromospheric activity is somewhat below the average level of chromospheric activity of main sequence stars.

In stars of the solar-type belonging to later spectral classes, x-ray emission is generated by the high-temperature plasma of the stellar corona [15]. The relationship between a star's rotation and its x-ray luminosity L_x was first discovered and estimated in Ref. 16. Figure 3 is a plot of the ratio of the x-ray luminosity to the bolometric luminosity, L_x/L_{bol}, as a function of rotation period P_{rot} for 824 stars from Ref. 17 and 80 stars from the HK-project according to data from the ROSAT All-sky Survey (0.1-2.4 keV) [18]. The x-ray luminosities of the stars from the catalog of Ref. 17 were determined for the same range, 0.1-2.4 keV, as the x-ray luminosities of the stars from the ROSAT catalog.

Figure 3 shows that there are two main modes of coronal activity: linear, in which the activity increases as

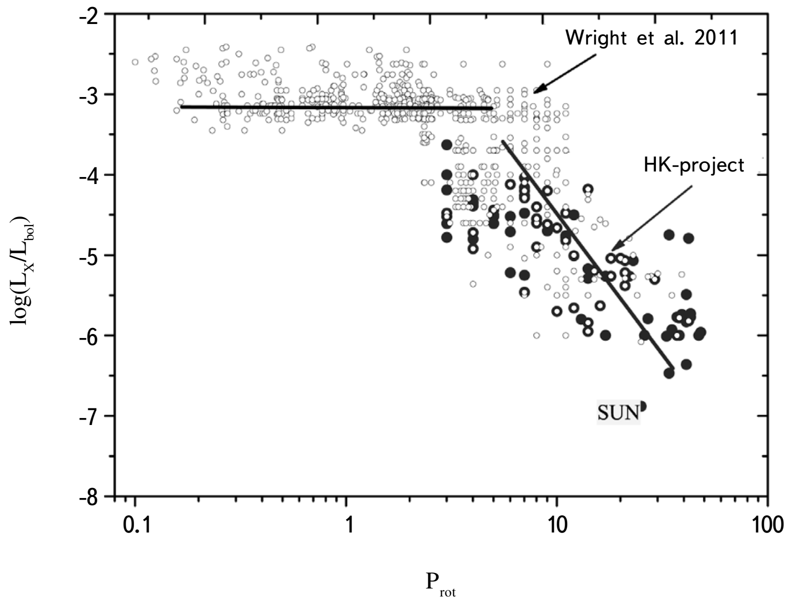


Fig. 3. Ratio of x-ray and bolometric luminosities as a function of rotation period.

the rotation period decreases, and a saturation mode, in which the ratio of the x-ray and bolometric luminosities is constant at $\log(L_X/L_{bol}) = -3.13$.

Stars from the HK-project which are not sufficiently young and active belong in the linear mode of Fig. 3. Here the sun confirms its unique position among solar-type stars: it has the lowest value of L_x/L_{bol} of all the stars examined here.

Over the 11-year activity cycle of the sun, the variations in the radiative flux of the solar atmosphere are very small, no more than 0.2%. It is evident that the variations in the radiative flux of the sun's photosphere and the other stars are related to variations in the areas of spots on the disk. The relative area occupied by spots (S_{spot}) on the surface of the sun and the other stars has been estimated [14,19]. It ranges from 0.2% (for the sun) to 2-3% for stars in the HK-project (spectral classes F, G, and K). For highly spotted stars (M-stars), S_{spot} reaches 10-15% [20-22].

An analysis of time series of observations of the fluxes of photospheric and chromospheric emission in the CaII lines for stars analogous to the sun showed that there is a stable empirical correlation between the average level of chromospheric activity and the variability in the photospheric continuum [23]. As a rule, more active stars have a higher level of variability in the photospheric continuum flux. The variability in the photospheric continuum flux of the sun was substantially lower than expected based on its level of chromospheric activity. It has been suggested [23] that over a longer time scale (hundreds of years), the position of the sun in the diagram of the variabilities in the flux from the photospheres as a function of chromospheric activity is not stable, and that with time the quantitative characteristics of the variability in the fluxes in the photospheric continuum may come to agree with this empirical dependence. At present, however, we can see that the sun confirms its unique position among the stars with activity of the solar type: the variations in the fluxes from the solar photosphere are unusually small.

3. Cyclical activity of stars in the HK-project

It can be seen that of the data bases on observation of stars of the solar-type with known values of the S-index, the sample of stars in the HK-project was specially acquired for the study of stars that are close analogs of our sun. These are isolated stars with masses close to that of the sun that belong to the main sequence. Close binary systems were eliminated from the program. In addition, as opposed to the other programs for planetary searches, the HK-project of the Mount Wilson Observatory was specially developed for the study of cyclical activity of the solar type in F, G, and K stars.

The combined simultaneous observations of radiative fluxes and rotation periods in the HK-project made it possible, for the first time in stellar astrophysics, to detect rotational modulation of the observed fluxes [24]. This meant that there are nonuniformities on the surface of a star that evolve over several rotation periods of the star about its axis. In addition, the evolution of the rotation periods of stars was a clear indication of differential rotation analogous to that in the sun in these stars.

The evolution of active regions on a star's surface over a time scale on the order of 10 years determines a cyclical activity analogous to that of the sun. Periodograms were calculated [1] for 111 stars in the HK-project to determine the duration of the cycles when cyclical activity was detected. The significance of the height of a high peak in the periodogram was evaluated by constructing Lomb-Scargle periodograms [25] using the FAP (false alarm probability) function. The stars with cycles were classified as follows: if the calculated cycle period $P_{cyc} \pm \Delta P$ has a function $\mathrm{FAP} \leq 10^{-9}$, then the star belongs to the "Excellent" class; if $10^{-9} < \mathrm{FAP} \leq 10^{-5}$, it belongs to the "Good" class; if $10^{-5} < \mathrm{FAP} \leq 10^{-2}$, it belongs to the "Fair" class; and, if $10^{-2} \leq \mathrm{FAP} \leq 10^{-1}$, then the star belongs to the "Poor" class.

Regular cycles were found for 50 of the 111 stars from the HK-project, with varying levels of reliability. The periods P_{cyc} ranged from 7 to 20 years. Cyclical activity of the "Excellent" class was found for 12 stars plus the sun out of these 50 stars and of the "Good" class, for 8. It should be noted that stars in the "Excellent" and "Good" classes have $\mathrm{FAP} \leq 10^{-5}$ and, by definition, have very stable cyclical activity periods P_{cyc}. Unstable cyclicity with $\mathrm{FAP} \geq 10^{-2}$ is a characteristic of the stars in the "Fair" and "Poor" classes, and stars without signs of cyclicity are classed as "Var."

The results of 4 years of direct observation of magnetic activity cycles in 19 stars of the solar-type in spectral classes F, G, and K are discussed in Ref. 2. The stars in this sample have masses ranging from 0.6 to $1.4 M_{\odot}$ (times the sun's mass) and rotation periods of 3.4 to 43 days. The observations were made with the NARVAL spectropolarimeter (Pic du Midi, France) during 2007-2011. According to these direct measurements, 17 of the 19 stars manifested a cyclicity analogous to the solar two-year cycles. It was found that the stars τBoo and HD 78366 (which are also in the Mount Wilson Observatory's HK-project) also have cycles with periods of from 2 to 3 years analogous to the sun's two-cycles. In Ref. 1, where the cyclicity was determined using Lomb-Scargle periodograms, these cycles

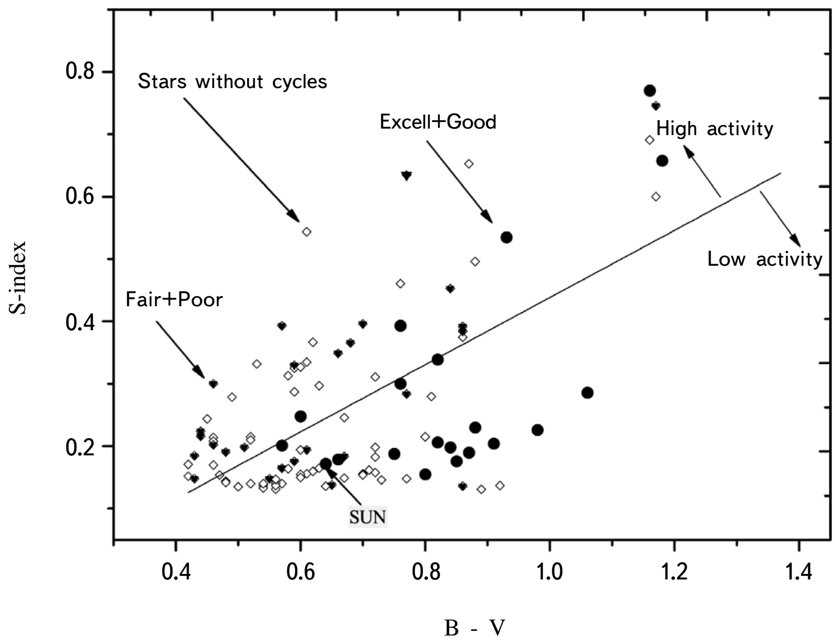


Fig. 4. Stars from the HK-project observed from 1969-1994: the S-index is plotted as a function of color index (*B-V*). The smooth line is the linear regression (1), the "Excellent + Good" stars are indicated by solid circles, the "Fair + Poor" stars, by triangles, and the stars without cycles, by hollow diamonds.

analogous to the sun's two-year cycles, were not detected in the stars τBoo and HD 78366. This can be explained in terms of an analogy with the solar cycles: the quasi-two-year cycles are characterized by (1) instability of their period and (2) a relatively small variation of the amplitude in the cycle. The amplitude of the variability of the emission in the quasi-two-year cycles of the sun is an order of magnitude smaller than that in the 11-year cycle. It was proposed [2] that if the period of their spectropolarimetric observations has been long enough, the cycles on an 11-year time scale observed in τBoo and HD 78366 at Mount Wilson would also be confirmed.

According to observations from the Kepler orbiting observatory, "shorter" cycles of chromospheric activity with a period of about two years have been found for stars of the solar-type in spectral classes F, G, and K [12,26]. A "short" cycle (analogous to the quasi-two-year solar cycle) with a duration of 2.7 years has also been found for the star EI Eri [3].

It turns out that the distribution of the stars with cycles in the "Excellent," "Good," "Fair," and "Poor" classes plays an important role: stars with stable "Excellent" and "Good" cycles and stars with unstable "Fair" and "Poor" cycles belong to different groups in plots of the S-index versus color index (*B-V*), the x-ray luminosity $\log L_x$ versus (*B-V*), and the period P_{cyc} of the chromospheric activity versus age, log(Age/yr). See Figs. 4, 5, and 7.

In Figs. 4 and 5 we can see that, on the average, stars with stable "Excellent" and "Good" cycles have lower levels of chromospheric and coronal activity than the stars with unstable cyclicity. Figure 7 confirms the fact that stars with stable "Excellent" and "Good" cycles stand out among the stars with cycles: while not all of the stars

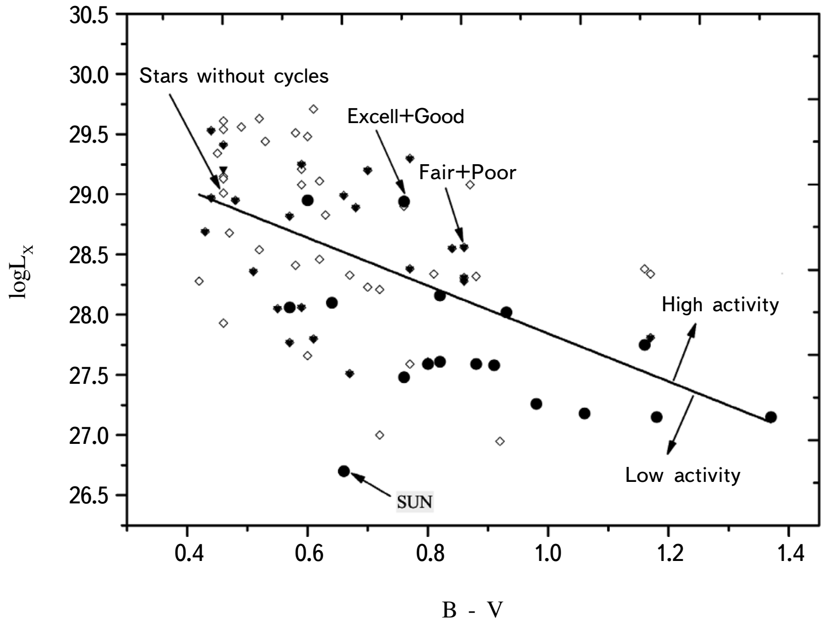


Fig. 5. Stars from the HK-project observed from 1969-1994: the x-ray luminosity L_x is plotted as a function of color index (*B-V*). The smooth line is the linear regression (2), the "Excellent + Good" stars are indicated by solid circles, the "Fair + Poor" stars, by triangles, and the stars without cycles, by hollow diamonds.

exhibit a dependence of the cycle periods on age, the average period of the cycles in "Excellent" and "Good" stars increase by roughly 20% as the age of the stars increases from $10^{8.5}$ to 10^{10} years.

The processes determining the complicated phenomena of stellar activity and covering essentially the entire atmosphere from the photosphere to the corona behave differently in solar-type stars in different spectral classes. The observational data from the HK-project at the Mount Wilson Observatory can be used to study the cyclical activity of solar-type stars at the same time as their chromospheric and coronal activity. We have selected data on the x-ray luminosity $\log L_x$ for 80 of the HK-project stars from the ROSAT All-sky Survey [18]. As noted previously [1], the average chromospheric activity of the stars or, more precisely, the *S*-index, increases with increasing color index (*B-V*). See Figs. 2 and 4.

Our regression analysis of the HK-project stars yielded the following linear regression:

$$S = -0.10 + 0.530 \cdot (B - V). \tag{1}$$

We denote the right hand side of Eq. (1) by $F(B-V)$. We treat stars with $S > F(B-V)$ as stars with a high level of chromospheric activity and those with $S < F(B-V)$ as stars with a low level of chromospheric activity (see Fig. 4). We then analyzed all 100 of the HK-project stars plus the sun in order to determine their level of chromospheric activity (high or low). We discuss the results below in a comparative analysis of stars in different

TABLE 1. Comparative Analysis of Cycles and Quality of Cyclical Activity for Stars in Different Spectral Classes

Spectral class	F2 - F9	G0 - G9	K0 - K7
$\Delta(B-V)$	0.42 - 0.56	0.57 - 0.87	0.88 - 1.35
Number of stars in spectral interval	39	44	27
Number of stars with known L_X	27	29	24
Rel. number of stars with elevated coronal activity	60%	48%	41%
Rel. number of stars with elevated chromospheric activity	56%	39%	60%
Rel. number of stars with chromospheric activity cycles	25%	40%	72%
Quality of chromospheric activity cycles "Excel + Good"/"Fair + Poor"	0/10	7/10	14/4

spectral classes (see Table 1).

For the 80 stars that have known coronal emission from the ROSAT data, we also carried out a regression analysis that yielded the following relationship between the x-ray luminosity (normalized to the bolometric luminosity) and the color index (*B-V*):

$$L_X = 29.83 - 1.99 \cdot (B-V). \tag{2}$$

We denote the right hand side of Eq. (2) by $P(B-V)$. By analogy with the analysis of the chromospheric activity of the stars, we treat stars with $\log L_X > P(B-V)$ as stars with a high level of coronal activity and those with $\log L_X < P(B-V)$ as stars with a low level of coronal activity (see Fig. 5). As noted above, in the case of chromospheric activity, there is a direct correlation: with increasing color index (*B-V*), the average index of chromospheric activity (the S-index) of the stars rises. In the case of x-ray emission, however, there is an inverse correlation: with increasing color index (*B-V*), the average value of $\log L_x$ decreases (see Figs. 4 and 5).

Most stars with elevated chromospheric activity are also characterized by elevated coronal activity. Here about 15% of the stars, including the sun, have coronal activity that is substantially lower than the level corresponding to their chromospheric activity (see Fig. 6).

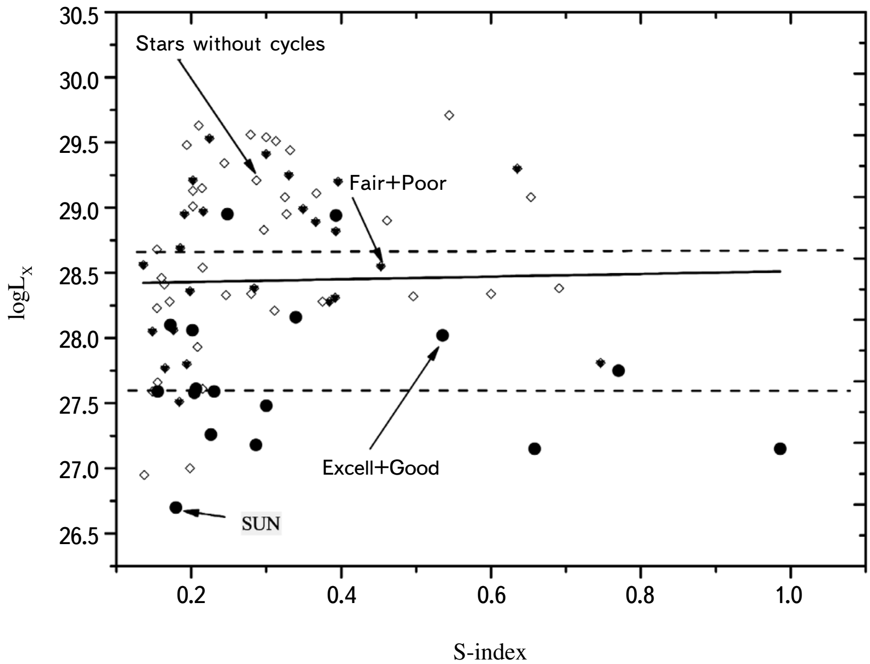


Fig. 6. Stars from the HK-project observed from 1969-1994: the x-ray luminosity logL_x is plotted as a function of the S-index. The smooth line is a linear regression, the "Excellent + Good" stars are indicated by solid circles, the "Fair + Poor" stars, by triangles, and the stars without cycles, by hollow diamonds.

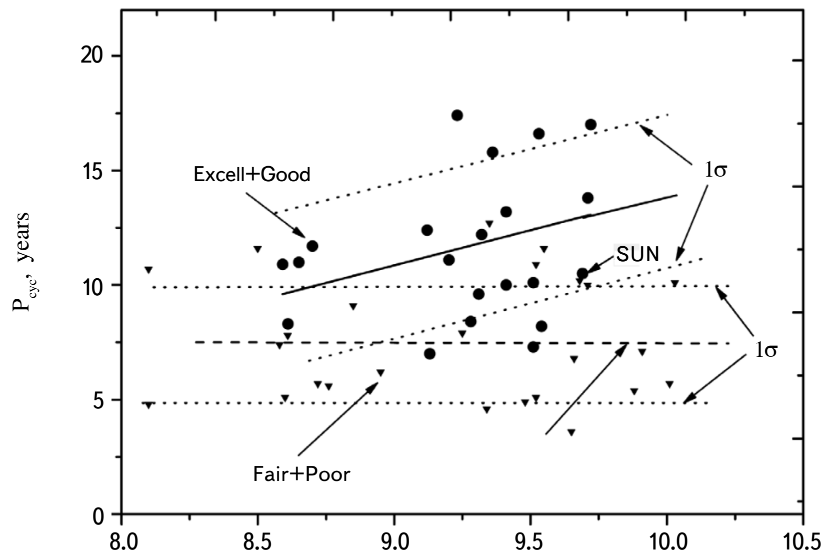
Figures 4 and 5 show that stars with cycles in the "Excellent" and "Good" classes have, for the most part (about 70%), a low level of chromospheric and coronal activity, as opposed to the stars with cycles in the "Fair" and "Poor" classes, the majority of which (about 75%) have a high level of chromospheric and coronal activity.

The presence or absence of marked cyclicity, as well as the quality of the cycles that are detected ("Excellent," "Good," "Fair," "Poor"), are quite different for stars in spectral classes F, G, and K (see Table 1).

The dashed lines are the median values for stars in classes "Fair" + "Poor" + "Var" (upper) and "Excellent" + "Good" (lower).

Figure 6 shows the relationship between the coronal and chromospheric emission of stars in the HK-project. The regression line separates the stars with relatively high and low fluxes L_x. It can be seen that stars without cycles and stars with indistinct cyclicity ("Fair" + "Poor" + "Var") have a relatively high level of coronal emission flux (the median corresponds to logL_x = 28.45). Here the stars in classes "Excellent" + "Good" are characterized on the average by a lower level of coronal emission flux (the median corresponds to logL_x = 27.45). In Ref. 18, it is proposed that the differences between the stars in these classes is related to instability of the convective zones lying below the photosphere.

It is clear from Table 1 that the quality of the chromospheric activity cycles (the ratio of the total number of stars with clearly marked cyclicity ("Excellent" + "Good") to the number of stars with poorly defined cyclicity



log(age/years)

Fig. 7. The period of cyclical activity P_{cyc} as a function of age for stars in the HK-project. Regressions are shown for stars from the complete sample (lower dashed line) and for stars with cycles of "Excellent + Good" class (upper solid line). The dotted lines for both fits indicate the intervals corresponding to the standard deviation 1σ.

("Fair" + "Poor")) differs substantially for stars in the different spectral classes F, G, and K.

We have analyzed the dependence of the duration of magnetic activity cycles in the stars on their age. The durations of the cycles were taken from Ref. 1. We calculated the age of the stars as a function of chromospheric activity using the formulas of Ref. 8.

Figure 7 shows the periods P_{cyc} of the stars as a function of their ages. The spread in the points about the regression line is very large. For the stars with "Excellent" + "Good" cycles, the duration of the cycles rises by roughly 20% as the age log(Age/yr) increases from 8.5 to 10. For the stars with "Fair" + "Poor" cycles, no increase in P_{cyc} with age is observed. Thus, the problem of determining P_{cyc} with maximal precision by, for example, frequency-time analysis (in particular by wavelet methods), is of great current interest.

4. Conclusion

The quality of cyclical activity analogous to the 11-year solar cycle is significantly better (from stars in classes "Fair + Poor", to "Excellent + Good") for G- and K-stars compared to F-stars. The 11-year cycles of F-stars (observed only in four cases) have been determined with a lower degree of reliability.

The chromospheric activity of stars from the HK-project is greatest for stars in spectral class K (see Table 1).

G-stars (and the sun) have a lower chromospheric activity among the stars we have examined. The elevated activity of the atmospheres of F-stars is also characterized by a higher chromospheric activity that is somewhat lower than for K-stars. This is consistent with the results of Ref. 10. The basic level of chromospheric activity S_{BL} from Ref. 10 begins to increase when (B-V) > 1. This increase in S_{BL} is related to a reduction in the continuum flux for the redder stars. The level of chromospheric activity in the sun is comparable to that in the stars from the HK-project which have distinct activity cycles (“Excellent” + “Good”) and similar color indices. On the other hand, the coronal activity of the sun is considerably lower than that of G-stars from the HK-project and the other observational programs.

Coronal activity is also more distinct in stars of spectral class F because of their more intense atmospheric activity (compared to stars in spectral classes G and K). It is not related to convective zones lying under the photosphere. Stable chromospheric cycles are practically nonexistent in F-stars.

It has been found that stars belonging to the “Excellent” + “Good” classes are characterized on the average by a lower level of coronal emission flux (the median corresponds to $\log L_X = 27.45$), while stars without cycles have a higher level of coronal emission flux (median $\log L_X = 28.45$).

At present there is great interest in the search for planets in the livability zone, i.e., in the region around stars where a planet with sufficient atmospheric pressure could support water in the liquid state. We believe that stars around which planets are orbiting should also be studied carefully. It may be that one of the conditions for a higher probability that a planet which can sustain life could be habitable will be a similarity of the central star to the unique characteristics of our sun: an extremely low level of variability in its photospheric emission with a very low level of coronal emission.

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