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X-ray/optical observations of stars with shallow convection zones (A8–G2 V)*

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Abstract. We present Walraven photometry and ROSAT All-Sky Survey data for a sample of 173 bright main-sequence stars with spectral types between A8V and G2V. These observations are part of a study of the onset of magnetic surface activity along the main sequence. Values for the effective temperature, surface gravity and interstellar reddening have been obtained from a comparison of the observed Walraven colours with theoretical values. These parameters have been used to derive accurate X-ray surface flux densities.

Key words: stars: activity; fundamental parameters — X-rays: stars

1. Introduction

Stars with spectral types later than ~F5 show magnetic surface activity, chromospheres and coronae like the Sun. Stars with earlier spectral types appear to have a weaker outer atmosphere, supposedly due to the shallowness or absence of outer convection zones in these stars (Schrijver 1993, and references therein). As part of a study of the onset of stellar activity along the main sequence, we have used ROSAT all-sky survey data to determine X-ray fluxes of a sample of 173 main-sequence stars, with spectral types between A8 and G2. In order to derive detailed quantitative information on the location of these stars in the Hertzsprung-Russell diagram, we have also made Walraven five-colour photometric observations.

The sample studied here was selected from the Bright Star Catalogue (BSC; Hoffleit & Jaschek 1982, lists almost all stars with $V_J < 6.5$ mag) according to the following criteria:

- Spectral type between A8 and G2; no spectral peculiarities noted; not double in spectral type classification (e.g., HR 32 with spectral type F2V+F6V is excluded).
- Luminosity class V;
- Right ascension between $0^h$ and $2^h$, or between $14^h$ and $24^h$, declination south of $+10^\circ$ (defining the region on the sky visible during the appointed observation times);
- Binaries for which both components occurred in the BSC are excluded, if the separation is less than $10''$.

The selected sample is listed in Table 1, excluding five stars for which no (photometric and X-ray) data are available (HR 591, HR 5542, HR 6593, HR 8245, HR 8735). Four stars have not been observed in the Walraven photometric system, and for 11 stars we have no ROSAT data available. These 15 stars with incomplete data are indicated as such in Table 1.

This paper reports the results of the ROSAT and Walraven observations. Spectroscopic observations and determinations of the rotational velocities for the sample stars have been described in Groot et al. (1996).

2. Walraven photometry

2.1. The observations

The photometric observations were made during 11 nights in 1989 between June 21 and July 29, with the Walraven photometer on the 90 cm Dutch telescope at the European Southern Observatory. This photometer (Lub & Pel 1977) provided simultaneous measurements of the stellar brightness in five passbands (called $V$, $B$, $U$, $W$, and $L$), between 3250 and 5500 Å. All measurements were made using a diaphragm with a 16 arcsecond diameter. An observation of each star consisted of four integrations of 16 seconds each, followed by two such integrations on the...
The correction factor \( f(n) \) to the uncertainty in the mean value and the correction factor \( g(n) \) to the standard deviation for a small number of observations \( n \)

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The differences between the Walraven apparent brightness \( V_W \) and the apparent brightness obtained from Johnson's apparent visual magnitude \( V_J \) appear to depend slightly on colour \((V-B)_W\). Johnson's apparent visual magnitudes have been obtained from the Bright Star Catalogue (BSC) (Hoffleit & Jaschek 1982). For the stars in our sample,
exceeding the five deviating stars from Sect. 2.1, the best-fit linear relation is given by:

\[
V_3 = -0.11(\pm 0.06)(V - B)_W - 2.5[V_W - 2.747(\pm 0.005)]. 
\]

The Walraven \((V - B)_W\) colour and Johnson’s \((B - V)_J\) are tightly related (Fig. 2). The best linear fit for our sample (excluding the five deviating stars from Sect. 2.1) is given by:

\[
(B - V)_J = 0.014(\pm 0.004) + 2.239(\pm 0.017)(V - B)_W. 
\]

The relations 3 and 4 are consistent with those derived by Van Paradijs et al. (1986) for a sample of OB-type stars.

3. Stellar parameters

The effective temperature \(T_{\text{eff}}\), surface gravity \(g\), and interstellar extinction \(E(V - B)\) (in the Walraven system) were derived for each star from a comparison of the observed Walraven colours with theoretical values. The theoretical \((V - B)_W\) and \((L - U)_W\) values as functions of \(T_{\text{eff}}\) and \(\log g\) were obtained from an empirically derived main-sequence relation between \(T_{\text{eff}}\), \(\log g\), \((V - B)_W\) and \((L - U)_W\), combined with differential colour-colour vectors from a folding of the Walraven system with the spectral energy distributions for a grid of Kurucz (1992) model atmospheres. Both the empirical Hyades main-sequence and the differential vectors for the Kurucz model atmospheres were kindly provided by Pel (1991). The models used cover the effective temperature range from 5500 K to 8500 K and the surface gravity range 2.0 to 4.5. Chemical abundances range from 0.003 times the solar value to the solar value. We have converted the empirically derived Hyades main-sequence relation, with \([\text{Fe/H}] = 0.12\), to a relation valid for solar abundances, and extrapolated it
to lower surface gravity values, using differential vectors from Kurucz model atmospheres. The use of differential vectors bypasses possible systematic offsets in the colours derived from Kurucz model atmospheres. Figure 3 shows the resulting \((V - B)_W - (L - U)_W\) diagram with lines of constant temperature and surface gravity, for solar abundances. Also, the location of the empirical Hyades main-sequence is indicated (dotted line, \([\text{Fe/H}] = 0.12\) and the main sequence as converted to solar abundance (thick solid line), and the positions of the sample stars are plotted. For a subsample of stars with supposedly small interstellar reddening, preliminary values for the effective temperature and the surface gravity were derived by equating the observed \((V - B)_W\) and \((L - U)_W\) with the theoretical ones. The subsample was checked for consistency on the assumed interstellar reddening, after deriving the extinction for every star by comparing with the (corrected) theoretical Walraven colours. These preliminary values for the effective temperature and the surface gravity were used to calculate the expected theoretical colours \((B - U)_W\) and \((U - W)_W\) for the same subsample. The differences between observed and theoretical values were interpreted as a systematic error in the theoretical colours, and were used to correct the theoretical colours. The colour \((B - L)\) is corrected using the corrections for \((B - U)\) and \((L - U)\).

After that, values for \(T_{\text{eff}}, \log g\) and \(E(V - B)\) were derived by comparing their observed colours \((B - U)_W, (B - L)_W, (U - W)_W\) with the corrected theoretical ones. If any of the stars, used for calibration, had significant extinction the whole procedure was repeated, without these reddened stars.

The final values for \(T_{\text{eff}}, \log g\) and \(E(V - B)\) for all stars, as listed in Table 2, their uncertainties and the uncertainties \(\sigma^2_{i,\text{th}}\) on the theoretical colours \(C_{i,\text{th}}\), have been derived simultaneously by minimising \(\chi^2\):

\[
\chi^2 = \sum_{i=1}^{4} \frac{(C_{i,\text{obs}} - C_{i,\text{th}})^2}{\sigma^2_{i,\text{obs}} + \sigma^2_{i,\text{th}}},
\]

where \(C_{i,\text{obs}}\) and \(\sigma_{i,\text{obs}}\) are the observed colour and its uncertainty, respectively. The uncertainties on the stellar parameters are determined by the values where \(\chi^2\) equals the minimum \(\chi^2\) plus one, and the uncertainties in the theoretical colours are determined by assuming that the quadratic deviation between the observed and the theoretical colour \(C_{i,\text{obs}} - C_{i,\text{th}}\) is on average equal to the sum of their quadratic uncertainties \(\sigma^2_{i,\text{obs}} + \sigma^2_{i,\text{th}}\).

We find that for the present sample the uncertainties in the theoretical colours are negligible in \((V - B)_W\) and \((B - U)_W\) (compared to the observational uncertainties). The uncertainty in the theoretical \((U - W)_W\) is 0.013, and the uncertainty in the theoretical \((B - L)_W\) is 0.015.

The uncertainties in the effective temperature, the surface gravity, and the colour excess \(E(V - B)\), are typically (68%): 60 K < \(\Delta T_{\text{eff}}\) < 170 K, 0.05 < \(\Delta \log g\) < 0.17, and 0.004 < \(\Delta E(V - B)\) < 0.009, respectively. An extra (unknown) uncertainty may occur if the stellar parameters are outside the range of the parameters of the calibration stars \((T_{\text{eff}}\text{ between } 6000 \text{ K and } 8000 \text{ K; } \log g \text{ between } 3.4 \text{ and } 4.4)\).

For five stars (HR 313, HR 7126, HR 8041, HR 8917 and HR 8935) we could not find consistent stellar parameters with this method, in the sense that the minimum \(\chi^2\) for these stars is larger than 10. We can find no reason why these stars should deviate in their colour-colour behaviour. These stars are indicated in Table 2 with a colon after the values. No uncertainties are given for these stars.

4. The X-ray data

The ROSAT All-Sky Survey was conducted from July 1990 until January 1991. During the survey the satellite scanned the sky in circles perpendicular to the direction of the Sun. Any particular position in the sky was in the 2° field of view of the Position Sensitive Proportional Counter (PSPC) for about 30 seconds once every 90 minutes, during at least 2 days (depending on the ecliptic latitude). The PSPC is sensitive in the energy range 0.1–2.4 keV. For a detailed description of the satellite and the PSPC we refer to Trümper (1983) and Pfeffermann et al. (1988), and for a description of the All-Sky Survey to Voges (1992).

The X-ray count rates have been derived as described in Chapter 2 of Piters (1995). A short summary will be given here. We selected a region around the position of the source, and two background regions on the same ecliptic longitude (i.e. on the same survey scans). From the number of counts in these three regions, and their effective exposure times we derived the most probable source count rate and its uncertainty, using a maximum-likelihood method based on Poisson statistics. A 3\(\sigma\) upper limit to the count rate is determined if the probability \(P_{3\sigma}\) that the counts in the source region are only background counts is larger than 0.025. With this threshold value we expect only 0.5 false detections in our sample (determined by the sum of \(P_{3\sigma}\) over all detections).

The resulting count rates and upper limit values are given in Table 5 (Col. 2). We detected 86 X-ray sources out of the total of 162 stars for which X-ray data were available.

The conversion of count rate \(r_s\) to flux density \((\text{ergs cm}^{-2}\text{s}^{-1})\) at Earth \(f_X\) is given by

\[
f_X = \frac{r_s}{C_X},
\]

where \(C_X\) is the energy-conversion factor, derived from the hydrogen column density \(n_H\), and from the probability distribution of the hardness ratio \(q(h)\), following the procedure as described in Chapter 2 of Piters (1995). This method assumes that the X-ray spectrum can be described by a single-temperature Mewe & Gronenschild.
(Mewe et al. 1985) spectrum which is subject to galactic absorption (Morrison & McCammon 1983). From the probability distribution of the hardness ratio (defined as the ratio of the source count rate in the high-energy band — channels 41 to 240, $\sim 0.4 - 2.4$ keV — and the total source count rate) we derive a probability distribution for the temperature. Because every temperature is associated with a value for $C_X$ the most probable value for $C_X$ and its uncertainty interval can be calculated from this distribution of temperature. The most probable value for the hardness ratio and its uncertainty are listed in Col. 3 of Table 5, and the most probable value for $C_X$ and its uncertainty interval are listed in Col. 4 of Table 5. For nearby stars in the galactic plane (distance less than 200 pc and galactic latitude between $-30^\circ$ and $+30^\circ$) we derived the X-ray flux density at the stellar surface, $R_X$.

The adopted $n_H$ from Paresce (1984), while for more distant stars we estimated $n_H$ from the interstellar reddening $E(V - B)$, as derived in Sect. 3, using the relation $E(B - V) = 2.39E(V - B) - 0.17E(V - B)^2$ and the expression $n_H = 5.8 \times 10^{21} E(B - V) \text{cm}^{-2}$ (Bohlin et al. 1978; close to the relation recently derived by Predehl & Schmitt 1995). The spread around this relationship is about 30%. The distance is derived from the parallax or, if the parallax is not known, from the distance modulus. The adopted $n_H$ values are listed in Table 5, Col. 5.

For each star detected in the ROSAT survey we derived the X-ray flux density at the stellar surface, $F_X$, the X-ray luminosity $L_X$, and the normalised X-ray flux density $R_X = L_X / L_{bol}$ from the flux density at the detector, $f_X$:

$$\log R_X = \log f_X + 0.4(V_J + BC) + 4.574,$$

$$\log F_X = \log R_X + 4 \log T_{eff} - 4.246,$$

$$\log L_X = \log F_X + 2 \log (R_* / R_\odot) + 22.784.$$

The effective temperatures $T_{eff}$ have been taken from Table 2, the bolometric correction $BC$ from Hayes (1978), which gives these corrections as a function of the effective temperature. Johnson’s apparent visual magnitudes $V_J$ have been obtained from the extinction corrected Walraven brightness $V_W$ and colour $(V - B)_W$ using Eq. (3). The stellar radii $R_*$ have been derived from the surface gravity, using the relation $R_* = \sqrt{GM / g}$. The mass $M$ is calculated as a function of effective temperature from the mass-spectral type relation, as given by Schmidt-Kaler (1982), combined with the spectral type-temperature relation as given by Hayes (1978). The numerical constants are based on the solar parameters used by Oranje et al. (1982). The values are listed for $log F_X$, $log L_X$ and $log R_X$ and their uncertainties are listed in Table 5, Cols. 6 to 8. These uncertainties are dominated by the uncertainties in the source count rate $r_s$, and in the hydrogen column density $n_H$, the latter being caused by the relatively large uncertainties in the distance and in $E(V - B)$.

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