The Sun in Time: Detecting and Modelling Magnetic Inhomogeneities on Solar-Type Stars

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We report on results of a program of coordinated multiwavelength observations of single G stars. While the spectral types are restricted to lie within a narrow range of the Sun's, they have ages ranging from $\sim$ 70 Myr to $\sim$ 9 Gyr, which makes them suitable proxies for the Sun at several stages of its life history from the ZAMS to the very late main-sequence phase.

1. Introduction

A detailed understanding of the probable evolution of solar magnetic activity throughout the Sun's lifetime cannot be obtained from evolutionary model calculations. It is necessary to study proxies for the Sun corresponding to different stages in its history. From several studies of stars of different ages (*e.g.,* Soderblom 1983) it can be concluded that the early Sun was rotating more rapidly than at present. Consequently its magnetic activity – its photospheric starspot and chromospheric plage activity, flares, coronal X-ray and radio emission, *etc.* – would have been enhanced over present levels, when magnetic braking has significantly reduced the strength of the solar dynamo. The correlation between age, rotation rate, and activity levels in single cool stars is well-established (*e.g.,* Skumanich 1972; Simon *et al.* 1985).

In 1990 we initiated a coordinated multiwavelength study which now includes ground-based *UBVRI* or *uvby* photoelectric photometry, *UV* (*IUE* and *EUVE*) and X-ray (*ROSAT*) observations of a number of nearby, single, solar-type stars which were selected as proxies for the Sun from an age of $\sim$ 70 Myr (the ZAMS Sun) to $\sim$ 9 Gyr (the terminal-age main-sequence or TAMS Sun). By *solar-type*, we mean main-sequence stars with masses, spectral types, and colors close to the Sun's: approximately $0.9M_\odot < M < 1.1M_\odot$, $F9/G0V < Sp.\ Type < G5V$, and $0.58 < B - -V < 0.70$. The group also includes the nearby G2 subgiant β Hyi as a proxy for the Sun at $\sim$ 9 Gyr (Dravins *et al.* 1993). However, the expression *solar-type* is frequently extended to the whole range of spectral types (F – M) to which stars showing evidence of solar-type magnetic activity belong. With the exception of β Hyi, our program stars in the G0 – G5 group will have similar convection-zone depths. On the other hand, there is no restriction on age ($\sim$ 70 Myr to $\sim$ 9 Gyr for the stars in our sample) and rotation periods ($P_{rot} \simeq 2.7d$ to $\sim 45d$). Ages for many of these stars are determined from moving-group membership. The program also contains stars selected for their close spectral similarity to the present Sun, with a view to determining whether the Sun is typical of stars of its age.

Up to the late 1970s it was by no means obvious that it would be possible to detect the presence of starspots on single dwarf G stars through observation of a rotational brightness modulation, as had already been done for the highly active RS CVn binaries. The solar analogy would suggest that the light variations might be only a fraction of one percent, beyond the limit of detectability by conventional ground-based photometry. Indeed, the solar irradiance variation due to rotational modulation has only recently been established by spacecraft measurements, and is up to 0.3% (Willson 1982; Foukal & Lean 1986). However, the Wilson (1978) survey of chromospheric Ca II HK emission revealed

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chromospheric variability to be common among solar-type stars. This program, continued by Baliunas and collaborators at Mt. Wilson, shows both rotational modulation of the Ca II HK flux and year-to-year variations in mean flux (Noyes *et al.* 1984; Radick *et al.* 1990).

Among the first photometric evidence of *light* variations in single solar-type stars that could be ascribed with some certainty to starspots were the observations by Dorren & Guinan (1982) of a small sample of the more active G – K stars in the Mt. Wilson Ca II HK program. Contemporaneous photometry and Ca II HK measures indicated that in the case of the K2 V star HD 149661 (12 Oph), the chromospheric emission was strongest at times of reduced stellar brightness, a clear suggestion that the bright chromospheric active areas (plages) are associated with dark photospheric inhomogeneities (starspots). In a follow-up project in 1983 at Kitt Peak National Solar Observatory (KPNO), we observed several single F – K stars, finding light variations of up to ~ 0.1 mag in several. In particular, we discovered HD 129333, a young G0 V solar-type star, to have the largest light variation of the G-stars (~ 0.06 mag) and a period of ~ 2.7d. This star is the youngest in our sample, with an age of ~ 70 Myr determined by its membership in the Pleiades Moving Group (Dorren & Guinan 1994a).

The advent of automatic photometric telescopes (APTs) has made long-term monitoring programs feasible, removing the drudgery of routine observation. Our program since 1988 has relied heavily on photometric data obtained by telescopes on Mt. Hopkins, AZ (the Phoenix-10; the Four College Consortium and Fairborn Observatory 0.8m APTs).

Other groups have investigated solar-type stars. A systematic program of high precision photometric monitoring of solar-type stars has been carried out since 1980, initially at Cloudcroft Observatory and subsequently at Lowell Observatory (Lockwood & Skiff 1988; Radick 1992). Their sample (including solar-type stars in the Hyades and Coma clusters, and 33 stars from the Mt. Wilson HK project) constitutes the largest set of solar-type stars which has been systematically monitored using concurrent photometry and Ca II HK observations. A number of important conclusions concerning the link between stellar rotation, age, and chromospheric activity have emerged from these programs (see Radick *et al.* 1990; Radick 1993; Lockwood 1993 and refs. therein).

Finally, direct measurements of magnetic fields on single stars have been made by Saar (1992 and refs. therein) using the Zeeman-broadening technique. For active G stars, the field strengths are typically 1,000 – 2,000 gauss, and filling factors 10 – 40%.

2. The Sun in time project

A list of the more intensively studied stars in the program is given in Table 1. Our own *UV* and X-ray observations have generally been supplemented by extracting all the available *IUE* archival spectra and existing X-ray observations. Most of the stars selected are nearby, bright, and have well-determined rotation periods from photometry or Ca II HK observations. Their ages are reasonably well-known from membership in moving groups or from isochronal fits and span the range from ZAMS to TAMS.

The principal aims include:

a) Investigating the evolution of the solar dynamo and solar magnetic activity using stars with nearly identical physical properties to the Sun (i.e., mass, radius, spectral type, temperature and depth of convective zone), but of different ages, and therefore different rotation rates. The prime concerns are the level of activity as a function of age, rotational modulation of optical brightness and *UV* and X-ray continuum and/or emission-line fluxes, and the search for activity cycles. The stars are not members of close binaries

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STAR	Spectral Type	m_V	B-V	dist. (pc)	P_{rot} (days)	Age	Log L_x ergs s^{-1}	Log F_{CIV} ergs s^{-1}	Log F_{MgII} ergs s^{-1}	Light Range $< \Delta V >$
HD 129333 = EK Dra	G0 V	7.52	+0.61	31	2.75	~70 Myr	29.85	28.42	29.55	0.060
HD 72905 = π^1 UMa	G1.5 V	5.64	+0.62	14	4.68	300 Myr	29.20	27.81	29.40	0.034
HD 206860 = HN Peg	G0 V	5.94	0.59	15.1	4.86	(300 Myr)	28.85	27.67	29.22	0.040
HD 39587 = χ^1 Ori	G1 V	4.41	0.60	10.0	5.08	300 Myr	28.95	27.78	29.52	0.030
HD 1835 = BE Cet	G2 V	6.39	0.65	20.4	7.65	600 Myr	28.70	27.89	29.23	0.028
HD 28099 = VB 64	G2 V	8.12	0.66	46.6	8.7	600 Myr	29.41	27.89	29.19	0.021
HD 20630 = κ^1 Cet	G5 V	4.83	0.68	9.3	9.2	(1 Gyr)	28.78	27.63	29.30	0.020
HD 114710 = β Com	G0 V	4.26	0.58	8.1	12.4	(~2 Gyr)	28.30	27.23	29.08	0.011
HD 190406 = 15 Sge	G5 V	5.8	0.61	17.2	13.5	(~2 Gyr)	28.30	–	29.02	0.008
HD 128620 = α Cen A	G2 V	-0.01	0.71	1.33	~30	5-6 Gyr	27.11	26.78	28.93	< 0.005
HD 2151 = β Hyi	G2 IV	2.80	0.62	6.5	~45	9 Gyr	26.90	26.80	29.13	< 0.006
SUN	G2 V	-26.74	0.66	1AU	25.5	4.6 Gyr	27.48	26.70	28.95	0.0015

TABLE 1. Properties of solar proxies in Sun in Time Program

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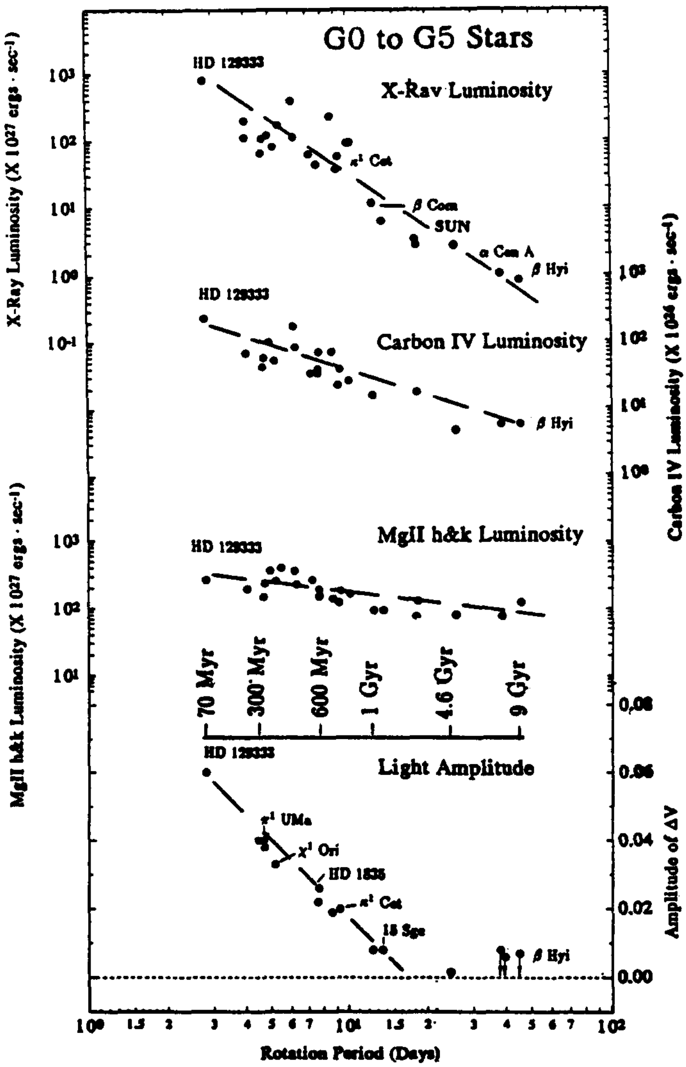

FIGURE 1. The dependence of magnetic activity on rotation for close solar analogs: dwarf G0 – G5 stars and the subgiant β Hydri. X-ray luminosity (coronal activity), C IV and Mg II h+k emission (TR and chromospheric activity) and maximum light curve amplitude (photospheric activity) all decline smoothly with increasing rotation period, or equivalently, age.

and thus are not spun-up or influenced by tidal effects or interaction as in the case of the RS CVn binaries and most BY Dra binaries. Figure 1 shows the decline of X-ray luminosity, C IV emission, and Mg II h+k emission with increasing rotation period (and age) for a sample of strictly solar-type (G0 – G5) stars, includings the stars of Table 1 (Dorren *et al.* 1994). The most dramatic decline occurs in the X-ray emission, which decreases by a factor of 1,000 between ZAMS and TAMS. An important consequence of limiting the range of spectral types (and hence masses) is the clear delineation of these activity-rotation-age relationships. Also shown is the dependence of the light variation on rotation period, to be discussed in the next section.

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b) Establishing the extent to which the Sun is typical of stars of its age and spectral type. We have included several bright nearby stars which are close solar analogs. In particular, HD 44594 is a close spectral match for the Sun in the 3,000 – 8,000 Å range (Hardorp 1978). *IUE* observations which we obtained in 1991 and 1992 show that the spectral similarity persists into the *IUE* wavelength regime, but also that *there is evidence for variability of about 20-30% in the Mg* II *(λ 2800) emission.*

c) Obtaining estimates of the solar UV *and X-ray emission fluxes throughout the Sun's post-ZAMS history.* This has an important bearing on the chemical and dynamical evolution of primeval planetary atmospheres and on the dispersal of the remnants of the solar nebula (see *e.g.,* Giampapa & Imhoff 1985). As an example we have derived the *UV* spectral irradiance of the ZAMS sun using HD 129333 (Dorren & Guinan 1994a).

3. Methods and results

3.1. *Photosphere: starspots*

Light variations in active chromosphere stars are observed using multiwavelength photoelectric photometry, usually *UBVRI* or *uvby*, often supplemented by wide and narrow-band Hα filter pairs to obtain a measure of the chromospheric Hα emission. If the stellar photosphere has a sufficiently extensive starspot coverage (a few percent or more) there will be a detectable modulation of the stellar brightness as the star rotates. Multiwavelength observations are essential to obtain the starspot temperatures and an estimate of their areal extent and distribution. In most cases the area obtained is probably a lower limit; what is actually being observed is the contrast between maximally and minimally spotted hemispheres.

Details of the modelling procedure have been given by Dorren (1987), whose analytic solution to the problem of integrating over a distribution of circular spots is particularly transparent, and straightforward to apply. As an example of modelling a particular star in some detail, see the article by Dorren *et al.* (1981) on the highly active RS CVn binary, HR 1099. Similar techniques have been used by many authors to obtain spot areas and temperatures for a large number of active chromosphere stars (*e.g.,* Eaton & Hall 1979; Rodonó *et al.* 1986; Budding & Zeilik 1987; Strassmeier 1990). For reviews see Eaton (1992) and Guinan & Giménez (1993).

From observations of the solar-type stars we draw the following general conclusions:

- All the G0 – G5 V stars studied with periods less than 12-13d show definite rotationally-modulated light variations. At $\sim$ 13d, the range of the $\langle v \sin i \rangle$-band variation is $\Delta V \simeq 0.008$ mag, and at 2.8d, $\Delta V \simeq 0.06$ mag. No definite rotationally-modulated light variations greater than 0.004 mag (the limiting precision of our photometry) have yet been detected for stars with $P \geq 14$d. However, detectable light variations do occur in single dwarf K and M stars with rotation periods of up to $\sim$ 40d. Variability appears to be rare among F stars earlier than about F8. The values of brightness changes given in Table 1 for α Cen and β Hyi are *upper limits*, obtained from published visual magnitudes. Figure 2 shows the light variations in three of the program stars. The relation between the maximum light curve range (corresponding to the greatest observed contrast between stellar hemispheres, and taken to be an indication of the maximum spot coverage) and rotation period is shown at the bottom of Figure 1.

- Starspot modelling of the *UBVRI* and *uvby* light curves, which show a clear wavelength dependence, indicates that spots cover an area of up to 6% of the total stellar

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surface in the G stars with temperature differences between spot and photosphere of 300 – 600 °K. In most cases, two spots are needed to fit the shapes of the light curves.

• The light curves are observed to change on a timescale comparable to the rotation period. This is illustrated by the light curve of χ^1 Ori shown in Figure 3. This is probably due to differential rotation together with waxing and waning of starspot groups. The other active, fast-rotating stars in our sample (HD 129333, π^1 UMa, HD 1835) show similar behavior. These stars also show evidence for differential rotation in their Ca II HK measures (Donahue 1993). Probably the clearest example of stellar differential rotation is seen in the long-period RS CVn system λ And (G8 IV-III + ?; $P_{rot} \sim$ 54d), for which light curves obtained over several seasons display a systematic pattern of evolution which is most simply understood in terms of differential rotation of two spot groups (Dorren & Guinan 1984). Remarkably, a very similar pattern of light-curve evolution to that of λ And is found in the RS CVn binary HR 7275 (K1 III-IV + ?; P_{rot} = 28.6 d). This has recently been analyzed by Strassmeier *et al.* (1994), who also conclude that differential rotation is a major factor.

• Long term photometry of solar-type stars has indicated the presence of activity cycles with timescales typically of several years (Lockwood & Skiff 1988). We shall show evidence for a 12-yr cycle in HD 129333 later in the paper.

But a word of caution – the G5 V star HD 135262, an apparently undistinguished star which originally had been used as comparison star for the active solar-type star HD 134319, exhibits relatively large ($\sim$ 0.1 mag), usually smooth variations which are clearly not produced by spots. The star is not a known binary, and in any case there are no indications of an eclipse. At present the origin of its light variations is a puzzle.

3.2. *Chromosphere and transition region*

IUE observations of chromospherically active stars have provided direct measures of chromospheric, TR, and coronal activity through net emission-line strengths. For example, the Mg II (2800) chromospheric line emission, which is generally strong, is a reliable indicator of plage activity. Hotter lines, among the strongest of which are C IV (1550), Si IV (1400), He II (1640), and N $\langle v \sin i \rangle$ (1240) signal the strength of the concurrent activity in the TR and corona, and physical conditions such as electron densities from emission line ratios (Jordan & Linsky 1987; Linsky 1990).

Figure 4 shows the Mg II h and k emission lines for 3 solar-type stars of ages from $\sim$ 70 Myr to $\sim$ 9 Gyr together with the Sun, illustrating the decline of chromospheric emission with age. Rotational modulation of the Mg II emission has been observed in HD 129333 (Dorren & Guinan 1994a). Boesgaard & Simon (1984) observed a clear modulation of the C IV emission in χ^1 Ori due to rotation. For most of the other solar-type stars in our program the C IV emission shows variations but there are insufficient observations to establish rotational modulation with certainty. On the other hand, a large number of stars in the Mt. Wilson Ca II HK project show rotational modulation of the chromospheric emission, from which accurate rotational periods have been derived. Several stars also show activity cycles of typically 5-17 years (Baliunas *et al.* 1985; Donahue 1993). For example, the active, Pleiades-age G0 V star, HD 129333, has a well-defined activity of $\sim 12 - 13$ years (see Figure 5).

3.3. *Corona*

The PSPC instrument on the *ROSAT* satellite provides high resolution X-ray spectra in the 0.1 – 2.4 keV range from which coronal temperatures may be derived. For single

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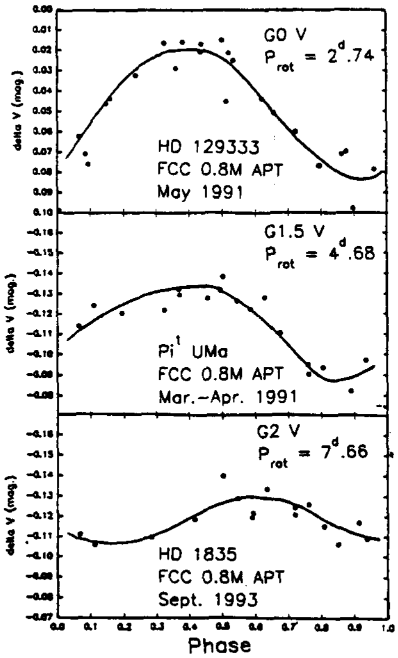

FIGURE 2. Light curves of solar proxies of different ages: HD 129333 (age ~ 70 Myr: the ZAMS Sun), π^1 UMa (~ 300 Myr), and HD 1835 (~ 600 Myr). The light variations are produced by the rotation of a spotted star. The ages of these stars are inferred from membership in moving star cluster groups.

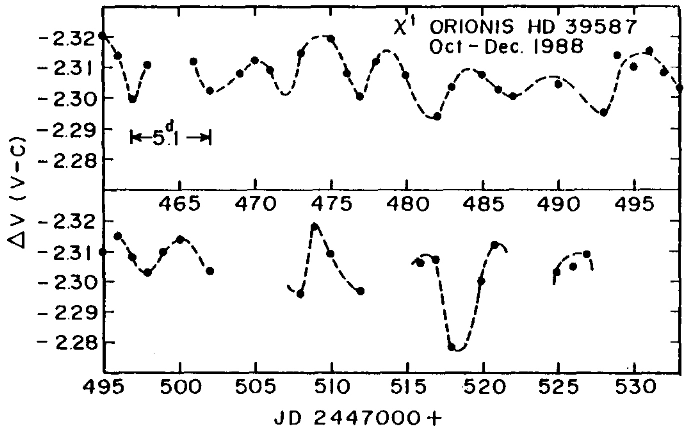

FIGURE 3. Long-term V-band light variations of χ^1 Ori (~ 300 Myr; P_{rot} = 5.1d) obtained with the Phoenix-10 APT. The changes in mean light level and light curve shape are indicative of variations in the spot coverage together with differential rotation.

solar-type stars, these temperatures are typically $10^6 - 10^7$ °K. The X-ray luminosities of single, solar-type stars are ~ $10^{27} - 10^{30}$ ergs s^{-1}, or up to 1,000 times the X-ray luminosity of the quiet Sun. For RS CVn systems, L_x is $10^{29} - 10^{31}$ ergs s^{-1}. In addition to the decrease in L_x with increasing rotation period (Figure 1), the *ROSAT* observations indicate a decrease in coronal temperature with increasing period. For example, the

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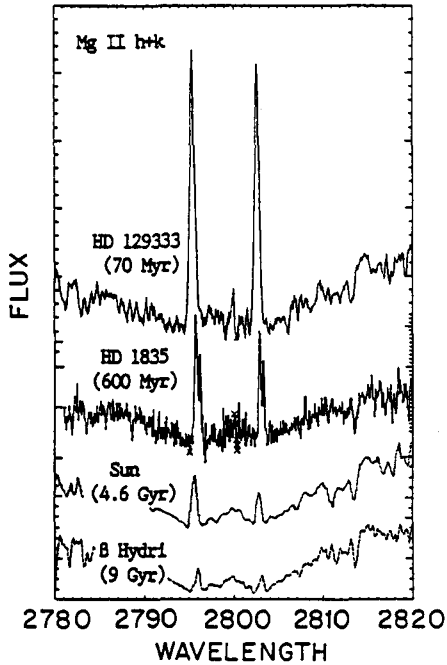

FIGURE 4. Mg II h and k emission lines of HD 129333 (age = 70 Myr), HD 1835 (600 Myr), the Sun (4.6 Gyr), and β Hydri (9 Gyr).

youngest star in our sample, HD 129333, has a coronal temperature of up to 10^7 °K; the oldest star, β Hyi, has a temperature of $1 - 2 \times 10^6$ °K (Dorren & Guinan 1994b).

In addition, radio (VLA or VLBI) observations provide information on non-thermal emission from coronal regions with temperatures of $10^7 - 10^8$ °K. Güdel (1993) recently detected HD 129333 as a radio source with a specific intensity of $\sim 1.8 \times 10^{14}$ ergs $s^{-1}Hz^{-1}$, or about 300 times stronger than the Sun. He has also reported a possible rotational modulation of the X-ray and radio flux from this star.

The recent launch of the *EUVE* satellite has opened a hitherto unexplored wavelength range (50-750 Å) to observation. *EUVE* is, moreover, the only instrument capable of providing *spectroscopy* of stellar coronae. Together, *IUE* and *EUVE* observations provide full spectroscopic coverage of the chromosphere, TR, and corona, *i.e.* over a temperature range from below 10^4 °K to above 10^7 °K. Altogether, the optical photometry and spectroscopy, ultraviolet spectroscopy, X-ray and radio observations produce a detailed picture of the relationship between active regions throughout the stellar atmosphere.

3.4. *Activity cycles*

Activity cycles have been observed for many of the F–K type stars in the Mt. Wilson HK project (Baliunas *et al.* 1985; Donahue 1993). Analysis of these data indicate no definite relation between the presence and length of an activity cycle and spectral type or rotation period (see Donahue 1993). We also note that a number of RS CVn-type binaries show long-term variations in their light curves that suggest the presence of a magnetic activity cycle (see Dorren & Guinan 1990).

In our program the best example of an activity cycle is seen in the long term variation of HD 129333 in mean light, mean Ca II HK index, and *UV* chromospheric and TR

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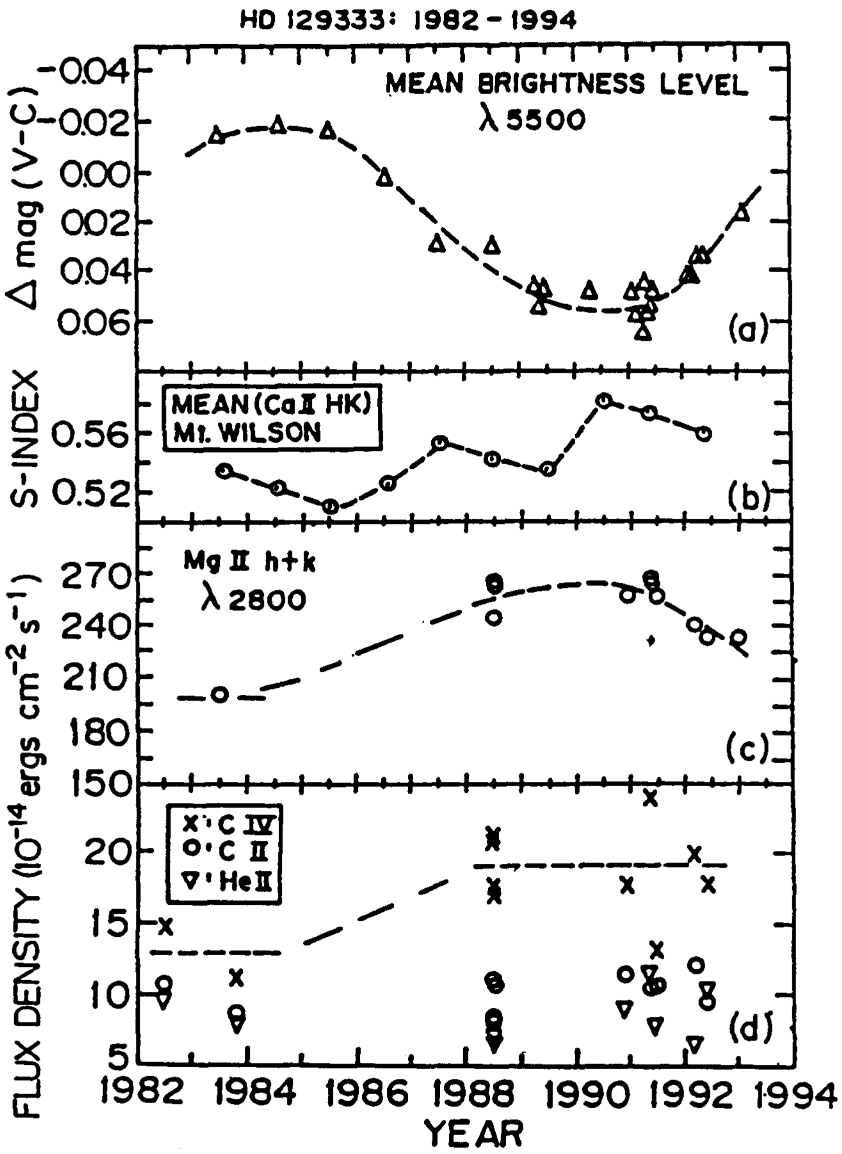

FIGURE 5. Long-term variations in HD 129333: mean V-band brightness, $\overline{\Delta V}$, referred to a comparison star; the Ca II HK emission line index (S); Mg II h+k emission line fluxes; C IV (1550Å), C II (1335Å), and He II (1640Å) emission line fluxes. An activity cycle of about 12-13 years' duration is suggested (from Dorren & Guinan 1994b.)

emission lines shown in Figure 5. There is clear evidence for an activity cycle lasting about 12 years.

4. The Sun — Normal or not? A final word

Whereas solar-type (G0-G5 V) stars with $P_{rot} > 14$ d show no measurable *photometric* variability, some K stars in this period range do have significant variations, most likely

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because of a greater convection zone depth. Some studies have suggested that the Sun may have smaller light variations than other solar-type stars (Radick 1994; Lockwood 1994), but this conclusion is based on a sample of stars that includes K stars as well as G stars and may therefore not be reliable. We reiterate the importance of restricting attention to *close* solar analogues.

Acknowledgments. This work has been supported in part by NASA *IUE* grants NAG 5-382, NAG 5-1703, *ROSAT* grant NAG 5-1662 and NSF grant (to EFG) AST-861362. We wish to thank Elizabeth Jewell for her editorial assistance and David Steelman and Anne McGhie for figure preparation.

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https://doi.org/10.1017/S0252921100024702 Published online by Cambridge University Press