THE ASTROPHYSICAL JOURNAL, 448:431–436, 1995 July 20

NASA-CR-204567

IN-92-CR
WAIVED
036287

X-RAY EMISSION FROM THE SUN IN ITS YOUTH AND OLD AGE

J. D. DORREN,[1,2,3] M. GÜDEL,[4,5] AND E. F. GUINAN[2,6]

Received 1994 September 9; accepted 1995 February 2

ABSTRACT

We have obtained *ROSAT* PSPC pointed observations of two nearby G stars of ages 70 Myr and $9\frac{1}{2}$ Gyr that are of unique importance as proxies for the Sun at the two extremes of its main-sequence evolutionary lifetime. The younger star, HD 129333 (EK Dra; G0 V), a rapid rotator with a 2.7 day period, is a strong source with an X-ray luminosity $L_X(0.2\text{–}2.4\ \text{keV}) = (7.5\text{–}11.5) \times 10^{29}$ erg s^{-1}. Modeling suggests a two-temperature corona with $T_1 = (2.0 \pm 0.3) \times 10^6$ K and $T_2 = (9.7 \pm 0.3) \times 10^6$ K (formal uncertainties). A continuous emission measure distribution, increasing to higher temperatures and with a cutoff at $(20\text{–}30) \times 10^6$ K, yields even better fits to the data. The old star, β Hyi (HR 98; G2 IV), represents the Sun in the future, near the end of its hydrogen-core burning stage, when it should be rotating more slowly (present $P_{\rm rot} = 25.4$ day) and should have lower levels of activity. The *ROSAT* measurements yield $L_X = (0.9\text{–}3.0) \times 10^{27}$ ergs s^{-1} and a rather cool, single coronal temperature of $T = (1.7 \pm 0.4) \times 10^6$ K. For comparison, the Sun has $L_X \approx 2 \times 10^{27}$ ergs s^{-1} and a coronal temperature of about $T = 2 \times 10^6$ K. These stars provide information on the decline of the stellar (and specifically solar) magnetic activity from extreme youth to old age. HD 129333 is also important in that it yields an estimate of the solar soft X-ray flux in the early solar system at the epoch of the terminal stages of planetary accretion.

Subject headings: stars: activity — stars: coronae — stars: individual (HD 129333, β Hydri) — Sun: evolution — Sun: X-rays, gamma rays

1. INTRODUCTION

We report on *ROSAT* PSPC (0.2–2.4 keV) X-ray observations of two nearby solar-type stars of greatly differing ages. These stars are of interest as proxies for the Sun near the beginning of its main-sequence evolution (the zero-age main sequence = ZAMS Sun), and in its terminal main-sequence stage (the TAMS Sun). The younger star, HD 129333, has an age of around 70 Myr if it is a member of the Pleiades Moving Group, and has thus recently arrived on the main-sequence (Soderblom & Clements 1987). It is rotating about 10 times faster than the Sun: its light variations, attributed to a rotational modulation due to starspots, indicate a rotation period which varies between 2.7 days and 2.8 days (Dorren & Guinan 1992, 1994). It has recently been designated as the variable star EK Dra (Kazarovets, Samus, & Goranskij 1993). In G stars the level of magnetic activity is related to the rotation rate (Skumanich 1972; Walter 1981; Pallavicini et al. 1981). As a consequence, the magnetic activity of HD 129333 is significantly greater than the present Sun's. This is manifested as enhanced chromospheric and transition region emission (~5–100 times that of the Sun) and greater starspot coverage (~50–100 times the total spot area of the average Sun). As this paper shows, a much greater enhancement (~2–3 orders of magnitude) occurs in the coronal X-ray emission; a similar enhancement of emission over the quiet Sun's has been reported for coronal microwaves (by approximately three orders of magnitude; Güdel, Schmitt, & Benz 1994; Güdel et al. 1995).

There is strong evidence from extensive photometric and *IUE* observations of this star that it is undergoing an activity cycle of about 12–14 yr duration (Dorren & Guinan 1994). The *ROSAT* observations were obtained during 1990–1993 in conjunction with *IUE* and ground-based photometric observations. HD 129333 is a somewhat problematic target since a recent investigation with CORAVEL finds it to have a low-mass, distant but unresolved companion (Duquennoy & Mayor 1991) with an orbital period of about 12 yr. The X-ray emission could be attributed with some confidence to the G star if it were modulated with a period close to the optical rotation period; the *ROSAT* all-sky survey data, which have a temporal coverage of almost two stellar rotation periods, indeed appear to be modulated with a period close to 2.7 days (Güdel et al. 1995). The X-ray luminosity reported below is also in agreement with what is expected from $v \sin i$ for active stars, and in particular the Pleiades early G-type stars (Pallavicini et al. 1981; Micela et al. 1990). Thus, we assume that the X-ray emission reported in this paper predominantly originates from the G star, an assumption that is supported by the high level of the X-ray luminosity. The *ROSAT* observations thus provide a quantitative measure of the enhancement of the solar coronal X-ray emission in the Sun's early youth.

The second star is β Hyi (G2 IV), a single, solar-type star, and the nearest subgiant. It has a well-determined age of 9.5 ± 0.8 Gyr, established from evolutionary tracks (Dravins et al. 1993a). Since its former main-sequence location was near G2, it may be taken to be representative of the Sun near the end of its main-sequence lifetime. At this age, chromospheric and transition region emission levels are extremely low compared to HD 129333, and about half the level of the present Sun (Dravins et al. 1993b). Nevertheless, there is evidence that an activity cycle (of 15–18 yr) persists even at this age (Dravins

[1] Department of Astronomy and Astrophysics, University of Pennsylvania, Philadelphia, PA 19104.
[2] Guest Investigator, *ROSAT*.
[3] Present address: 701 Hillborn Avenue, Swarthmore, PA 19081.
[4] Paul Scherrer Institute, Würenlingen and Villigen, CH-5232 Villigen PSI, Switzerland.
[5] Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, CO 80309-0440.
[6] Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085.

TABLE 1

STELLAR PROPERTIES AND COMPARISON WITH THE SUN

Star	Spectral Type	$B-V$ (mag)	V (mag)	M_V (mag)	Parallax (arcsec)	$R/R_\odot$	P_{rot} (days)	Age
HD 129333......	G0 V	0.61	7.53	+5.1	0.032 ± 0.005	0.92	2.75	70 Myr[a]
Sun	G2 V	0.65	...	+4.8	...	1	25.4	4.6 Gyr
β Hyi	G2 IV	0.62	2.8	+3.75	0.153 ± 0.007	1.6	45:	9.5 ± 0.8 Gyr

[a] Indicative ages of the Pleiades Moving Group are, for example, the ages of the Pleiades and the α Per open clusters; i.e., 70 Myr and 50 Myr, apart from possibly considerable intrinsic scatter in the clusters (see discussion in Soderblom et al. 1993). Published parallaxes place HD 129333 on or even below the ZAMS (see Dorren & Guinan 1994); this and the spectroscopic properties seem to exclude a pre-ZAMS star, and thus the age is $\gtrsim$30–40 Myr.

et al. 1993b). It was known to be a weak X-ray source from *EXOSAT* observations, which yielded an X-ray luminosity $L_X(0.02\text{–}2.5\ \text{keV}) = 4.5 \times 10^{26}$ ergs s^{-1}. The modeling permits two solutions for the coronal temperature: 5×10^5 K or 4×10^6 K (Dravins et al. 1993a). The greater sensitivity of the *ROSAT* PSPC offers an improved determination of the X-ray flux and coronal temperature. As in the case of HD 129333 our *ROSAT* observations were complemented by near-simultaneous *IUE* observations. Photometry of this southern hemisphere object was unavailable, but modern observations show no evidence for variability (Dravins et al. 1993c; Stobie 1971). Dravins et al. (1993a) have emphasized the significance of X-ray observations of β Hyi for an understanding of the contribution of the various mechanisms of coronal heating in a very old solar-type star. Table 1 contains the properties of HD 129333 and β Hyi from Dorren & Guinan (1994) and Dravins et al. (1993c), respectively.

2. *ROSAT* OBSERVATIONS AND ANALYSIS

The *ROSAT* observing log for all pointed PSPC observations is given in Table 2. In addition to the pointed observations, *ROSAT* observations of HD 129333 were obtained during the all-sky survey in late 1990; the latter provided valuable information on rotational modulation and the flare frequency (Güdel et al. 1994, 1995) and will be an important contribution to long-term studies because the survey data were obtained very close to the star's magnetic activity maximum.

In Table 2 we also list the values of the column density N_H, the coronal temperature(s) T, and the emission measure(s) EM obtained from spectral fits to the pulse height spectra (cols. [5]–[9]). The fitting procedures were done in the XANADU/XSPEC software package using the Raymond-Smith expressions for the emissivities (Fig. 1). Solar photospheric abundances were used for HD 129333, while for the somewhat metal-poor β Hyi, we adopted a lower metallicity, viz., [Me/H] = −0.2 (Dravins et al. 1993a).

The HD 129333 data required a two-temperature model with $T_1 = (2.0 \pm 0.3) \times 10^6$ K and $T_2 = (9.7 \pm 0.3) \times 10^6$ K. The errors indicate the range of the means obtained for the three observing sessions. In Table 1, we give the 90% confidence intervals for each observation; notice that those are formal errors that do not include any model inaccuracies, detector gain uncertainties, or possible variability in time. The X-ray luminosity is $L_X(0.2\text{–}2.4\ \text{keV}) = (7.5\text{–}11.5) \times 10^{29}$ ergs s^{-1}; the range indicates variation between the different data sets, but *not* the uncertainty in the parallax or in the spectral fits (see Tables 1 and 2). The value of L_X is among the highest values of X-ray luminosity for single, cool main-sequence stars. Among the Pleiades cluster stars themselves, the mean X-ray luminosity of solar-type Pleiads ($0.5 \le B-V \le 0.8$) observed with *Einstein* was 2.7×10^{29} ergs s^{-1} (Micela et al. 1990). With *ROSAT*, the mean L_X is found at the similar value of $\sim 3 \times 10^{29}$ ergs s^{-1} (Stauffer et al. 1994). The most luminous G stars in the Pleiades reach $L_X = 2\text{–}3 \times 10^{30}$ ergs s^{-1} (Stauffer et al. 1994), indicating that the X-ray emission of HD 129333 is

TABLE 2

ROSAT OBSERVING LOG AND ANALYSIS RESULTS FOR 1 OR 2 TEMPERATURE FITS[a]

Star (1)	Date (2)	Filter (3)	Obs. Time (ks) (4)	log N_H (cm^{-2}) (5)	log T_1 (K) (6)	log T_2 (K) (7)	EM$_1$ (10^{52} cm^{-3}) (8)	EM$_2$ (10^{52} cm^{-3}) (9)	χ^2/ν (10)	L_X (10^{29} ergs s^{-1}) (11)
HD 129333......	1990 Jul 16	None	0.566	...	...	...	...	...	...	Bad data
HD 129333......	1990 Jul 14–16	Boron	1.822	...	...	...	...	...	...	Bad data
HD 129333......	1991 May 9	None	7.502	$19.40^{+0.14}_{-0.10}$	$6.21^{+0.04}_{-0.05}$	$6.99^{+0.01}_{-0.01}$	$1.18^{+0.11}_{-0.10}$	$2.71^{+0.14}_{-0.14}$	192/126	11.5
HD 129333......	1991 May 9	Boron	1.748	...	...	$7.00^{+0.04}_{-0.02}$	...	$2.65^{+0.41}_{-0.32}$	14.1/16	
HD 129333......	1993 Apr 15–16	None	5.815	$19.10^{+0.27}_{-0.50}$	$6.31^{+0.05}_{-0.05}$	$6.97^{+0.03}_{-0.02}$	$1.05^{+0.13}_{-0.13}$	$1.50^{+0.12}_{-0.11}$	112/93	8.0
HD 129333......	1993 Apr 15	Boron	1.463	...	...	$6.98^{+0.03}_{-0.03}$	...	$2.14^{+0.30}_{-0.31}$	20.2/13	
HD 129333......	1993 Oct 19	None	5.157	$18.80^{+0.43}_{-...}$	$6.36^{+0.06}_{-0.06}$	$6.97^{+0.03}_{+0.04}$	$1.10^{+0.14}_{-0.14}$	$1.28^{+0.12}_{-0.12}$	92.5/86	7.5
β Hyi	1991 May 11	None	1.906	...	$6.32^{+0.06}_{-0.04}$	...	$0.0158^{+0.0022}_{-0.0020}$	...	6.9/8	0.030
β Hyi	1991 Apr 21	Boron	1.707							
β Hyi	1992 Nov 17–29	None	2.757	...	$6.15^{+...}_{-...}$	...	$0.0037^{+...}_{-...}$	...	6.9/3	0.0094
β Hyi	1992 Nov 17–19	Boron	1.463							

[a] Subscript and superscript values denote the 90% confidence ranges; their absence means that no convergence was achieved in their determination. Note that boron filter data effectively isolate the higher temperature plasma component. Distances assumed for calculations of EM and L_X: 31.0 pc for HD 129333 and 6.54 pc for β Hyi; ν is the number of degrees of freedom for the fit.

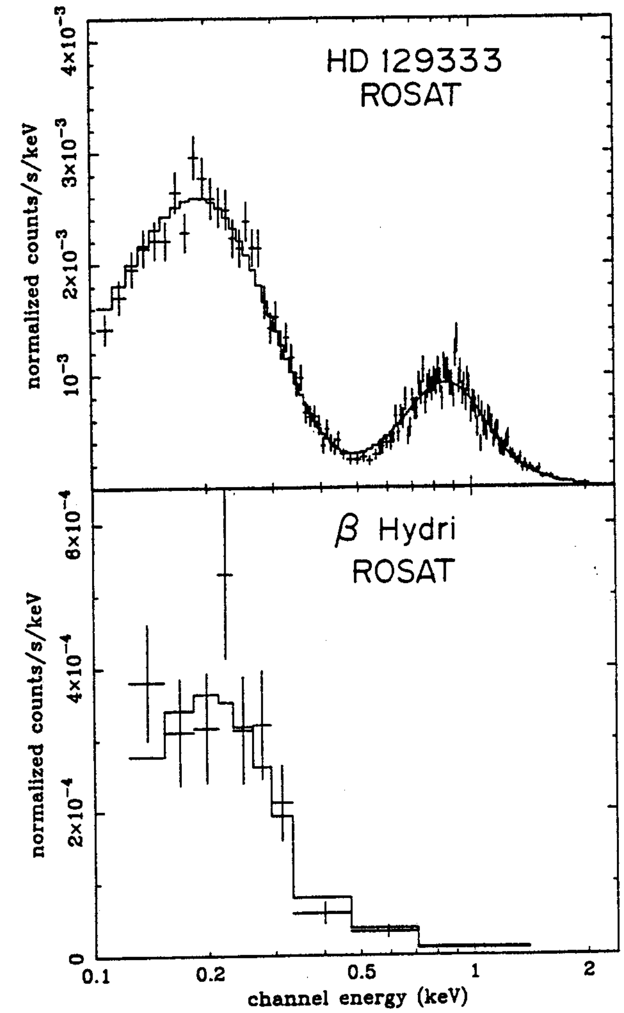

FIG. 1.—Pulse-height spectra observed by the *ROSAT* PSPC without filter (*crosses*) and best fits (*histogram*). *Top*: HD 129333 observed on 1991 May 9. Fit is based on a differential emission measure distribution of Raymond-Smith type optically thin plasmas (see Table 3). *Bottom*: β Hyi observed on 1991 May 11. Best fit is based on a single-temperature Raymond-Smith type plasma component at $T \sim 2$ MK (see Table 2). The higher energy bump is predominantly due to the plasma at high temperature (~ 10 MK); its absence in the β Hyi spectrum indicates a cool corona.

in the range of the strongest X-ray emission found among Pleiades solar-type stars.

Because the χ^2 statistics indicate poor fit results for some observations, we performed fits assuming a simplified differential emission measure (DEM) distribution with a power-law T-dependence and an upper temperature cutoff of the form DEM = const $(T/T_{max})^{\alpha}$ below T_{max}, and DEM = 0 above. The results are given in Table 3.

In addition the light curve analysis of our three pointed observations show HD 129333 to be variable within $\sim 25\%$ on timescales of several hours (Fig. 2); the shortest "event," on 1993 April 15, was an increase in flux by $\sim 15\%$ within 100 minutes, followed by a decrease within the same time interval to a level $\sim 25\%$ lower. Recalling the longer *ROSAT* survey observations (Güdel et al. 1994, 1995), the slow variation may be due to rotational modulation, while the shorter peak is most likely to be identified with an X-ray flare, particularly since the count rate in the harder *ROSAT* channels dropped more rapidly after the flare.

For the weaker source β Hyi the *ROSAT* data, which have poorer S/N, were adequately fitted by a one-temperature model, with $T = (1.7 \pm 0.4) \times 10^6$ K. Any high-temperature signature at ~ 1 keV in the *ROSAT* spectrum must be below the detection threshold (Fig. 1). β Hyi has an X-ray luminosity of $L_X(0.2\text{–}2.4 \text{ keV}) = (0.9\text{–}3.0) \times 10^{27}$ ergs s^{-1}. Although the spectral fit to the second episode data is somewhat poor due to a small number of source photons (~ 135) in the softest channels, the PSPC count rate itself was definitely lower by a factor of 2.4 during the second episode (0.049 counts s^{-1}) compared to the first episode (0.12 counts s^{-1}); this suggests that the star's X-ray radiation is intrinsically variable and that the range of X-ray luminosities reflects different degrees of X-ray activity (see Tables 1 and 2 for additional sources of error). The earlier *EXOSAT* observations gave an X-ray luminosity $L_X(0.02\text{–}2.5 \text{ keV}) = 4.5 \times 10^{26}$ ergs s^{-1} and a coronal temperature of $T = 5 \times 10^5$ K or 4×10^6 K (Dravins et al. 1993a). The lower temperature is incompatible with our fits to the *ROSAT* pulse-height spectra. β Hyi, a star of about twice the age of the Sun, has thus an X-ray luminosity comparable to (i.e., 40%–150% of) the Sun's, but coronal temperatures somewhat cooler than the Sun's average. Its surface flux is about $2\frac{1}{2}$ times smaller, given its radius of 1.6 $R_\odot$.

The validity of simplified 1-T or 2-T spectral fits has been examined (Majer et al. 1986; Schmitt et al. 1990; Pasquini, Schmitt, & Pallavicini 1989), with the conclusion that an emission measure which is a continuous function of temperature is likely to be more realistic (see also Dupree et al. 1993). It appears that the emission measures at the two temperatures are sensitive parameters which emulate a more realistic, continuous emission measure distribution. *ASCA* observations, with their higher spectral resolution and greater energy range, may help to decide between the two alternatives.

3. DISCUSSION

In Figure 3, the X-ray luminosities of HD 129333, β Hyi, and an additional group of solar proxies (single G0 V to G5 V stars) are plotted against rotation period (Dorren, Guinan, & DeWarf 1994). HD 129333 is the youngest and most rapidly rotating star in the group and has the greatest X-ray luminosity. The ages and representative coronal temperatures of

TABLE 3

DIFFERENTIAL EMISSION MEASURE FITS TO HD 129333 DATA (no filter)

Date	log N_H (cm^{-2})	log T_{max} (K)	Slope α	χ^2/ν	L_X (10^{29} ergs s^{-1})
1991 May 9	$19.32^{+0.09}_{-0.18}$	$7.46^{+0.07}_{-0.07}$	$0.71^{+0.14}_{-0.10}$	163/127	11.5
1993 Apr 15–16......	$19.46^{+0.17}_{-0.26}$	$7.31^{+0.11}_{-0.08}$	$0.48^{+0.14}_{-0.14}$	103/94	8.11
1993 Oct 19	$19.51^{+0.19}_{-0.26}$	$7.25^{+0.14}_{-0.09}$	$0.44^{+0.16}_{-0.16}$	88/87	7.83

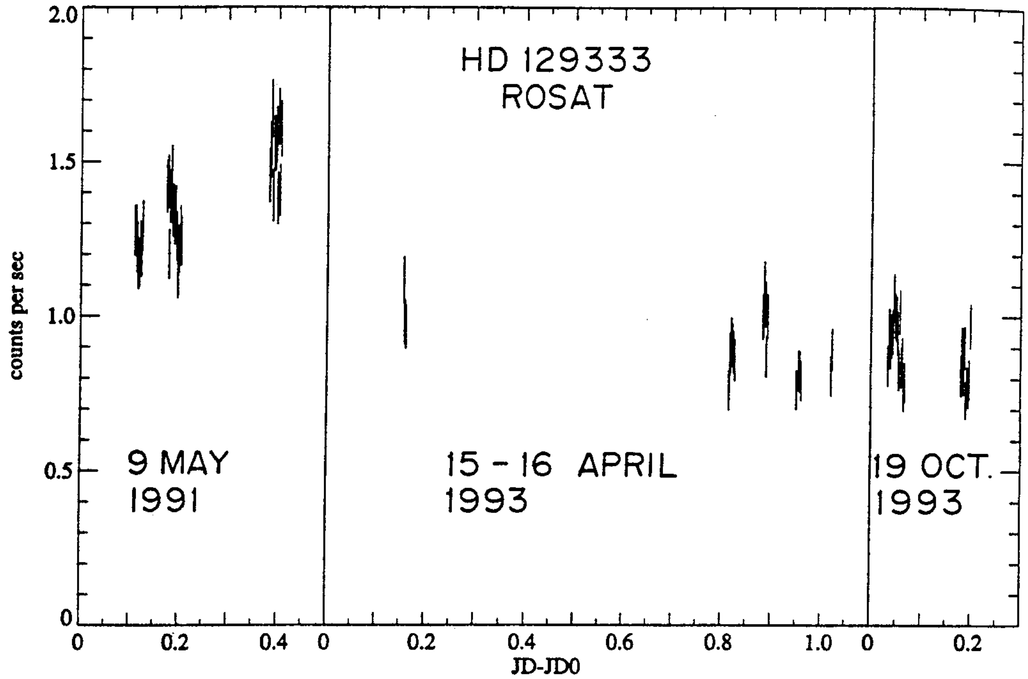

FIG. 2.—X-ray light curve segments of HD 129333 from the three *ROSAT* pointed observations *without* filter. Bin width for individual points is 201 s. Time series on p[illegible] at JD0 = 2,448,385.9 = 1991 May 9, 9.6 hr UT (*left*); JD0 = 2,449,092.8 = 1993 April 15, 7.2 hr UT (*middle*); JD0 = 2,449,279.55 = 1993 October 19, 1.2 hr [illegible] notice slow variability and long-term decrease of count rate. Short timescale count rate increases (e.g., toward the end in the middle panel) appear to be fl[illegible] the large scatter at day 0.4 in the left panel is due to the wobbling motion of *ROSAT* (principal period of 402 s) and consequent brief shadowing of the so[illegible] ne wire mesh in the PSPC detector.

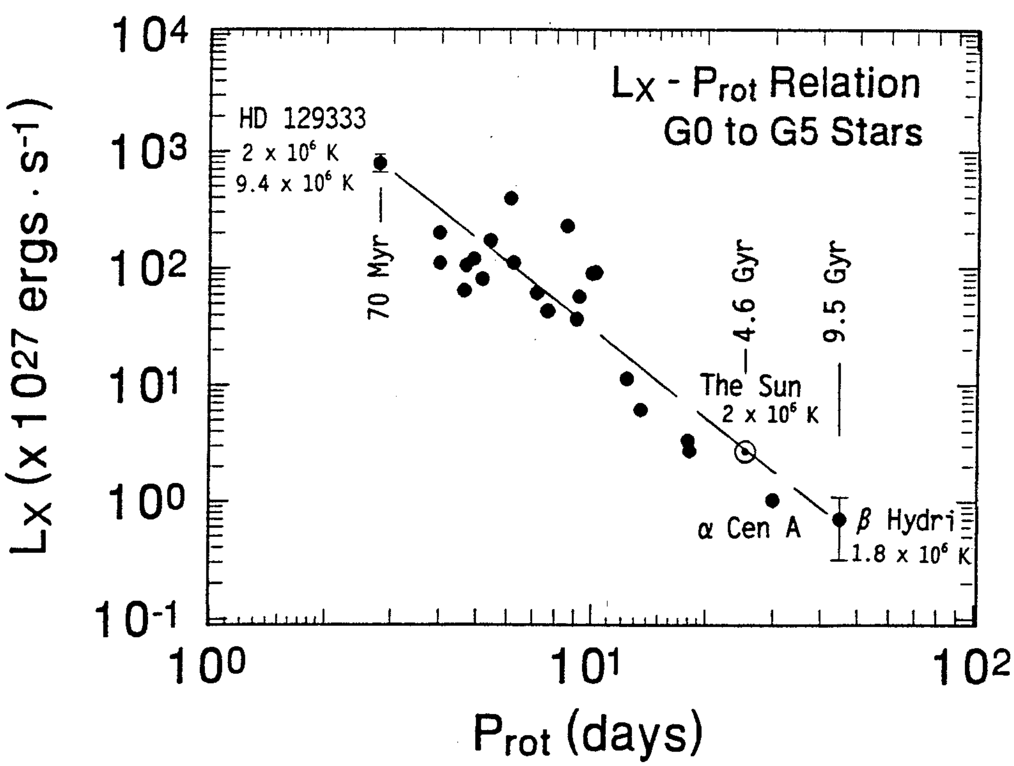

FIG. 3.—Coronal X-ray luminosity L_X of solar analogs of spectral type G0 V–G5 V as a function of rotation period. Representative stellar ages are shown, and the coronal temperatures of the ZAMS and TAMS Sun, HD 129333, and β Hyi are indicated, as well as the average coronal temperature of the Sun itself.

HD 129333, β Hyi, and the Sun are also shown. For this restricted range of spectral types, there is a clear correlation between X-ray luminosity and rotation period. A straight-line fit to the log-log plot gives the relation: $L_X \approx 9 \times 10^{30} P^{-2.5}$ ergs s^{-1}, with P the observed rotation period in days. For stars of solar radius, this becomes $L_X \approx 5 \times 10^{26} v_{eq}^{2.5}$ ergs s^{-1}, where v_{eq} is the equatorial surface velocity in km s^{-1}. Considered as solar proxies, these stars illustrate the decline of coronal X-ray emission *and* the decrease in coronal temperature as the solar dynamo runs down. For HD 129333 the ratio F_X/F_{bol} of surface X-ray flux to bolometric flux may be as large as 3×10^{-4}, which is comparable to the highest values of this ratio found in RS CVn stars or very active single cool stars. For β Hyi the ratio is 2×10^{-7}, while for the Sun it is approximately 5×10^{-7} (Ayres, Marstad, & Linsky 1981). Table 4 contains a comparison of relevant properties of HD 129333, β Hyi, and the Sun.

Our modeling indicates a coronal structure for HD 129333 that comprises at least two plasma components at different temperatures. A continuous emission measure analysis with a simple functional dependence yields a significantly better fit despite having fewer parameters. The same modeling procedure requires only a single coronal temperature for β Hyi. As indicated in Tables 2 and 3, the old star β Hyi is significantly different from HD 129333 in that no high-temperature component is required by the data (Fig. 1). In HD 129333 the high-temperature component is also the component associated with the dominant emission measure.

Moreover, given the limited high-energy resolution of the *ROSAT* PSPC, the HD 129333 data suggest that the high temperature may not arise from an isolated system of hot loops, but rather from the higher temperature part of a multitude of loops of different temperature structure, each loop having a continuous temperature distribution.

The ratio between the high-T and low-T emission measures systematically declined between 1990 and 1993, while at the same time the high-temperature cutoff T_{max} and the power-law exponent α in the expression $(T/T_{max})^{\alpha}$ *also* decreased. In fact, the lower T emission measure remains *constant* within the errors, and the variation in flux is due to the higher T plasma only. A somewhat high emission measure is indicated in the boron filter data obtained on 1993 April 15 a few hours before the nonfilter observations. Notice that the variability of the higher temperature emission measure is contrary to what has been reported for rotational modulation, where the cooler plasma showed stronger modulation (Güdel et al. 1995). On the other hand, the temperature values themselves do not vary significantly beyond what could be attributed to instrumental sensitivity variations. The long-term optical and *IUE* observations of HD 129333 (Dorren & Guinan 1994) show that it reached an activity maximum in 1990 (Fig. 4); thus the higher temperature emission measure decreases as the stellar activity declines, so that *the mechanism producing the high-temperature component becomes less effective at lower activity levels.* Whether frequent or nearly continuous flaring (which presumably becomes also weaker at times of weaker activity) is responsible for heating to $\sim 10^7$ K cannot be decided with the present data.

As the emission measure declines, the total X-ray flux also declines, suggesting a decrease in the area covered by active regions. We caution, however, that the variability in the X-ray luminosity could also be attributed to a nonuniform distribution of X-ray–emitting material around the star (Güdel et al. 1995). Nevertheless, the fact that the high-temperature emission measure and the X-ray luminosity decay concurrently with the decline of other activity indicators (Dorren & Guinan 1994) suggests that the variation is related to the activity cycle.

The old star β Hyi appears to be strongly variable on a long timescale: its X-ray luminosity varies by a factor of 3 between our two observations made in 1991 May and 1992 November. Since an F-type star in the *ROSAT* field which was also detected as an X-ray source did not reveal comparable variability, the difference in count rates for β Hyi appears to be real. This is not too surprising. The Sun's average nonflaring X-ray luminosity varies by an order of magnitude between activity maximum and minimum (Zombeck 1990). Newly emerging

TABLE 4

COMPILATION OF RESULTS ON MAGNETIC ACTIVITY IN HD 129333 AND β HYDRI, AND COMPARISON WITH THE SUN

Parameter	HD 129333	Sun	β Hydri
Rotation period (d)	2.75[a]	25.4	45:[b]
Activity cycle period (yr)	12–14[a]	11	15–18[c]
log L_R (ergs s^{-1} Hz^{-1})[d]	13.6–14.6[e]	10.6	...
log L_X (ergs s^{-1})	29.9–30.1	~27.3	27.0–27.5
log $L_{C IV}$ (ergs s^{-1})[f]	28.41	26.55	26.64
log $L_{Mg II}$ (ergs s^{-1})[f]	29.44	29.0	29.05
log F_X (ergs s^{-1} cm^{-2})	7.2–7.4	4.5	3.8–4.3
log $F_{C IV}$ (ergs s^{-1} cm^{-2})[f]	5.70	3.77	3.44
log $F_{Mg II}$ (ergs s^{-1} cm^{-2})[f]	6.73	6.22	5.85
Average coronal T (10^6 K)	2 and 10	~2	1.4–2
Average coronal EM (10^{52} cm^{-3})	1.3–2.7	~0.007[g]	0.004–0.016

[a] See also Dorren & Guinan 1994.
[b] From Dravins et al. 1993c.
[c] From Dravins et al. 1993b.
[d] L_R denotes the microwave luminosity at 8.5 GHz.
[e] From Güdel et al. 1994, 1995.
[f] $F_{C IV}$ and $F_{Mg II}$ denote surface fluxes for C IV 1549 Å line emission and Mg II 2800 Å line emission, respectively, and $L_{C IV}$ and $L_{Mg II}$ are the corresponding luminosities (from Dorren, Guinan, & DeWarf 1995; see also Dorren & Guinan 1994).
[g] Modeled from T and L_X based on a Raymond-Smith type plasma model.

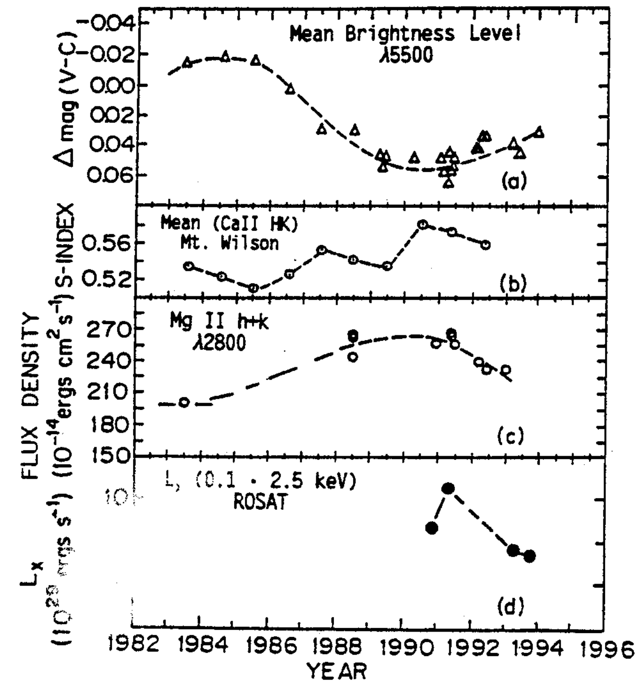

FIG. 4.—Long-term optical, UV, and X-ray variations of HD 129333 which suggest an activity cycle of 12–14 yr duration: (*a*) mean *V*-band brightness, shown as the magnitude difference between HD 129333 and a comparison star; (*b*) Ca II H + K emission (Baliunas & Donahue 1993); (*c*) Mg II *h* + *k* emission; (*d*) X-ray luminosity (*ROSAT* all-sky survey flux in 1990 November from Güdel et al. 1994, 1995).

magnetic flux or disappearance of an active region has a much more dramatic effect on a weakly active star than on an active star with a high coronal filling factor.

If, as is generally believed, the dynamo is the mechanism responsible for the variability of the magnetic activity, then our observations suggest a general weakening of the solar magnetic dynamo in time: as the Sun gets older, loss of angular momentum through a magnetic wind decelerates the convective zone. The number and/or size of active regions may decrease, the temperature of active regions may decline, or a combination of both may occur, resulting in a decrease in X-ray emission and in the exponent α of the temperature dependence, as the higher temperature component weakens relative to the cooler contributions. Magnetic heating of the corona, possibly by flarelike processes, diminishes, leading to a decline in the average coronal temperatures and leaving a relatively cool and inactive corona at the TAMS stage. The β Hyi coronal temperature of 1.7×10^6 K does, however, not exclude the presence of a hydrodynamically expanding stellar wind similar to the Sun's (see § 4.1 in Dravins et al. 1993a); angular momentum loss could thus still continue at the TAMS age. Beyond that age, internal redistribution of angular momentum may begin to control the stellar magnetic activity.

We wish to thank Michael Corcoran for help in the early stages of the *ROSAT* data analysis. Jürgen H. Schmitt provided us with a continuous emission measure table file for spectral fits to *ROSAT* data. The useful comments of the referee are appreciated. We acknowledge support from MPE and ESO in the use of the MIDAS/EXSAS data analysis package for the *ROSAT* data. The *ROSAT* project has been supported by the Bundesministerium für Forschung und Technologie (BMFT) and the Max-Planck-Gesellschaft (MPG). M. G. acknowledges the hospitality of the Institute of Astronomy of ETH Zürich where part of this work was done. This research has been supported by NASA *ROSAT* grants NAG 5-1662 and NAG 5-1703, and by NASA *IUE* grants NAG 5-382 and NAG 5-1703. We also acknowledge the support of NSF grant AST 86-16362. M. G. has been supported by the Swiss National Science Foundation (grant 8220-033360) and by NASA grant NAG 5-1887 to the University of Colorado.

REFERENCES

Ayres, T. R., Marstad, N. C., & Linsky, J. L. 1981, ApJ, 247, 545
Baliunas, S. L., & Donahue, R. A. 1993, private communication
Dorren, J. D., & Guinan, E. F. 1992, BAAS, 24, 1205
———. 1994, ApJ, 428, 805
Dorren, J. D., Guinan, E. F., & DeWarf, L. E. 1994, in Eighth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. J.-P. Caillault (Dordrecht: Kluwer), 399
Dorren, J. D., Guinan, E. F., & DeWarf, L. E. 1995, in preparation
Dravins, D., Linde, P., Ayres, T. R., Linsky, J. L., Monsignori-Fossi, B., Simon, T., & Wallinder, F. 1993a, ApJ, 403, 412
Dravins, D., Linde, P., Fredga, K., & Gahm, G. F. 1993b, ApJ, 403, 396
Dravins, D., Lindgren, L., Nordlund, A., & VandenBerg, D. A. 1993c, ApJ, 403, 385
Dupree, A. K., et al. 1993, ApJ, 418, L41
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Güdel, M., Schmitt, J. H. M. M., & Benz, A. O. 1994, Science, 265, 933
Güdel, M., Schmitt, J. H. M. M., Benz, A. O., & Elias, N. M. II, 1995, A&A, in press
Kazarovets, E. V., Samus, N. N., & Goranskij, V. P. 1993, Info. Bull. Var. Stars, 3840
Majer, P., Schmitt, J. H. M. M., Golub, L., Harnden, F. R., & Rosner, R. 1986, ApJ, 300, 360
Micela, G., Sciortino, S., Vaiana, G. S., Harnden, F. R., Jr., Rosner, R., & Schmitt, J. H. M. M. 1990, ApJ, 348, 557
Pallavicini, R., Golub, L., Rosner, R., Vaiana, G. S., Ayres, T., & Linsky, J. L. 1981, ApJ, 248, 279
Pasquini, L., Schmitt, J. H. M. M., & Pallavicini, R. 1989, A&A, 226, 225
Schmitt, J. H. M. M., Collura, A., Sciortino, S., Vaiana, G. S., Harnden, F. R., Jr., & Rosner, R. 1990, ApJ, 365, 704
Skumanich, A. 1972, ApJ, 171, 565
Soderblom, D. R., & Clements, S. D. 1987, AJ, 93, 920
Soderblom, D. R., Stauffer, J. R., MacGregor, K. B., & Jones, B. F. 1993, ApJ, 409, 624
Stauffer, J. R., Caillault, J.-P., Gagné, M., Prosser, C. F., & Hartmann, L. W. 1994, ApJS, 91, 625
Stobie, R. S. 1971, M.N.A.S.So. Africa, 30, 31
Walter, F. M. 1981, ApJ, 245, 677
Zombeck, M. V. 1990, Handbook of Space Astronomy and Astrophysics (2d. ed.; Cambridge: Cambridge Univ. Press)