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Chromospheric Activity, Rotation and Age On Lower Main Sequence Stars*

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ABSTRACT

New empirical relations between stellar CaII emission and rotation or age are derived by analyzing Wilson's CaII flux measurements (1968, 1978) of lower main sequence stars, and then we correlate them with their age and rotation rate.

It is found that stellar chromospheric emission decays smoothly with age as a star slows down rotationally, establishing that both the emission level and rotation rate decrease with the square root of age.

I. INTRODUCTION

In our earlier analysis (Park and Yun (1983)) of Wilson and Woolley's spectroscopic data (1970) on CaII emission strength of K-M type stars, we demonstrated that Skumanich's empirical relation between CaII emission flux and stellar age can be extended to field stars, thus confirming his inverse square root law. In this analysis we converted Woolley and Wilson's eye estimate I of CaII emission strength to Vaughan's CaII flux index S (Vaughan et al. (1978)), which was obtained by measuring the emission flux in 1Å bands centered on CaII H and K lines and referenced to the neighboring mean continuum. We proceeded furthur by calibrating the observational parameter S into the chromospheric flux to the stellar bolometric flux as suggested by Middelkoop (1982).

Noting that the observed chromospheric flux is made up of radiation from both the chromosphere and the photosphere, we have corrected it by subtracting off the photospheric contributions, thus arriving at the true chromospheric flux which we called "CaII flux excess". Finally, we correlated the true chromospheric flux to stellar age, which resulted in a new empirical relation, indicating that the CaII flux excess decreases with the stellar age τ as $\tau^{-0.51}$.

In the present study we extended our earlier analysis to F-G type main sequence stars

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by analyzing Wilson CaII flux measurements (1968, 1978) to generalize the findings on the relationship between the CaII true chromospheric flux and stellar age and to further examine their close association with rotation.

In section II we present the estimates of the true CaII chromospheric flux obtained from the analysis of Wilson's CaII data and subsequent interpretation of the analysis. Section III describes how to derive the quantitative relationship between the CaII flux and age or stellar rotation period from the resulting analysis. A brief summary and discussions will be given in section IV.

II. ANALYSIS

First of all, we selected stars for which measurements of CaII emission flux, age and/or rotation rate are available. Since the measured CaII emission fluxes are usually normalized to the neighboring local continuum, they are color dependent. As noted earlier, the observed fluxes are made up of radiation from both the photosphere and the chomosphere. Accordingly, we have to make proper corrections in order to derive a quantity which represent truly the level of the chromospheric activity.

For this purpose we developed a procedure in our earlier study (Park and Yun (1983)) which proved to be successful for deducing the true chromospheric flux from the observed quantity such as Wilson's F or Vaughan's S. We do not repeat the detailed procedure here, but we simply outline the technique briefly.

When the observed CaII fluxes are given in terms of Wilson's flux index F, we convert it to Vaughan's flux index S by using the following relation

$$S=0.0194+0.824F+0.562F^2, \tag{1}$$

which has been obtained by fitting Vaughan's data (see his Table 1 in Vaughan et al. (1978)) by least squares. The color dependence of the observed flux S increases rapidly as the surface temperature decreases since the continuum falls off steeply toward the later spectral type. In order to correct this effect we adopted the Middelkoop's technique (1982), which allows one to estimate CaII H-K surface flux, F(H)+F(K) from Vaughan's CaII flux index S by

$$F(K)+F(H)=C_{cf}ST^4_{eff} \tag{2}$$

with

$$\log C_{cf}=1.13(B\text{-}V)^3-3.91(B\text{-}V)^2+2.84(B\text{-}V)-0.47, \tag{3}$$

and then convert them to Linsky's absolute flux (F_k+F_h) through

$$\log(F_k+F_h)=\log(F(K)+F(H))-8.1. \tag{4}$$

We proceeded to make further correction by subtracting the photospheric contribution from the deduced CaII H-K flux (F_k+F_h), resulting in the true chromospheric fluxes $(F'_k+F'_h)$ and F'_k

$$F'_k+F'_h=0.814(F_k+F_h)+1.1\times10^3 \tag{5}$$

$$F'_k=0.432(F_k+F_h)-2.11\times10^3 \tag{6}$$

(see Park and Yun (1983) for further details). In this procedure $(B-V)$ has been taken from Nicolet (1978) and T_{eff}, from Lee (1982) and Linsky et al. (1979).

In search for the relation between the chromospheric activity level and age of F-G type main sequence stars we made use of Wilson's observations (1968, 1978). In the present analysis we have considered only 52 stars whose age is well determined. The selected stars and their age are listed in Table 1. The stellar age (listed in the last column of the table) has been taken from Lee (1982) and Duncan (1981), where Lee determined the age from the isochrones given by Mengel et al. (1979) and Duncan used the relation between stellar mass and lithium abundance. We may note that the stellar age determined by lithium abundance is known to be most accurate for the spectral range of F7-G5 (Duncan (1981)). Therefore, we have used preferentially Duncan's stellar age in our analysis. Finally, we evaluated their true chromospheric fluxes $F'_k+F'_h$ and F'_k according to the method described above, and they are listed in the 6th and 7th columns of the table.

In attempting to correlate the chromospheric activity and stellar rotation, there are not many objects of which both measurements of the rotation and the CaII emission flux are available, despite that considerable progress has been made lately in measuring stellar rotational velocity. Recently, Baliunas et al. (1983) observed a sample of 47 late type main sequence stars, including the sun and 8 giants. They measured CaII emission strength daily over a period of several months at Mt. Wilson and determined the rotational period rather accurately from detecting their rotational modulations. Stimets and Giles (1980) made a similar analysis to determine stellar rotational period by using Wilson's data (1978). Among the published data we were just able to find only 28 main sequence stars which meet the requirements. They are listed in Table 2, where the values of the rotational velocity V and CaII flux S are taken from Baliunas et al. (1983) and Stimets and Giles(1980), and $(B-V)$ taken from Nicolet (1978).

We made similar estimates of the true chromospheric CaII fluxes, $F_k'+F_h'$ and F_k' of our selected 28 stars, and they are listed in the last two columns of Table 2. Based on our estimates, the relative error in log F_k' induced by 15% variations of S, $(B-V)$ and T_{eff} are found to be 0.6%, 2.3% and 0.03%, respectively, and the combined relative error in log F_k' is expected to be less than 3%.

Table 1. Chromospheric activity indices F and S of Wilson's F-G type main sequence stars, estimates of their true chromospheric Ca II flux and age. (* refers to the age determined by Lee (1982))

HD	B-V	F	S	Teff	log(F'k)	log(F'h+F'k)	logAGE
10307	0.62	0.1544	0.1592	5794	5.8450	6.1221	9.48
13555	0.43	0.1524	0.1573	6152	6.0050	6.2816	9.60
16234	0.49	0.1431	0.1481	5929	5.9125	6.1894	9.81 *
19994	0.57	0.1556	0.1604	5970	5.9310	6.2079	9.66
26913	0.70	0.3901	0.4210	5521	6.1165	6.3928	8.95
26923	0.59	0.2790	0.2903	5848	6.1420	6.4183	8.95
29645	0.57	0.1382	0.1434	5781	5.8260	6.1032	9.90
32923	0.65	0.1504	0.1553	5728	5.7912	6.0685	10.11 *
33256	0.44	0.1451	0.1501	6152	5.9855	6.2621	9.90 *
34411	0.63	0.1488	0.1537	5998	5.8826	6.1595	9.58
35296	0.53	0.2848	0.2968	5875	6.1882	6.4644	8.30
39587	0.59	0.2972	0.3109	5888	6.1838	6.4600	8.78
48682	0.56	0.1528	0.1576	5728	5.8563	6.1333	9.52 *
52711	0.60	0.1578	0.1626	5861	5.8876	6.1645	9.45 *
76151	0.67	0.2646	0.2744	5754	6.0301	6.3066	9.10
78366	0.60	0.2310	0.2379	5875	6.0573	6.3337	9.00
81809	0.64	0.1856	0.1905	5702	5.8802	6.1572	9.50
86728	0.66	0.1532	0.1580	5875	5.8347	6.1118	9.65
88737	0.56	0.2204	0.2266	5957	6.0824	6.3588	9.00
89125	0.50	0.1576	0.1624	5998	5.9705	6.2472	9.58
95128	0.61	0.1473	0.1522	5861	5.8524	6.1295	9.52
97334	0.61	0.3172	0.3338	5834	6.1861	6.4623	9.08
102870	0.55	0.1513	0.1562	6053	5.9530	6.2297	9.30 *
109358	0.59	0.1548	0.1596	5834	5.8777	6.1547	9.59 *
110897	0.55	0.1494	0.1543	5794	5.8716	6.1485	9.46
114710	0.57	0.1920	0.1971	5984	6.0247	6.3012	9.30
117176	0.71	0.1444	0.1494	5483	5.6433	5.9214	9.90 *
120136	0.48	0.1784	0.1832	6427	6.1468	6.4231	9.00
126053	0.63	0.1675	0.1722	5808	5.8760	6.1530	9.20
136202	0.54	0.1227	0.1285	6095	5.8842	6.1611	9.58 *
141004	0.60	0.1623	0.1671	5834	5.8913	6.1683	9.54
142373	0.56	0.1377	0.1429	5689	5.8014	6.0787	9.56
142860	0.48	0.1502	0.1551	6166	6.0022	6.2788	9.65 *
143761	0.60	0.1426	0.1477	5768	5.8175	6.0947	9.75 *
154417	0.58	0.2414	0.2491	5834	6.0771	6.3525	9.08
157214	0.62	0.1492	0.1541	5598	5.7706	6.0480	10.15 *
187691	0.55	0.1428	0.1478	6026	5.9211	6.1980	9.56
187923	0.65	0.1464	0.1514	5728	5.7800	6.0574	9.59 *
190406	0.61	0.2080	0.2136	5781	5.9758	6.2525	9.40
194012	0.51	0.1895	0.1945	5984	6.0426	6.3191	9.42
206860	0.59	0.3140	0.3301	5848	6.1979	6.4741	8.70
216385	0.48	0.1348	0.1401	6067	5.9298	6.2066	9.42
224930	0.67	0.1809	0.1857	5333	5.7278	6.0055	10.37 *
1835	0.66	0.3490	0.3712	5794	6.1822	6.4584	8.95
3443	0.72	0.1840	0.1889	5420	5.7153	5.9930	10.04 *
3651	0.85	0.1940	0.1991	5224	5.5165	5.7955	10.33 *
20630	0.68	0.3390	0.3593	5662	6.1105	6.3868	9.30
23249	0.92	0.1570	0.1618	4831	5.1875	5.4705	9.87
30495	0.63	0.2810	0.2926	5998	6.1627	6.4389	9.17
103095	0.75	0.1780	0.1828	5143	5.5761	5.6546	10.40 *
149661	0.82	0.3530	0.3759	5358	5.8779	6.1548	9.58 *
165341	0.86	0.3720	0.3989	5309	5.8340	6.1111	9.80

Table 2. Stellar rotation and estimated true chromospheric CaII flux of 28 main sequence stars. (* refers to the data taken from Stimets and Giles (1980))

HD	B-V	S	Vel(km/sec)	PERIOD(day)	log(F'k)	log(F'h+F'k)
16673	0.52	0.2005	10.0	6.2	6.0728	6.3493
212754	0.52	0.1390	5.0	13.0	5.9134	6.1903
25998	0.54	0.2820	23.0	2.5	6.2542	6.5303
187691	0.56	0.1460	4.0	15.0	5.9112	6.1881
154417	0.57	0.2590	7.0	7.7	6.0993	6.3757
206860	0.58	0.3190	11.0	4.6	6.1888	6.4659
6920	0.60	0.1990	4.0	13.1	5.9572	6.2339
190406	0.61	0.1900	4.0	13.5	5.9248	6.2017
1835	0.66	0.3712	6.0	7.6	6.2019	6.4781
20630	0.68	0.3593	5.0	9.4	6.1103	6.3867
26913	0.70	0.4210	7.0	7.2	6.1165	6.3929
152391	0.76	0.4120	4.0	11.0	5.9722	6.2489
149661	0.81	0.3310	1.9	21.3	5.8327	6.1098
155885	0.86	0.3990	1.9	22.9	5.7607	6.0382
155886	0.86	0.3370	2.0	20.3	5.6871	5.9650
17925	0.87	0.6060	6.0	6.6	5.8415	6.1186
166620	0.87	0.2100	1.0	42.0	5.3788	5.6591
22049	0.88	0.5330	4.0	11.3	5.8589	6.1359
4628	0.89	0.1940	1.0	37.9	5.3756	5.6559
160346	0.96	0.3140	1.0	33.5	5.4135	5.6934
16160	0.97	0.2310	1.2	29.3	5.2375	5.5197
190007	1.12	0.7970	2.3	29.0	5.4897	5.7689
156026	1.16	0.8930	2.2	18.0	5.3933	5.6735
201091	1.18	0.6030	1.0	37.9	5.0736	5.3588
201092	1.38	0.9870	0.7	48.0	4.7594	5.0547
39587	0.59	0.3109	10.3	5.1*	6.1837	6.4599
131156	0.76	0.4471	7.3	6.2*	6.0748	6.3512
165341	0.86	0.3989	2.2	20.1*	5.8341	6.1112

III. RELATIONS BETWEEN THE TRUE CHROMOSPHERIC CaII FLUX AND AGE OR ROTATION

Now, we are in a position to put the relation between the true chromospheric CaII flux and age τ or rotation period P on a quantitative basis for the lower main sequence field stars we analyzed.

A close correlation between the chromospheric activity measured by F_k' or $\frac{1}{2}(F_k'+F_h')$ and age τ is shown in Fig. 1, where the solid lines are represented by

$$\log F_k' = -0.47 \log \tau + 10.41 \tag{7}$$

and

$$\log\left(\frac{F_k'+F_h'}{2}\right) = -0.47 \log \tau + 10.39, \tag{8}$$

with the correlation coefficient $r=0.84$. As noted from these equations, the chromospheric activity decreases smoothly with age τ as $\tau^{-0.47}$ in agreement with our earlier findings where the activity was found to decrease with the age as $\tau^{-0.51}$.

A similar study is made to correlate the chromospheric activity to stellar rotation, using

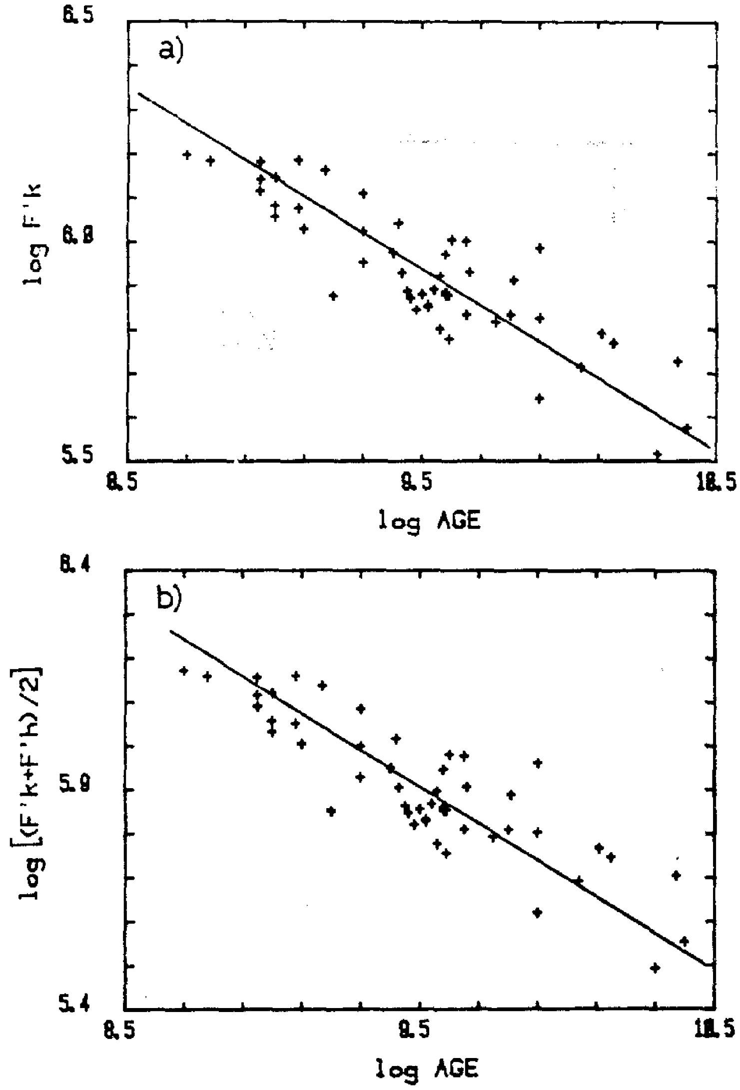

Fig. 1. Relation between chromospheric activity and stellar age

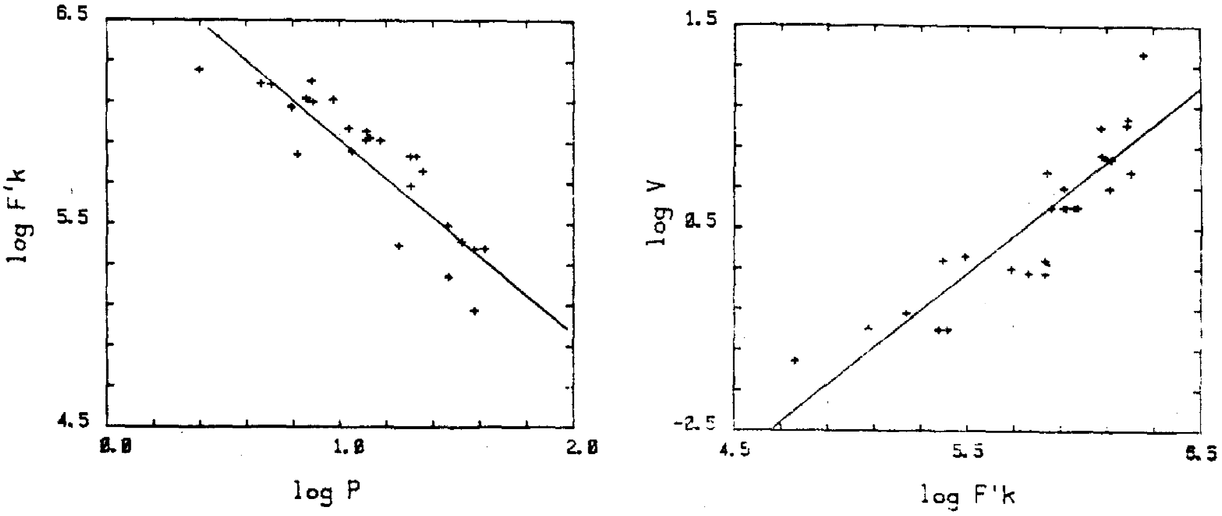

Fig. 2. Relation between chromospheric activiy and stellar rotation.

the results of our analysis given in Table 2. They are presented in Fig. 2, and the solid lines in the figure are represented by

$$\log F_k' = -1.03 \log P + 6.95 \tag{9}$$

and

$$\log F_k' = \log V - 5.3 \tag{10}$$

respectively. P is the rotational period and V is the equatorial velocity. As can be seen from equation (9), the level of the chromospheric activity decays with the rotation period P as 1/P.

IV. SUMMARY AND DISCUSSIONS

In the present study we generalized our earlier analysis by extending our study to F-G type main sequence stars, using Wilson's CaII flux measurement (1968, 1978). This analysis shows that the level of the stellar chromospheric activity decreases with age τ as $\tau^{-0.47}$, consistent with Skumanich's inverse square root law, thus firmly establishing quantitatively its validity.

We also made a similar correlation study to relate the chromospheric activity to the stellar rotation on a quantitative basis, employing recent observations of rotational velocity made by Baliunas et al. (1983) and Stimets and Giles (1980). It is found that the chromospheric activity decreases with rotational period P, inversely proportional to P as suggested by Skumanich (1972). In passing, we may note that we were able to derive a unique relationship between the deduced true chromospheric CaII flux and the rotation period for the whoe range of spectral types F through M, as contrast to that of Vaughan et al. (1981) where they were not able to do so because of their use of color dependent chromospheric activity index S as a parameter representing the activity level.

Finally, we wish to make some comments on the close association among the stellar chromospheric activity, stellar age and stellar rotation. According to a widely accepted picture, the chromospheric activity is believed to be magnetically induced, and the magnetic field is known to be generated by the coupling of rotation and convection through a magnetic dynamo action. Therefore, it is quite natural to expect a close relation between stellar rotation and the magnetically induced chromospheric activity. The smooth decay of the chromospheric activity means the slow-down of the dynamo action, probably resulting from steady spin-down through angular momentum shedding by stellar winds. This picture appears to be compatible with our findings on the close relation between stllar rotation rate and chromospheric activity.

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