AGES OF A–TYPE VEGA–LIKE STARS FROM UVBYβ PHOTOMETRY

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ABSTRACT

We have estimated the ages of a sample of A–type Vega–like stars by using Strömgren uvbyβ photometric data and theoretical evolutionary tracks. We find that 13 percent of these A stars have been reported as Vega–like stars in the literature and that the ages of this subset run the gamut from very young (50 Myr) to old (1 Gyr), with no obvious age difference compared to those of field A stars. We clearly show that the fractional IR luminosity decreases with the ages of Vega–like stars.

Subject headings: planetary systems — circumstellar matter — infrared: stars — stars: early–type

1. INTRODUCTION

There are several unusual sub–groups among the A–type stars, such as the metallic–line stars (Am), the peculiar A stars (Ap), λ Bootis type stars, and shell stars (Abt & Morrell 1995). Another class of stars with many members amongst the A dwarfs is that of the Vega–like stars. Vega–like stars show excess IR emission attributable to an optically thin dust disk around them. These disks are believed to have very little or no gas (Lagrange et al. 2000). It is very important to know the ages and, hence, the evolutionary stages of these stars, since they are believed to be signposts of exo–planetary systems or of on–going planet formation. However, determining the ages of individual A–type stars is a very difficult task. Some indirect age dating methods for A–type stars include the use of late–type companions if any exist (HR 4796A and Fomalhaut; see Stauffer et al. 1995; Barrado y Navascués et al. 1997; Song 2000) or using stellar kinematic groups (Fomalhaut, Vega and β Pictoris; see Barrado y Navascués 1998 and Barrado y Navascués et al. 1999). The use of Strömgren uvbyβ photometry (Asiain et al. 1997), however, provides a more direct and general determination of the ages of A–type stars.

The photometric uvbyβ system as defined by Strömgren (1963) and Crawford & Mander (1966) allows for reasonably accurate determination of stellar parameters like effective temperature Teff, surface gravity g, and metallicity for B, A, and F stars (Crawford 1979; Napiwotzki et al. 1993, and references therein). The Teff and g values can then be used to estimate directly the ages of stars when they are coupled with theoretical evolutionary tracks (though for individual stars these estimates have relatively large error bars).

In this letter, we describe our application of this technique to a volume limited sample of 200 A stars.

2. METHOD

2.1. T eff and log g determination

Extensive catalogues of uvbyβ data have been published by Hauck & Mermilliod (1980), Olsen (1983), and Olsen & Perry (1984). We have used these catalogues and WEBDA1 databases to find uvbyβ photometry data for our sample of A–type stars.

Numerous calibration methods of effective temperature and surface gravity using uvbyβ photometry have been published (Napiwotzki et al. 1993; Smalley & Dworetsky 1995, and references therein). Moon & Dworetsky (1985), in particular, demonstrate that their calibration yields Teff and log g to a 1 σ accuracy of 260 K and 0.10 dex, respectively. However, as pointed out by Napiwotzki et al. (1993), log g from Moon & Dworetsky’s calibration depends on the Teff value while the most desirable calibration method should not. Therefore, we used the Moon & Dworetsky (1985) grids with Napiwotzki et al.’s gravity modification to eliminate the log g dependence on Teff for early–type stars. The subsequent temperature calibration is in agreement with the integrated–flux temperatures (Teff = (πF/σ)1/4) from Code et al. (1976), Beeckmans (1977), and Malagnini et al. (1986) at the 1% level and the accuracy of log g ranges from ≈ 0.10 dex for early A stars to ≈ 0.25 dex for hot B stars (Napiwotzki et al. 1993).

A rapidly rotating star has a surface gravity smaller at the equator than at the poles and both the local effective temperature and surface brightness are therefore lower at the equator than at the poles. Thus, in comparing a rotating star with a non–rotating star of the same mass, the former is always cooler. But the apparent luminosity change of a rotating star depends on the inclination angle (i) such that a pole–on (i = 0°) star is brighter and an edge–on (i = 90°) star is dimmer than a non–rotating star (Kraft 1970). In all cases, the combination of the luminosity and temperature changes result in an older inferred age.

1 Web version of BDA (Open clusters database, Mermilliod 1995) http://obswww.unige.ch/webda
compared to the non–rotating case. This effect is prominent in spectral types B and A in which most stars are rapidly rotating ($v \sin i \geq 100$ km/sec). Recently, Figueras & Blasi (1998) simulated the effect of stellar rotation on the Strömgren uvby$\beta$ photometric indices. They concluded that the effect of stellar rotation is to enhance the stellar main sequence age by an average of 40%. Therefore, we included the stellar rotation correction suggested by Figueras & Blasi (1998). However, their rotation correction schemes are available only for stars with spectral type between approximately B7–A4. We extended the range of rotation correction such that for stars earlier than B7, we used the correction scheme for B7 stars and for stars later than A4, we used the correction scheme for A4 stars. Therefore, stars earlier or later than the Figueras & Blasi’s (1998) range will have more uncertain ages.

Large uncertainties in estimated ages are mainly due to the large error in log $g$. However, using a rotation correction scheme based on the projected stellar rotational velocities ($v \sin i$) rather than a scheme based on the true stellar rotational velocities ($v$) may have resulted in uncertainties also. The stellar rotation decreases the effective temperature depending on the inclination angle (small change of $T_{\text{eff}}$ for $i \approx 0^\circ$ but large change of $T_{\text{eff}}$ for $i \approx 90^\circ$) but the current rotation correction scheme cannot distinguish between the case of large $v$ with small $i$ and the case of small $v$ with large $i$. Thus, rotation correction using $v \sin i$ instead of $v$ may cause uncertainty in stellar ages.

2.2. Ages of Open Clusters

The theoretical evolutionary grids of Schaller et al. (1992) were used to estimate ages of stars from $T_{\text{eff}}$ and log $g$. To verify that our age dating method is working, we applied the method to a few open clusters with ages determined by other methods – 7 Perseus (80 Myr), Pleiades (125 Myr), NGC 6475 (220 Myr), M34 (225 Myr), and Hyades (660 Myr). The ages for the first two clusters are based on recent application of the lithium depletion boundary method (LDBM) (Basri & Martín 1999 and Stauffer et al. 1999 for 7 Perseus; Stauffer et al. 1998 for Pleiades). The ages for the other clusters are from upper main sequence isochrone fitting (UMSIF), and are taken from Jones & Prosser (1996) or Lynagh (1987). The age scales based on the two different methods (LDBM and UMSIF) are not yet consistent with each other, and both have possible systematic errors. The current best UMS isochrone ages for 7 Perseus and the Pleiades are in the range 50–80 Myr and 80–150 Myr.

In Figure 1, one can see that the isochrones of these open clusters are fairly well reproduced. However, there are some deviations from the expected values. Stars that are younger than or close to 100 Myr, like stars in 7 Perseus, tend to locate below the theoretical 100 Myr isochrone. So we assigned an age of 50 Myr for the stars below the 100 Myr isochrone. At intermediate ages, the open cluster data provide a mixed message – the M34 Strömgren age appears to be younger than the UMSIF age, whereas the NGC 6475 Strömgren age seems older than the UMSIF age. This could be indicative of the inhomogeneous nature of the ages (some from LDBM, some from relatively old UMS models, some from newer models) to which we are comparing the Strömgren ages.

If we could use $v$ data instead of $v \sin i$ and if one could make a rotation correction scheme by using $v$ values, then the new correction scheme would tighten more stars for a given cluster to the locus of the cluster compared to the uncorrected case. However, the $v \sin i$ rotation correction scheme used in this study shifts the loci of clusters and only moderately reduces the standard deviations of ages (see, e.g., the case for the Pleiades in Figure 2).

3. FIELD A STARS AND VEGA–LIKE STARS

We have identified 200 A dwarfs within 50 pc with known $v \sin i$ values and measured uvby$\beta$ photometric indices. The distance limit of 50 pc was chosen so that the photospheres of most A–type stars within the given volume should be detected in the 12 $\mu$m IRAS band and that the volume should contain enough A–type stars to draw a statistically significant result. Since rotation greatly affects the estimated stellar ages, we only included stars with known $v \sin i$ values (from SIMBAD) throughout this study. $T_{\text{eff}}$ and log $g$ values were calculated and corrected to account for the rotation effects as described in the previous section. Among these A–stars, 26 have been identified as possible Vega–like stars by cross–indexing the current list with Song’s (2000) master list of “proposed” Vega–like stars. Estimated ages, along with other data — spectral type, fractional IR luminosity $f$, uvby$\beta$ photometric data, and $v \sin i$ — are summarized in Table 1. The frequency of Vega–like stars in our sample is 13% in good agreement with the results from other volume limited surveys: 14±5% from Plets & Vynckier’s (1999) survey of the incidence of the Vega phenomenon among main sequence and post main sequence stars and about 15% or more from the review article on the Vega phenomenon by Lagrange et al. (2000).

More than 95% of our sample stars are listed in the IRAS Point Source Catalog and/or Faint Source Catalog and were detected at least at 12 $\mu$m, and about 75% of them were detected at 12 and 25 $\mu$m. Based on the 12 and 25 $\mu$m IRAS fluxes, we checked whether there could be more IR excess stars besides the 26 already reported in the literature. Photospheric IR fluxes at the IRAS bands were calculated by using

$$F_\nu = 6.347 \times 10^2 \frac{\pi^2 R^2}{\lambda^3} \exp \left( \frac{2\pi R}{\lambda m} \right) - 1\ [Jy] \quad (1)$$

where $\pi$ is parallax in arcseconds, $R$ is stellar radius in solar radii, $\lambda$ is wavelength in $\mu$m, and $T$ is stellar effective temperature in Kelvin (Song 2000). In Equation 1, $R$ and $T$ values were calculated from the $M_v$ versus $R$ or $T$ relations (Cox 2000) where $M_v$ values were determined from apparent visual magnitude (from SIMBAD) and Hipparcos distance data. Uncertainties of IR fluxes ($\Delta F_\nu$) were calculated from

$$\Delta F_\nu = F_\nu \left( \frac{\pi_0}{\pi}, \frac{R_0}{R}, T_0 \right) \left[ \frac{2\pi \Delta \pi}{\pi} + \frac{2\Delta R}{R} \right] \ [Jy] \quad (2)$$

where flux uncertainty due to $\Delta T$ is negligible (less than 0.02% for a given 1% error in $T$ at 10,000K). Average flux uncertainties due to $\pi$ and $R$ uncertainties are 3% and 4%, respectively. If we define the significance of IR excess ($r_\nu$) as excess IR flux normalized by the uncertainty,
then it can be calculated by \( r_v = (F_{IRAS} - F_v)/\Delta F \) where \( \Delta F \) is the total flux uncertainty due to \( \Delta F_v \) and \( \Delta F_{IRAS} \) (\( F_{IRAS} \) and \( \Delta F_{IRAS} \) stand for flux value and flux uncertainty value from the IRAS catalog, respectively). \( \Delta F_v \) and \( \Delta F_{IRAS} \) were added in quadrature to calculate the total flux uncertainty \( \Delta F \). We define the \( \text{Vega-like stars to be those that show significant IR excesses, } r_v \geq 3.0, \) at three or more IRAS bands, with the most prominent excess at 60 \( \mu \)m. We have found that 51 additional stars show significant IR excesses \( (r_v \geq 3.0) \) at both 12 and 25 \( \mu \)m. However, only 14 of them turned out to be legitimate \( \text{Vega-like star candidates}. \) The other 37 stars are either luminosity class III stars (whose IR excesses would not arise because of a circumstellar dust disk) or stars whose excess radiation can easily be explained with a nearby companion star within the IRAS beam. The new \( \text{Vega-like candidates are summarized in Table 2 with their } r_v \text{ values at 12 and 25 } \mu \text{m. Determining the } f \text{ values for the } \text{Vega-like candidates with only 12 and 25 } \mu \text{m IR flux measurements is difficult, because, for most of the cases, stellar photospheric flux dominates compared to any excess at these wavelengths; thus a slight error in the photospheric flux calculation results in a large error in } f \text{ values. For this reason, we have not taken these stars into account in our consideration of } f \text{ versus age relation (see below).}

The photospheric flux calculated from the Plets & Vynckier’s (1999) empirical relation between the visual magnitude and the IRAS 12 \( \mu \)m magnitude is always higher than the photospheric flux values calculated by using equation 1; thus the significance of the IR excess for most of the new \( \text{Vega-like stars falls below the } 3 \sigma \text{ threshold when Plets & Vynckier’s method used. Therefore, these } 14 \text{ new candidates have to be treated with care. We considered two different sets of } \text{Vega-like stars: (1) using all proposed } \text{Vega-like stars (case A, } N=26 \text{ and (2) using only the bona-fide stars (case B, } N=20 \text{). The second column of Table 1 indicates the case(s) to which the star belongs. Our conclusion, discussed below, does not depend on the choice of case.}

We assume that all of the A stars in the sample are post-ZAMS stars. We make that assumption because of simple timescale arguments (the ratio of < 10 Myr old stars to the number of 100–300 Myr old stars should be of order < 10/200 or 5%), and because we expect pre-ZAMS A stars to be located generally in star forming regions, which would make them easy to identify. There is no obvious age difference between field A–type stars and A–type Vega–like stars within 50 pc with both groups running the gamut from very young (50 Myr) to old (1 Gyr). This result (and those in Silverstone (2000) and Song et al. (2000)) contrasts with Habiing et al.’s (1999) claim of the Vega phenomenon ending sharply at around 400 Myr.

We have checked whether a correlation exists between ages and dust properties by comparing our estimated ages of A–type Vega–like stars and their fractional IR luminosities, \( f \equiv (L_{IR}/L) \), found in Song (2000). Unfortunately, a plot of \( f \) versus age is not very informative mainly because of the large uncertainties of the estimated ages for individual stars. Therefore, we divided the \( \text{Vega-like stars into two groups, one for the stars younger than 200 Myr and the other for stars older than 200 Myr, and calculated each group’s average } f \text{–value (Table 3). Clearly, the younger A–type Vega–like stars have higher } f \text{ values compared to those of the older ones (case–independent). However, we cannot more accurately quantify this relation because the uncertainties in } T_{eff} \text{ and } \log g \text{ are large.}

4. SUMMARY AND DISCUSSION

In an attempt to determine the ages of A–type Vega–like stars, we have used a technique involving \textit{wbyb3} photometry and theoretical \( \log T_{eff} - \log g \) evolutionary tracks. In addition, we have applied corrections for the effects of rapid rotation. As a test of this procedure, we have estimated the ages of a few open clusters and find that our values are in good agreement with their standard ages. We then applied this age dating method to the 200 A–type stars within 50 pc with known \( v \sin i \) values. Thirteen percent of these A stars have been reported as \( \text{Vega-like stars in the literature and their ages run the gamut of very young} \) (50 Myr) to old (1 Gyr) with no obvious age difference compared to the field A–stars. The younger Vega–like stars have higher \( f \) values compared to those of the older ones.

\( \text{Vega-like stars are closely related to the } \lambda \text{ Boo stars. These are metal–deficient A–stars with IR excesses. Vega itself is discussed as a possible member of the } \lambda \text{ Boo class (Holweger & Rentzsch-Holm 1995). An age determination of } \lambda \text{ Boo stars was presented by Iliev & Barzova (1995) based on the assumption that } \lambda \text{ Boo stars are main sequence stars. However, Holweger & Rentzsch-Holm (1995) argue that } \lambda \text{ Boo stars are probably pre–main sequence stars. If } \lambda \text{ Boo stars are indeed closely related to the } \text{Vega-like stars, then, based on our determination of the main sequence nature of } \text{Vega-like stars, it is likely that most of the } \lambda \text{ Boo stars are main sequence stars.}

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## Table 1

### A–stars with IR excesses

| HD number | Case Sp. | $f \equiv L_{IR}/L_*$ | $\beta$ | $\nu$ sin $i$ | Corrected age (Myr) |
|-----------|---------|-------------------------|---------|--------------|---------------------|
|           | number  | $\times 10^3$           | $b - y$ | $m_1$        | $c_1$               |
|           | name    |                         |         |              | $\log T_e$          |
|           | type    |                         |         |              | $\log g$            |
|           |         |                         |         |              | lowest | upper |
| 3003      | A       | A0V                     | 15      | 0.014        | 0.179               | 2.910 | 115  | 3.993 | 4.347 |
| 14055     | AB      | A1V                      | 0.048   | 0.005        | 0.166               | 1.048 | 2.889 | 240  | 4.028 | 4.188 |
| 38678     | AB      | A2Vann                   | 0.17    | 0.054        | 0.188               | 0.996 | 2.877 | 230  | 3.990 | 4.189 |
| 39014     | AB      | A7V                      | 0.11    | 0.126        | 0.182               | 0.961 | 2.790 | 225  | 3.937 | 3.797 |
| 39060     | AB      | A3V                      | 3       | 0.094        | 0.196               | 0.891 | 2.859 | 140  | 3.955 | 4.352 |
| 40932     | AB      | Am                       | 0.23    | 0.093        | 0.200               | 0.981 | 2.853 | 20   | 3.919 | 3.966 |
| 50241     | AB      | A7IV                     | 1.1     | 0.126        | 0.175               | 0.998 | 2.788 | 230  | 3.938 | 3.866 |
| 71155     | AB      | A0V                      | 0.062   | -0.007       | 0.158               | 1.026 | 2.896 | 130  | 4.013 | 4.205 |
| 74956     | AB      | A1V                      | 0.22    | 0.034        | 0.151               | 1.087 | 2.876 | 85   | 3.979 | 3.857 |
| 78045     | AB      | Am                       | 0.03    | 0.077        | 0.188               | 0.960 | 2.871 | 40   | 3.928 | 4.184 |
| 91312     | AB      | A7IV                     | 0.093   | 0.121        | 0.208               | 0.850 | 2.821 | 135  | 3.922 | 4.191 |
| 95418     | AB      | A1V                      | 0.0062  | -0.006       | 0.158               | 1.088 | 2.880 | 40   | 3.991 | 3.883 |
| 99211     | AB      | A0V                      | 0.012   | 0.117        | 0.194               | 0.894 | 2.822 | 145  | 3.925 | 4.069 |
| 102647    | A       | A3V                      | 0.012   | 0.043        | 0.211               | 0.973 | 2.899 | 120  | 3.958 | 4.299 |
| 125162    | AB      | A0sh                     | 0.042   | 0.051        | 0.183               | 0.999 | 2.894 | 100  | 3.966 | 4.188 |
| 135379    | A       | A3V                      | 0.24    | 0.043        | 0.200               | 1.011 | 2.914 | 60   | 3.949 | 4.281 |
| 139006    | AB      | A0V                      | 0.023   | -0.001       | 0.146               | 1.058 | 2.871 | 135  | 4.008 | 3.952 |
| 159492    | A       | A7V                      | 0.094   | 0.102        | 0.204               | 0.883 | 2.858 | 80   | 3.927 | 4.322 |
| 161868    | AB      | A0V                      | 0.068   | 0.015        | 0.173               | 1.051 | 2.898 | 220  | 4.011 | 4.199 |
| 172167    | AB      | A0V                      | 0.013   | 0.003        | 0.157               | 1.088 | 2.903 | 15   | 3.987 | 4.031 |
| 172555    | AB      | A7V                      | 0.9     | 0.112        | 0.200               | 0.839 | 2.839 | 175  | 3.942 | 4.376 |
| 178253    | A       | A0/A1V                   | 0.064   | 0.018        | 0.184               | 1.060 | 2.889 | 225  | 4.008 | 4.112 |
| 181296    | AB      | A0Vn                     | 0.14    | 0.000        | 0.157               | 1.002 | 2.916 | 420  | 4.133 | 4.898 |
| 192425    | A       | A2V                      | 0.067   | 0.028        | 0.188               | 1.024 | 2.920 | 160  | 3.987 | 4.354 |
| 210956    | AB      | A3V                      | 0.046   | 0.037        | 0.206               | 0.990 | 2.906 | 100  | 3.957 | 4.291 |
| 218396    | AB      | A5V                      | 0.22    | 0.178        | 0.146               | 0.678 | 2.739 | 55   | 3.868 | 4.166 |

## Table 2

### New A–type Vega–like candidates

| HD number | other name | Sp. type | $r_\nu$ | Remark |
|-----------|------------|----------|---------|--------|
| 2262      | κ Phe      | A7V      | 3.8     | 3.3    |
| 6961      | 33 Cas     | A7V      | 3.7     | 3.6    |
| 18978     | 11 Eri     | A4V      | 3.9     | 3.5    |
| 20320     | 13 Eri     | A5m      | 4.1     | 3.1    | SB    |
| 78209     | 15 UMa     | A1m      | 5.0     | 3.7    |
| 87696     | 21 LMi     | A7V      | 3.4     | 3.3    |
| 103287    | γ UMa      | A0V      | 4.8     | 4.2    | SB    |
| 112185    | ε UMa      | A0p      | 7.5     | 6.4    | SB    |
| 123998    | η Aps      | A2m      | 5.0     | 4.0    |
| 137898    | 10 Ser     | A8IV     | 4.0     | 4.0*   |
| 141003    | β Ser      | A2IV     | 5.0     | 4.0    | Double |
| 192696    | 33 Cyg     | A3IV–Vn  | 5.7     | 4.7    | SB    |
| 203280    | α Cep      | A7IV     | 10.2    | 5.5    |
| 214846    | β Oct      | A9IV–V   | 7.1     | 5.8    |

*100 µm excess, 25 µm excess $r_\nu = 1.9$

## Table 3

### Ages and f values of Vega–like stars

| Case range of stars | Average f ($\times 10^3$) |
|---------------------|---------------------------|
| A < 200 Myr         | 12, 1.79                  |
| > 200 Myr           | 14, 0.18                  |
| B < 200 Myr         | 7, 0.71                   |
| > 200 Myr           | 13, 0.17                  |
Fig. 1.— Strömgren $uvby\beta$ photometric age determination of a few open clusters.
Fig. 2.— Effect of stellar rotation correction applied to Pleiades stars.
Fig. 3.— Field A stars without excess and A-type Vega-like stars within 50 pc. Large solid circles denote stars for case B only, small solid circles and large solid circles form the set for case A. HD 181296 was not plotted because of its unusually high log $g$ value.