Astronomy & Astrophysics

LETTER TO THE EDITOR

An investigation of chromospheric activity spanning the Vaughan-Preston gap: impact on stellar ages[*],[**]

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ABSTRACT

Context. Chromospheric activity is widely used as an age indicator for solar-type stars based on the early evidence that there is a smooth evolution from young and active to old and inactive stars. However, this transition may require modification as chromospheric activity is not a viable age indicator for stars older than 1 Gyr.
Aims. We analysed chromospheric activity in five solar-type stars in two open clusters, in order to study how chromospheric activity evolves with time.
Methods. We took UVES high-resolution, high S/N ratio spectra of 3 stars in IC 4756 and 2 in NGC 5822, which were combined with a previously studied data-set and reanalysed here. The emission core of the deep, photospheric Ca II K line was used as a probe of the chromospheric activity.
Results. All of the 5 stars in the new sample, including those in the 1.2 Gyr-old NGC 5822, have activity levels comparable to those of Hyades and Praesepe.
Conclusions. A likely interpretation of our data is that solar-type-star chromospheric activity, from the age of the Hyades until that of the Sun, does not evolve smoothly. Stars change from active to inactive, crossing the activity range corresponding to the Vaughan-Preston gap, on a time-scale that might be as short as 200 Myr. Evolution before and after such a transition is much less significant than cyclical and long-term variations. We show that data presented in the literature to support a correlation between age and activity could be also interpreted differently in the light of our results. Suggestions have been published that relevant stellar structures and/or dynamos are different for active and inactive stars. These provide a natural explanation for the observations presented here. More observations are required in order to strengthen our results, especially a long-term follow up of our two targets in the 1.2-Gyr old cluster NGC 5822.

Key words. stars: chromospheres

1. Introduction

It was already noticed in the early 60 s (Wilson 1963) that chromospheric activity decreases during the main sequence life time of late type stars like the Sun, and that the strength of the emission in the core of the broad and deep Ca II H and K lines is a reliable indicator of chromospheric activity level. From that time on, the possibility of using H and K emission to measure stellar ages has been widely explored and an impressive amount of data on stellar chromospheric activity has been collected, especially in the Mount Wilson program, started by Wilson (1968), and, more recently, during planet-search surveys (see e.g. Isaacson 2009). Unfortunately, chromospheric activity as an age indicator suffers a major limitation. Activity cycles equivalent to the 11-year long solar one, longer-term activity variations, which caused the Maunder-minimum in the Sun, and, in some stars, a

hidden dependence on stellar mass (Cardini & Cassatella 2007) and rotational modulation, strongly affect the level of activity. We believe that there is an even more severe limitation on the use of chromospheric activity as an age indicator: its decay almost stops after about 1.5 Gyr, therefore activity is not a reliable indicator of age for stars older than that.

Two papers support this view: Pace & Pasquini (2004), hereafter Paper I, of which this study can be considered a continuation, and Lyra & Porto de Mello (2005). Nevertheless, many other works pointed out the existence of a correlation between chromospheric activity and age, and many attempts were made to calibrate chromospheric ages (Soderblom et al. 1991; Donahue 1993; Lachaume et al. 1999). It is of primary importance to understand the limitations of chromospheric activity as a reliable age indicator, since it has been used to study, for example, the age-metallicity relation in the Galactic disk (Rocha-Pinto et al. 2000), and the age of stars hosting planetary systems (Saffe et al. 2005).

In order to understand how chromospheric activity decays, observations in solar-type stars in open clusters are the most appropriate tool, since their ages can be determined much more

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precisely than for field stars. The paucity of old open clusters in the solar neighbourhood hindered our progress until the advent of the 8- and 10-meter class telescopes, which made possible the acquisition of spectra of solar-type stars in several old and distant clusters at a resolution and a signal-to-noise ratio high enough to distinguish and resolve the emission core in the CaII K line. This is necessary to accurately correct for the absorption by interstellar lines of Ca II and thus to reliably measure chromospheric activity.

To the sample analysed in Paper I, we have added data on 5 solar-type stars in the open clusters NGC 5822 and IC 4756. We selected the two new target clusters mainly on the basis of their age, specifically because we wanted their ages to lie between those of the Hyades and Praesepe and those of IC 4651 and NGC 3680, studied by Salaris et al. (2004). As a result we have chromospheric activity data for 25 stars younger than 1 Gyr, 2 stars at about 1 Gyr, 7 stars at about 1.5 Gyr, and 6 at solar age.

The availability of UVES spectra allowed us to also accurately measure temperatures and metallicities for our target stars, which have been used in the present work, but the details of which will be published elsewhere.

2. Observations and sample

Target stars were selected to be high-probability single members of IC 4756 and NGC 5822 and to be as similar to the Sun as possible. The choice was made on the basis of the photometry by Herzog et al. (1975) for IC 4756 and by Twarog et al. (1993) for NGC 5822. The former study was made with photographic plates, and the cluster suffers from variable extinction, therefore the photometric precision was not good enough to exclude binaries with a high level of confidence. On the other hand, probabilities of membership published therein are based on a proper motion study which uses a time baseline of 43 years, therefore are quite accurate. Spectra were taken with the UVES spectrograph at the focus of the Kuyen telescope. Observations were carried out between April and September 2004. The wavelength coverage is from 3200 to 4600 Å for the blue arm, and from 4800 to 6800 Å for the red arm. The slit width for the former was set to 0.8 arcsec, and for the latter to 0.4 arcsec, giving a resolution of $R \approx 60\,000$ and $R \approx 100\,000$ respectively (Dekker et al. 2000). Data were reduced using the UVES pipeline (Modigliani et al. 2004).

From 2 to 7 spectra were obtained for each star. Radial velocity measurements were used to strengthen single-member selection. Details will be given elsewhere (Pace et al. 2009, in preparation). The final new sample consists of 3 stars in IC 4756 and 2 in NGC 5822.

To the best of our knowledge, Salaris et al. (2004) provide the most recent set of age evaluations for a sample of open clusters that includes all of those analysed by us. They find an age of 0.7 Gyr for both Hyades and Praesepe, 0.8 Gyr for IC 4756, 1.2 Gyr for NGC 5822, 1.4 Gyr for NGC 3680, 1.7 Gyr for IC 4651, and 4.3 Gyr for M 67.

3. Data analysis and results

As an indicator of chromospheric activity we used F'_K, i.e. the energy flux of the Ca II K line emitted per unit surface in the chromosphere. It is common practice in the literature to normalise chromospheric fluxes to bolometric emission and to use

the logarithmic scale (Noyes et al. 1984). Hence we also used as a proxy of the chromospheric activity: $\log R'_K = \log\left(F'_K/\sigma T^4_{\rm eff}\right)$.

Normalisation of the spectra was done as in Paper I. From Paper I we also took 1–Å K index measurements for NGC 3680, IC 4651 and M 67. Index measurements in Praesepe and Hyades stars were slightly revised with respect to the values published in Paper I: the new indices are about 15 mÅ higher. The stars in IC 4756 and NGC 5822 showed the redshifted interstellar K absorption line which affected the chromospheric K-line feature. To measure the 1-Å K index in these stars, we integrated the normalised flux only in the uncontaminated part of their profile. The Praesepe stars are unaffected by IS absorption, thus allowing us to calculate a ratio between the flux measured over the 1-Å and that measured over the portion of the feature which is unaffected by interstellar lines in all stars. The initial measures for the affected stars were then multiplied by this factor to give a final corrected 1-Å K index. The errors involved in the measurement of the 1-Å K index were evaluated to be within 6%. The 1-Å K index and chromospheric activity measurements, along with stellar parameters, are given in Table 1.

In Fig. 1 we show the average cluster spectra for IC 4756 and NGC 5822 and, for comparison, that of Praesepe and the solar one. The interstellar feature is apparent in IC 4756 and NGC 5822.

For the Sun, we used the 1-Å K index measurements made by White & Livingston (1981). They monitored solar chromospheric activity from the first minimum to the maximum of the 21st solar-activity cycle.

Subtraction of the photospheric contribution to the 1-Å K index was made as follows. For the Sun, we adopted the same photospheric correction as in Paper I, computed using a solar-photosphere synthetic spectrum (courtesy of P. Bonifacio). For the other stars, the photospheric contribution was computed by scaling the solar photospheric contribution by a factor that depends on the stellar parameters. These scaling factors were computed using the spectral synthesis code of MOOG (Sneden 1973, version 2002), and Kurucz's grid of models (Kurucz 1993). Stellar parameters, namely temperature, gravity, microturbulence and metallicity, were known from Paulson et al. (2003) for the Hyades stars, and from Pace et al. (2008) for the remainder of the old sample, and from our chemical analysis for the new sample (Pace et al. 2009, in preparation).

In order to transform the 1-Å K index, which is an equivalent width, into an intrinsic flux, namely F'_K, we proceeded as in Paper I, except that we did not use published photometry, but we transformed stellar temperatures and metallicities into $B - V$ colours inverting Eq. (1) in Sousa et al. (2008). For the Sun we adopted $B - V = 0.65$ mag (Pasquini et al. 2008). The use of stellar temperatures instead of published colours avoids the cluster-to-cluster bias introduced by the error in the cluster reddening.

Because of the way we measured the index in the new sample of stars, we preferred not to use a triangular filter in the integration of the index, as done, for instance, in Paulson et al. (2002). Owing also to the lack of common standards, we could not make our $\log R'_K$ coincident with the widely used chromospheric activity indicator $\log R'_{\rm HK}$.

4. Discussion

In Fig. 2 we plot the temperature of the stars versus their chromospheric activity. This is done using as an indicator of chromospheric activity both $\log R'_K$ (left panel) and F'_K (right panel).
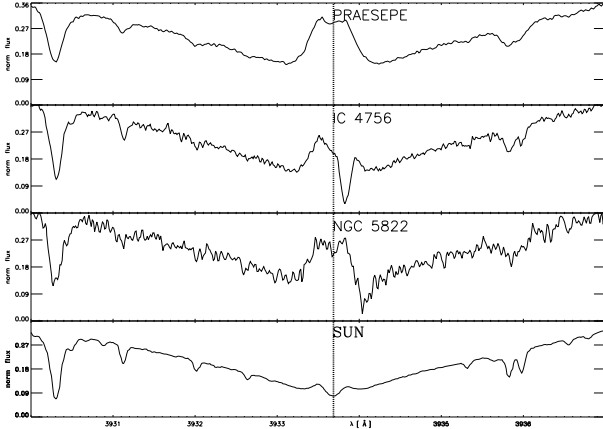
Fig. 1. The mean cluster Ca II K-line emission of IC 4756 and NGC 5822 is compared with that of Praesepe and with the Sun. All the spectra are normalised in the same way. Note the narrow IS absorption lines in the spectra of IC 4756 and NGC 5822.

The data are those shown in Table 1. The distribution of chromospheric activities is markedly bimodal: the more active stars are those in the Hyades, Praesepe, IC 4756, and NGC 5822, while the inactive stars are those in IC 4651, NGC 3680, and M 67 and the Sun. Within either group there is little difference between stars belonging to different clusters, although any small correlation with age using averages within the active group would be obscured by the cyclic range in individual stars. But the two groups are separated by a wide range of activities in which only two stars lie. This range coincides with what is known as the Vaughan-Preston gap, an underpopulated chromospheric-activity range identified by Vaughan & Preston (1980) using a large sample of stars in the solar neighbourhood.

According to these ages and to the data shown in Fig. 2, no strong age-activity correlation appears to exist after 0.7 Gyr, just a rapid transition from active to inactive that occurs in a very short time, namely 200 Myr, between the age of NGC 5822 and that of NGC 3680. With this data it seems unlikely that a strong age-activity relationship could be masked by the scantiness of the data, or by the activity variations. Thus we can confidently conclude that chromospheric activity drops much faster between the ages of NGC 5822 and NGC 3680 than it does in the half Gyr before and in the 4 Gyr after. We would expect most of the stars in the gap to be young stars in an inactive phase or old stars in an active phase rather than stars at a certain age. In our sample we have one in either category. Two alternative explanations might be considered. Either our two targets in NGC 5822 were both in an exceptionally active phase when we observed them, or the age difference between the oldest active and the youngest inactive cluster is much larger than that claimed by Salaris et al. (2004). In the former case, NGC 5822 solar-type members would normally lie in the middle of the Vaughan-Preston gap. Owing to the extremely small sample of stars at this crucial age, it is well worth follow-up spectroscopic observations of the two NGC 5822 members to accurately measure their time-averaged chromospheric activity, and to add to the sample single members in the interesting temperature range. The possibility that the age of NGC 5822 has been over-estimated by Salaris et al. (2004) might be seriously considered because it was not determined directly, but by means of a photospheric index calibrated for a sample of 11 clusters. But in this case its age would need to have been overestimated by almost a factor of two.

According to Pace et al. (2008), Paulson et al. (2003) and the chemical analysis of the present sample of stars, the metallicity of the clusters studied ranges from [Fe/H] = –0.04 dex in NGC 3680 to [Fe/H] = 0.27 dex in Praesepe. Since the 3 coeval active clusters have similar levels of chromospheric activity despite having different metallicities ([Fe/H] = 0.01, 0.13 and 0.27 dex), metallicity does not appear to play a major role within the limited range of values spanned by our clusters.

Chromospheric activity undergoes large variations on short time–scales. For instance, the chromospheric activity of the Sun, from the highest activity peak to the Maunder minimum, spans a range that goes from the lower boundary of the Vaughan-Preston gap to slightly above the level of the most inactive stars (only 8% of the solar neighbourhood stars less active than the lowest solar value). This range, according to the current calibration of the age-versus-$\log R'_{HK}$ relationship, corresponds to an age interval from 2.5 to 8 Gyr (Henry et al. 1996). However, members of binary or multiple systems have a similar level of chromospheric activity. It is mainly this circumstance that led Soderblom et al. (1991) to claim that chromospheric activity correlates well with age and allows a calibration. In the light of the results presented here, we suggest alternative explanations should be sought.

Another calibration of the chromospheric activity evolution with time is that of Lachaume et al. (1999). From Fig. 4 therein, it can be seen that their result agrees with ours as far as inactive stars are concerned, i.e. chromospheric activity does not evolve after it has crossed the Vaughan-Preston gap, at least until the solar age. As far as active stars older than the Hyades are concerned, there are 4 to 6 data-points (for two stars it is not possible to say whether or not they are younger than the Hyades and therefore out of the range considered in the present study). For this group, the Pearson coefficient indicates a level of anti-correlation between age and $\log R'_{HK}$ that is insignificant (–0.27) or fair (–0.57), depending on how many stars we consider. We conclude that these data are compatible with the conclusion that, within the age range from 0.7 to 1.2 Gyr and from 1.4 Gyr to solar age, any age-activity relationship must be weaker than the short term variations.

From Mamajek & Hillenbrand (2008) it is clear that the one open cluster that supports a strict monotonicity of the chromospheric activity time evolution (once short-time scale variations are smoothed out) in the age range between that of the Hyades and that of M 67 and the Sun, is NGC 752. This cluster, according to Salaris et al. (2004), is older than NGC 5822 and younger than NGC 3680, i.e. exactly in the range in which we expect the transition to occur. Therefore, again, these data are not incompatible with the scenario we suggest, in which the intermediate chromospheric activity level of NGC 752 would be due to its age.

The two groups of stars on opposite sides of the Vaughan-Preston gap differ not only in their chromospheric activity level, but also in its trend with the colour/temperature. This can be seen in Fig. 2, and it is much more evident when a larger spectral-type range is considered (see e.g. Mamajek & Hillenbrand 2008). Furthermore, temporal variations of chromospheric activity are large and irregular for active stars and small and regular for inactive ones. Several attempts have been made to provide a physical explanation for this, for example Durney et al. (1981) proposed a transition from a complex to a simpler magnetic-field morphology which occurs at the time when the rotation decreases enough to reach a threshold value. More recently, Barnes (2003) detected two sequences in the period-versus-colour diagram of open clusters, and he associated them with two different rotation morphologies, intertwined with stellar magnetic fields.
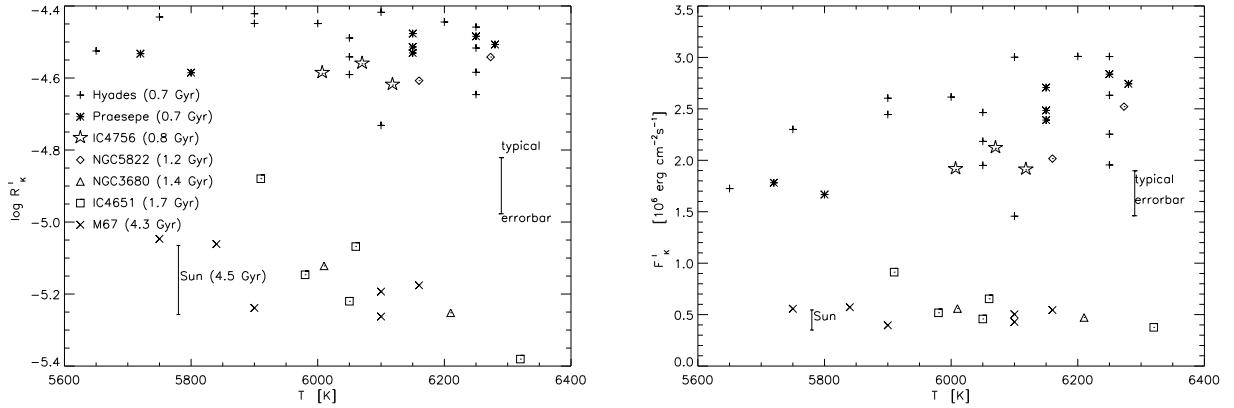
Fig. 2. Spectroscopic temperature versus chromospheric activity, using as a proxy of chromospheric activity both log R'_K (*left panel*) and F'_K (*right panel*). For the Sun, the bar corresponding to its full variation during a cycle is plotted. The typical error bar shows the typical uncertainty ($\pm 1\sigma$) evaluated from the error analysis, assuming an uncertainty in the temperature of 110 K. Had we just added the counts to measure the 1-Å K index in the new sample stars, which gives a secure lower limit (see Sect. 3), we would have measured in the 2 NGC 5822 stars a value of log R'_K lower by only 0.09 and 0.07. The ages come from Salaris et al. (2004).

Böhm-Vitense (2007) suggested a change of dynamo mechanism to explain the fact that stars occupy two very distinct sequences in a rotation period-versus-cycle period diagram. The kind of scenario in which a transition of the nature of the dynamo takes place at a specific point of the stellar lifetime could be used to explain the phenomena reported and discussed by us.

References

Barnes, S. A. 2003, ApJ, 586, 464
Böhm-Vitense, E. 2007, ApJ, 657, 486
Cardini, D., & Cassatella, A. 2007, ApJ, 666, 393
Dekker, H., D'Odorico, S., Kaufer, A., Delabre, B., & Kotzlowski, H. 2000, Proc. SPIE, 4008, 534
Donahue, R. A. 1993, Ph.D. Thesis,
Durney, B. R., Mihalas, D., & Robinson, R. D. 1981, PASP, 93, 537
Isaacson, H. T. 2009, American Astronomical Society Meeting Abstracts, 213, #408.07

Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439
Herzog, A. D., Sanders, W. L., & Seggewiss, W. 1975, A&AS, 19, 211
Lachaume, R., Dominik, C., Lanz, T., & Habing, H. J. 1999, A&A, 348, 897
Lyra, W., & Porto de Mello, G. F. 2005, A&A, 431, 329
Kurucz, R. L. 1993, ATLAS9 Stellar Atmosphere Programs (Kurucz CD-ROM No. 13)
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Modigliani, A., Mulas, G., Porceddu, I., & Dammiani, F. 2004, VLT-MAN-ESO-19500-3016
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Pace, G., & Pasquini, L. 2004, A&A, 426, 1021
Pace, G., Pasquini, L., & François, P. 2008, A&A, 489, 403
Pasquini, L., Biazzo, K., Bonifacio, P., Randich, S., & Bedin, L. R. 2008, A&A, 489, 677
Paulson, D. B., Saar, S. H., Cochran, W. D., & Hatzes, A. P. 2002, AJ, 124, 572
Paulson, D. B., Sneden, C., & Cochran, W. D. 2003, AJ, 125, 3185
Rocha-Pinto, H. J., Maciel, W. J., Scalo, J., & Flynn, C. 2000, A&A, 358, 850
Saffe, C., Gómez, M., & Chavero, C. 2005, A&A, 443, 609
Salaris, M., Weiss, A., & Percival, S. M. 2004, A&A, 414, 163
Sneden, C. 1973, ApJ, 184, 839
Soderblom, D. R., Duncan, D. K., & Johnson, D. R. H. 1991, ApJ, 375, 722
Sousa, S. G., Santos, N. C., Mayor, M., et al. 2008, A&A, 487, 373
Twarog, B. A., Anthony-Twarog, B. J., & McClure, R. D. 1993, PASP, 105, 78
Vaughan, A. H., & Preston, G. W. 1980, PASP, 92, 385
White, O. R., & Livingston, W. C. 1981, ApJ, 249, 798
Wilson, O. C. 1963, ApJ, 138, 832
Wilson, O. C. 1968, ApJ, 153, 221

Table 1. The sample with the 3 different chromospheric indices.

Star	T_{eff}	1–Å K index	F'_{K} [10^6 erg/ cm^2 s]	$\log R'_{\text{K}}$
	[K]	[mÅ]		[dex]
Hyades, 0.7 Gyr				
van Bueren 1	6250	180	1.95 ± 0.17	–4.65 ± 0.04
van Bueren 2	6050	223	2.18 ± 0.24	–4.54 ± 0.05
van Bueren 10	6100	281	3.00 ± 0.31	–4.42 ± 0.04
van Bueren 15	5750	308	2.30 ± 0.34	–4.43 ± 0.06
van Bueren 17	5650	272	1.73 ± 0.29	–4.53 ± 0.07
van Bueren 18	5900	294	2.60 ± 0.33	–4.42 ± 0.05
van Bueren 31	6200	261	3.01 ± 0.28	–4.44 ± 0.04
van Bueren 49	6050	207	1.95 ± 0.21	–4.59 ± 0.05
van Bueren 52	6050	248	2.46 ± 0.27	–4.49 ± 0.05
van Bueren 65	6250	202	2.25 ± 0.20	–4.58 ± 0.04
van Bueren 66	6250	253	3.01 ± 0.27	–4.46 ± 0.04
van Bueren 73	6000	270	2.61 ± 0.30	–4.45 ± 0.05
van Bueren 88	6250	228	2.63 ± 0.23	–4.52 ± 0.04
van Bueren 97	5900	279	2.44 ± 0.31	–4.45 ± 0.05
van Bueren 118	6100	161	1.46 ± 0.15	–4.73 ± 0.04
Praesepe, 0.7 Gyr				
KW 49	6150	233	2.39 ± 0.25	–4.53 ± 0.04
KW 100	6150	255	2.71 ± 0.28	–4.48 ± 0.04
KW 208	6280	238	2.74 ± 0.25	–4.51 ± 0.04
KW 326	5800	234	1.67 ± 0.25	–4.59 ± 0.06
KW 368	5720	270	1.78 ± 0.29	–4.53 ± 0.07
KW 392	6250	248	2.84 ± 0.26	–4.48 ± 0.04
KW 418	6150	239	2.48 ± 0.26	–4.51 ± 0.04
NGC 3680, 1.4 Gyr				
Eggen 60	6010	95 ± 5	0.56 ± 0.09	–5.12 ± 0.07
Eggen 70	6210	84 ± 10	0.47 ± 0.16	–5.25 ± 0.14
IC 4651, 1.7 Gyr				
AMC 1109	6060	102 ± 10	0.65 ± 0.14	–5.07 ± 0.10
AMC 2207	6050	85 ± 10	0.46 ± 0.13	–5.22 ± 0.13
AMC 4220	5910	133 ± 20	0.91 ± 0.24	–4.88 ± 0.12
AMC 4226	5980	93 ± 15	0.52 ± 0.18	–5.15 ± 0.15
Eggen 45	6320	74 ± 10	0.38 ± 0.16	–5.38 ± 0.18
M 67, 4.3 Gyr				
Sanders 746	5750	108 ± 20	0.56 ± 0.20	–5.05 ± 0.16
Sanders 1048	5900	85 ± 10	0.40 ± 0.12	–5.24 ± 0.13
Sanders 1092	6160	88 ± 15	0.54 ± 0.22	–5.18 ± 0.17
Sanders 1255	5840	105 ± 20	0.57 ± 0.22	–5.06 ± 0.17
Sanders 1283	6100	82 ± 15	0.43 ± 0.21	–5.26 ± 0.21
Sanders 1287	6100	90 ± 10	0.50 ± 0.14	–5.19 ± 0.12
NGC 5822, 1.2 Gyr				
TATM 11003	6160	197 ± 8	2.02 ± 0.22	–4.61 ± 0.05
TATM 11014	6270	217 ± 7	2.52 ± 0.24	–4.54 ± 0.04
IC 4756, 0.8 Gyr				
HER 165	6070	211 ± 7	2.12 ± 0.23	–4.56 ± 0.05
HER 240	6010	206 ± 6	1.91 ± 0.22	–4.59 ± 0.05
HER 97	6120	190 ± 9	1.91 ± 0.22	–4.62 ± 0.05
Solar cycle 21, from White & Livingston (1981)				
Sun	5780	95 ± 10	0.45 ± 0.10	