Stellar Activity and the Strömgren Photometric Metallicity Calibration of Intermediate-Type Dwarf Stars

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ABSTRACT. We consider the effect of stellar activity, as measured by X-ray luminosity, on metallicities of solar-neighborhood F and G dwarfs derived from Strömgren photometry. Rocha-Pinto & Maciel (1998) correlated the calcium emission-line index in a meaningful way (see, e.g., West et al. 2004). With recent large photometric and spectroscopic surveys explored by several authors, commencing with Giampapa et al. (1979). With recent large photometric and spectroscopic surveys, the question can be addressed in a statistically meaningful way (see, e.g., West et al. 2004). Rocha-Pinto & Maciel (1998) correlated the calcium emission-line index \( \log R'_{\text{Hk}} \) against metallicities calculated from Strömgren photometry and found that their most active stars had surprisingly low values of inferred \([\text{Fe/H}]_{\text{phot}}\).

In highly active stars, the equivalent width of metallic absorption lines can be reduced by chromospheric emission in the lines (see, e.g., Basri et al. 1989). For extremely active stars, this effect may reduce the Strömgren \( m_1 \) index, which is intended to measure line blanketing (Crawford 1975), leading to a falsely low photometric metallicity. Rocha-Pinto & Maciel (1998) appealed to an activity-\( m_1 \) correlation to explain the apparent low photometric metallicity (and corresponding apparent old age) of the most active nearby stars as an artifact of their chromospheric activity. In this paper we make a similar comparison, adopting as an indicator of stellar activity the soft X-ray luminosity measured by ROSAT, and using a photometric metallicity calibration (Martell & Laughlin 2002, hereafter ML02) that was developed to be more accurate for higher metallicity stars than the Schuster & Nissen (1989, hereafter SN89) calibration.

1. INTRODUCTION

The effect of chromospheric activity on photometric techniques for measuring the metallicities of stars has been explored by several authors, commencing with Giampapa et al. (1979). With recent large photometric and spectroscopic surveys, the question can be addressed in a statistically meaningful way (see, e.g., West et al. 2004). Rocha-Pinto & Maciel (1998) correlated the calcium emission-line index \( \log R'_{\text{Hk}} \) against metallicities calculated from Strömgren photometry and found that their most active stars had surprisingly low values of inferred \([\text{Fe/H}]_{\text{phot}}\).

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2. THE METALLICITY DATA SET

In ML02, the authors used a set of 664 F, G, and K dwarfs located within 100 pc of the Sun to derive an empirical relation between Strömgren photometric indices and metallicity. The selection criteria for the ML02 “calibration stars” are as follows: they are the members of the Cayrel de Strobel et al. (2001) compilation of \([\text{Fe/H}]\) abundances that have absolute magnitudes \( M_V > +1.0 \), \( \text{Hipparcos} \) parallaxes greater than 0\,\(^\circ\)01, and that are also in the Hauck & Mermilliod (1998) compilation of Strömgren photometry. The calibration used a Levenberg-Marquardt algorithm (e.g., Press et al. 1992) to find the coefficients for a general third-order polynomial relating \([\text{Fe/H}]\) to the Strömgren indices \( b-y \), \( m_1 \), and \( c_1 \). When the distributions of the residuals (i.e., \([\text{Fe/H}]_{\text{spec}} - [\text{Fe/H}]_{\text{phot}}\)) for the ML02 and SN89 calibrations were compared, the former was found to be more accurate. This can be seen in Figure 1, which shows a Gaussian fit to each distribution. Both the central offset and the half-width at half-maximum (HWHM) of the fits are smaller for the ML02 calibration.

We have modified slightly the methodology of ML02: in the Cayrel de Strobel et al. (2001) metallicity catalog, many stars have multiple \([\text{Fe/H}]\) measurements, which were treated as separate objects for the purposes of the ML02 polynomial fitting. For the present work, we averaged such multiple \([\text{Fe/H}]\) values together, both to reduce the effect of outlying measurements and to prevent multiple counting of stars in our histograms and plots. For stars with multiple observations, we took the observational error in \([\text{Fe/H}]\) to be the standard deviation in the mean, calculated from those multiple measurements. For stars

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with single observations, or where the standard deviation was zero, we adopted as the error the mean of the standard deviation for all of the multiply observed stars. That quantity has a value of 0.0824 dex. We then refitted the ML02 Strömgren photometry-metallicity relation, and while the values of the coefficients did change, the overall quality of the fit stayed roughly constant. The same residual-distribution test was done as in ML02, and the results are also shown in Figure 1. The Gaussian fits to the new residual distribution (hereafter MS04) and that of ML02 are almost equivalent: the center falls at $-0.0248$ for the ML02 calibration, and at $-0.0266$ for the MS04 calibration. The HWHM for ML02 is 0.0868, and 0.0890 for MS04. In the residual distribution for the SN89 calibration, the center of the Gaussian fit is at $-0.0517$, and the HWHM is 0.1097, values that are clearly different from the ML02 and MS04 calibrations.

The resulting calibration is

$$[\text{Fe/H}]_{\text{phot}} = -41.836891 + 153.922030(b-y) + 53.6783461m_1 + 129.01008c_1 - 101.47843(b-y)^2 + 161.87500m_1^2 - 150.07528c_1 - 412.75949(b-y)m_1 - 370.84617(b-y)c_1 + 52.187608m_1c_1 - 103.14707(b-y)^3 + 81.084037m_1^3 + 53.244338c_1 + 651.10576(b-y)^2m_1 + 204.52658(b-y)^3c_1 - 452.44692m_1^2(b-y) - 80.536525m_1^2c_1 + 247.37448c_1(b-y) - 90.169531c_1m_1 + 128.07586(b-y)m_1c_1.$$ (1)

The differences between photometric metallicities derived from this new calibration and those of ML02 and Schuster & Nissen (1989) are shown in Figures 2 and 3, respectively, as a function of the spectroscopic metallicity of the calibrating stars. These diagrams give an appreciation for the uncertainty in using these fitting functions to derive [Fe/H] from Strömgren colors. We should point out that the calibration stars for ML02 and MS04 do not extend to metallicities as low as the calibrators used by Schuster & Nissen (1989), and these former calibrations should only be employed over the range in [Fe/H] shown in Figures 2 and 3.

The change in coefficients between the ML02 and MS04 calibrations lead us to investigate how strongly the coefficients depend on the assumed errors in the spectroscopic [Fe/H] values of the calibrating stars. If the errors are assumed to be the same for all stars, the coefficients are insensitive to the value of the assumed error: they are the same whether the assumed error is 0.05, 0.10, or even 0.20 dex.

By contrast, more complicated behavior resulted when we allowed the errors in [Fe/H] to vary among the calibration stars. For each star with multiple [Fe/H] measurements, we calculated the mean [Fe/H] value, the standard deviation $\sigma$ in these [Fe/H] values, and the standard deviation in the mean $\sigma_{\text{rms}}$.

These two fits differed in the error adopted for all of the singly observed stars; in the first case this error was taken to be the average value of $\sigma$ from the multiply observed stars, while in the second case an error twice this amount was adopted. It is the former of these fits that corresponds to equation (1). The coefficients, as a rule, were larger for the second fit. Most of the terms involving $(b-y)$ and $m_1$ stayed fairly constant, although two of the largest changes were in the coefficients of $(b-y)^2m_1$ and $(b-y)m_1^2$, which are the two largest coefficients in the calibration.

We also experimented with setting to zero the four coefficients whose values varied the most with changes in the errors. This caused all the other coefficients to decrease. However, the quality of the fits, as measured by Gaussian parameters, stayed roughly constant as we varied the assumed values of the errors.
and all had centers closer to zero and smaller HWHMs than the SN89 calibration.

3. THE ROSAT DATA SET

The ROSAT observatory conducted an All-Sky Survey (RASS) of X-ray sources (Voges et al. 1999) during 1990 and 1991 using the on-board PSPC imaging detector (Pfeffermann et al. 1987). Hünsch et al. (1998) searched the RASS data for detections at the locations of all main-sequence and subgiant stars listed in the Bright Star Catalogue (BSC; Hoffleit & Warren 1991). We sifted the “calibration stars” used by ML02 for...
those also included in the catalog of Hünsch et al. (1998). This produced a set of 146 stars, which we refer to as the “RASS-BSC calibration” sample. Figures 4 and 5 show the distribution of distances and spectroscopic metallicities, respectively, for these stars. Distances derived from the Hipparcos Catalogue (ESA 1997), together with a table of bolometric corrections from Allen’s Astrophysical Quantities (Cox 2000), were used to convert the RASS fluxes in the 0.1–2.4 keV energy range into X-ray luminosities and to calculate log \( (L_x/L_{bol}) \).

According to Hünsch et al. (1998), the RASS has a typical flux limit of \( 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\). This can readily be seen in Figure 6, which shows a plot of the X-ray luminosities of the RASS-BSC calibration stars versus distance. Very few of these stars are more than 60 pc distant, and the majority are within 25 pc of the Sun. We note for comparison with Figure 6 that a solar-like dwarf with \( M_V = 4.7 \) at a distance of 20 pc will have an apparent magnitude of \( V = 6.2 \), which is at the limit of the BSC. A star at this distance would require an X-ray luminosity of \( L_x > 5 \times 10^{27} \) ergs s\(^{-1}\) to be detected in the RASS. Since the goal of this paper is to investigate whether the Strömgren metallicity calibration is compromised among stars with high log \( (L_x/L_{bol}) \), the RASS flux limit may not adversely bias our analysis; the most active of our calibration stars are above the RASS flux limit all the way out to 100 pc. In § 4 we test for possible bias by showing that the photometric trends for the RASS-BSC calibration stars within 25 pc are the same as for the full sample. However, we refrain from using the calibration data to form conclusions about any possible dependency of X-ray activity on stellar metallicity: the RASS flux limit biases against the presence of low-metallicity stars in our sample, because of their relatively low space density in the solar neighborhood compared to near-solar abundance stars. Indeed, nearly all of the RASS-BSC stars found in our Strömgren-[Fe/H] calibration sample have metallicities of [Fe/H] \( \leq -0.5 \).

4. DISCUSSION

To investigate the question of whether chromospheric activity affects the metallicity derived from Strömgren photometry, we looked for trends involving \([\text{Fe/H}]_{\text{phot}} - [\text{Fe/H}]_{\text{spec}}\) among the RASS-BSC calibration stars. Figure 7 shows the difference between \([\text{Fe/H}]_{\text{phot}} - [\text{Fe/H}]_{\text{spec}}\) as a function of \( \log (L_x/L_{bol}) \) for the full set of RASS-BSC calibration stars out to 100 pc, and a best-fit line obtained by a regression of \([\text{Fe/H}]_{\text{phot}} - [\text{Fe/H}]_{\text{spec}}\) versus \( \log (L_x/L_{bol}) \). The slope of the best-fit line is 0.0121 ± 0.0144, which is fairly consistent with there being no trend. The linear Pearson correlation coefficient calculated for the data is 0.0696. Figure 8 shows the same quantities for those RASS-BSC calibration stars within 25 pc, and the slope of that best-fit line is 0.0210 ± 0.0179. The correlation coefficient for these data is 0.1287. Both correlation coefficients are quite small; there appears to be no significant evidence that metallicities derived from equation (1) are compromised by stellar activity among normal solar neighborhood dwarf stars.

We have conducted a similar analysis using the same set of
stars, but with the photometric metallicity calibration of Schuster & Nissen (1989) rather than equation (1). The results are shown in Figures 9 and 10, again for stars within 100 and 25 pc of the Sun, respectively. Once again, there is no evidence that the photometric metallicities depart from the spectroscopic values in any way correlated with stellar activity. The correlation coefficient is 0.0915 for the 100 pc set and 0.1775 for the 25 pc set.

The lack of trends in Figures 7–10 is not surprising; the Hünsch et al. (1998) stars in our calibration set have little overlap with the Rocha-Pinto & Maciel (1998) “very active” stars, among which the authors find that stellar activity may affect the Strömgren colors. Those “very active” stars have \( \log R'_{\text{HK}} > -4.3 \) and tend to be either very young or in close or interacting binary systems. We find that the lower limit on X-ray luminosity for their “very active” category of stars is \( \log (L_\gamma/L_{\text{bol}}) \approx -4.1 \). There are only five stars (out of 146) with such high X-ray luminosity in our RASS-BSC calibration set, none of which are within 25 pc of the Sun. Hence, the sample of RASS-BSC stars that we have been using, as selected from the compilation of Hünsch et al. (1998), avoids the uppermost end of the stellar X-ray luminosity function.

In summary, we find no evidence for a trend in \( [\text{Fe/H}]_{\text{spec}} - [\text{Fe/H}]_{\text{phot}} \) with \( \log (L_\gamma/L_{\text{bol}}) \), regardless of whether \( [\text{Fe/H}]_{\text{phot}} \) is based on equation (1) or the previous widely used calibration of Schuster & Nissen (1989). We conclude that for most normal single stars, there is no need to apply a correction for chromospheric activity to metallicity calibrations based on Strömgren photometry.
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