THE ASTROPHYSICAL JOURNAL, 546:352–357, 2001 January 1

AGES OF A-TYPE VEGA-LIKE STARS FROM *uvbyβ* PHOTOMETRY

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Received 2000 August 17; accepted 2000 August 21

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% 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: circumstellar matter — infrared: stars — planetary systems — stars: early-type

1. INTRODUCTION

There are several unusual subgroups 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, Backman, & Artymowicz 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 exoplanetary systems or of ongoing 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, Hartmann, & Barrado y Navascués 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, Torra, & Figueras 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 $T_{\rm eff}$, surface gravity g, and metallicity for B, A, and F stars (Crawford 1979; Napiwotzki, Schönberner, & Wenske 1993, and references therein). The $T_{\rm eff}$ 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 paper, we describe our application of this technique to a volume-limited sample of 200 A stars.

2. METHOD

2.1. $T_{\rm eff}$ *and* log *g Determination*

Extensive catalogs of *uvbyβ* data have been published by Hauck & Mermilliod (1980), Olsen (1983), and Olsen & Perry (1984). We have used these catalogs and WEBDA[1] 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 $T_{\rm eff}$ 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 $T_{\rm eff}$ 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 $T_{\rm eff}$ for early-type stars. The subsequent temperature calibration is in agreement with the integrated-flux temperatures $[T_{\rm eff} = (\pi F/\sigma)^{1/4}]$ from Code et al. (1976), Beeckmans (1977), and Malagnini et al. (1986) at the 1% level and the accuracy of log g ranges from $\approx$0.10 dex for early A stars to $\approx$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 nonrotating 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 nonrotating star (Kraft 1970). In all cases, the combination of the luminosity and temperature changes result in an older inferred age compared to the nonrotating case. This effect is prominent in spectral types B and A, in which most stars are rapidly rotating ($v \sin i \geq 100$ km s^{-1}). Recently, Figueras & Blasi (1998) simulated the effect of stellar rotation on the Strömgren *uvbyβ* photometric indices. They concluded that the effect of stellar rotation is to enhance the stellar main-sequence age by an average of

[1] Web version of BDA (open clusters database, Mermilliod 1995); http://obswww.unige.ch/webda.

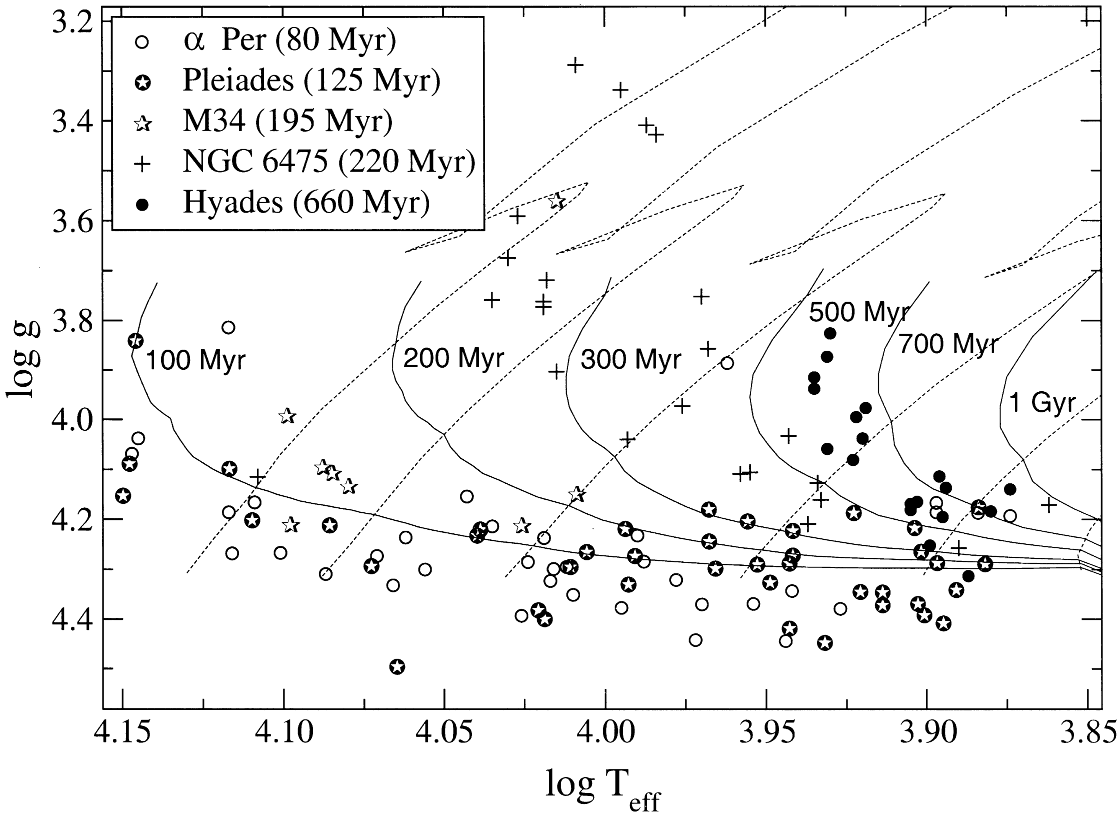

FIG. 1.—Strömgren *uvbyβ* photometric age determination of a few open clusters

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 and 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

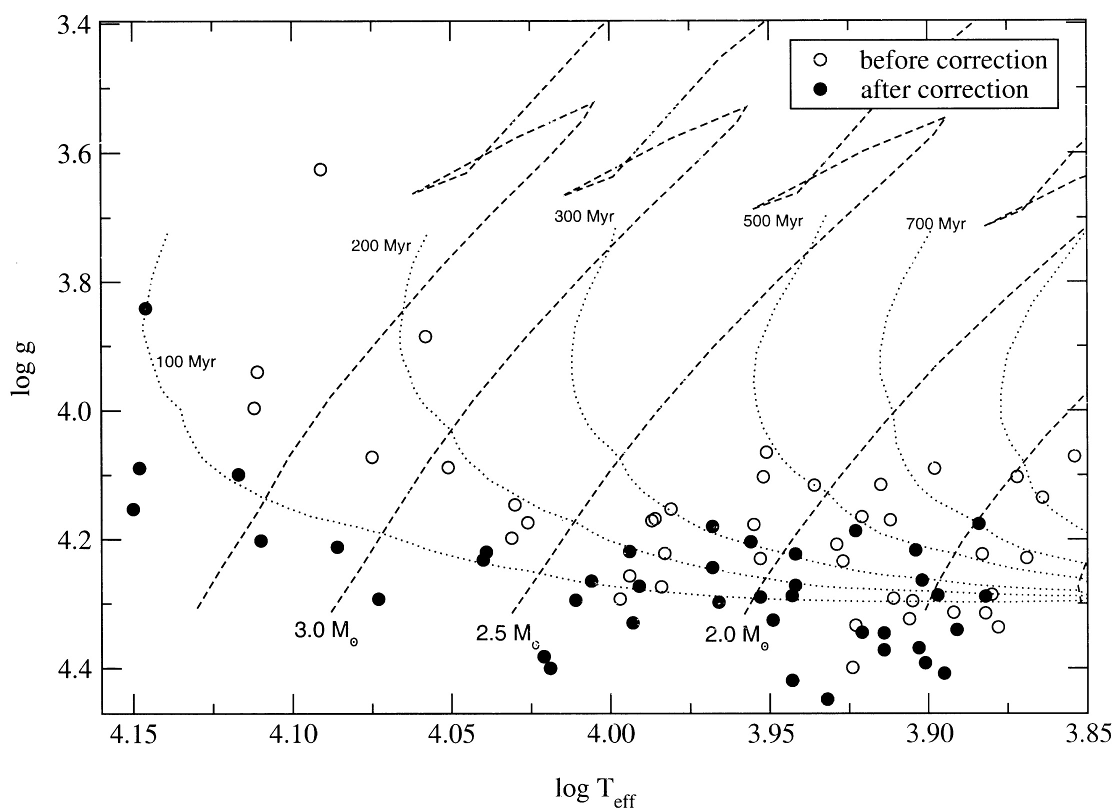

FIG. 2.—Effect of stellar rotation correction applied to Pleiades stars

Figueras & Blasi (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 $T_{\rm eff}$ for $i \approx 0°$ but large change of $T_{\rm eff}$ for $i \approx 90°$), 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 $T_{\rm eff}$ 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—α 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 α Perseus; Stauffer, Schultz, & Kirkpatrick 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 Lyngå (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 α 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 α 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 Fig. 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 (see Fig. 3). 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 μm *IRAS* band and that the volume should contain enough A-type stars to draw a

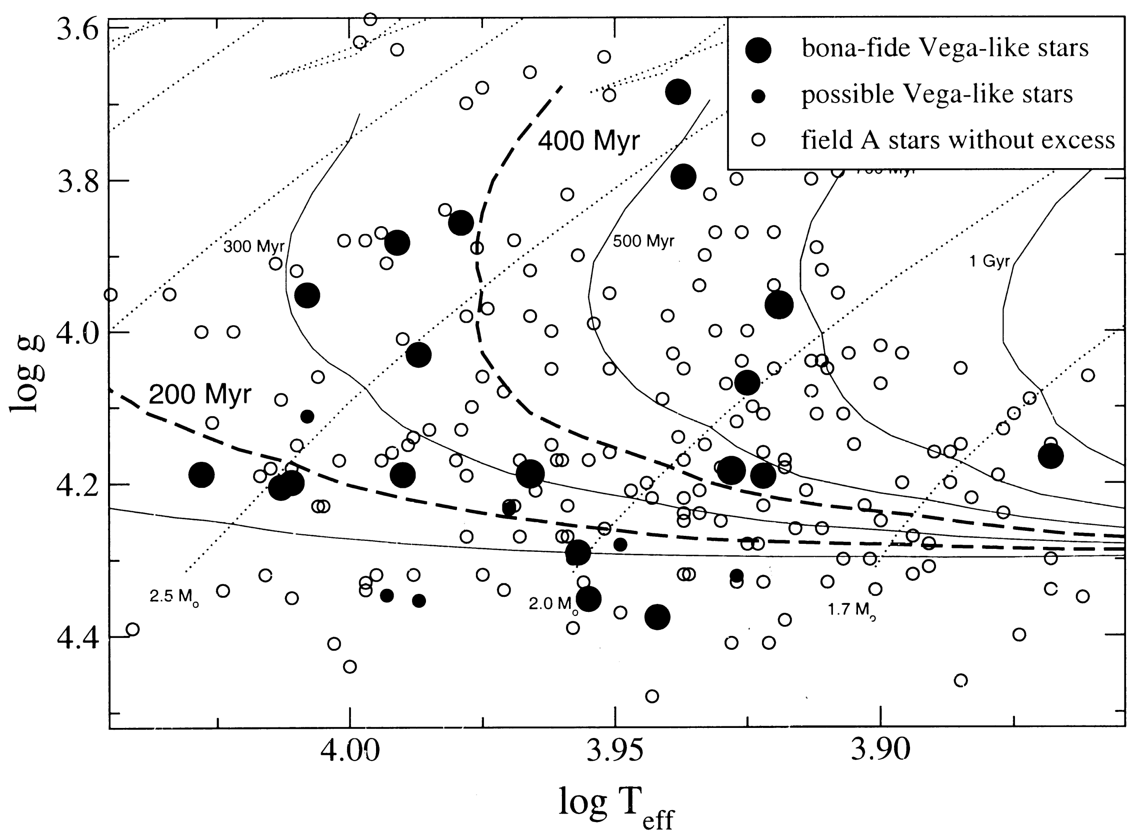

FIG. 3.—Field A stars without excess and A-type Vega-like stars within 50 pc. Large solid circles denote stars for case B only; small solid circles and large solid circles form the set for case A. HD 181296 was not plotted because of its unusually high log g value.

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. $T_{\rm eff}$ 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 μm, and about 75% of them were detected at 12 and 25 μm. Based on the 12 and 25 μm *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

$$F_\nu = 6.347 \times 10^4 \frac{\pi^2 R^2}{\lambda^3} \frac{1}{\exp(14{,}388/\lambda T) - 1} \text{ [Jy]} , \quad (1)$$

where π is parallax in arcseconds, R is stellar radius in solar radii, λ is wavelength in μm, and T is stellar effective tem perature in kelvins (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 (ΔF_ν) were calculated from

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

where flux uncertainty due to ΔT is negligible (less than 0.02% for a given 1% error in T at 10,000 K). Average flux uncertainties due to π and R uncertainties are 3% and 4%, respectively. If we define the significance of IR excess (r_ν) as excess IR flux normalized by the uncertainty, then it can be calculated by $r_\nu = (F_{\rm IRAS} - F_\nu)/\Delta F$, where ΔF is the total flux uncertainty due to ΔF_ν and $\Delta F_{\rm IRAS}$ ($F_{\rm IRAS}$ and $\Delta F_{\rm IRAS}$ stand for flux value and flux uncertainty value from the *IRAS* catalog, respectively). ΔF_ν and $\Delta F_{\rm IRAS}$ were added in quadrature to calculate the total flux uncertainty (ΔF). We define the bona fide Vega-like stars to be those that show significant IR excesses, $r_\nu \geq 3.0$, at three or more *IRAS* bands, with the most prominent excess at 60 μm. We have found that 51 additional stars show significant IR excesses ($r_\nu \geq 3.0$) at both 12 and 25 μm. However, only 14 of them turned out to be legitimate 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 Vega-like candidates are summarized in Table 2 with their r_ν-values at 12 and 25 μm. Determining the f-values for the Vega-like candidates with only 12 and 25 μm IR flux

TABLE 1

A-Stars with IR Excesses

				$uvby\beta$ Photometric Data					Corrected		Age (Myr)		
HD Number	Case	Spectral Type	$f \equiv L_{\rm IR}/L_* \times 10^3$	$b-y$	m_1	c_1	β	$v \sin i$ (km s^{-1})	log T_e	log g	Lower	Best	Upper
3003	A	A0 V	15	0.014	0.179	0.991	2.910	115	3.993	4.347	...	50	247
14055	AB	A1 Vnn	0.048	0.005	0.166	1.048	2.889	240	4.028	4.188	50	163	245
38678	AB	A2 Vann	0.17	0.054	0.188	0.996	2.877	230	3.990	4.189	50	231	347
39014	AB	A7 V	0.11	0.126	0.182	0.961	2.790	225	3.937	3.797	522	541	663
39060	AB	A3 V	3	0.094	0.196	0.891	2.859	140	3.955	4.352	...	50	299
40932	AB	Am	0.23	0.093	0.200	0.981	2.853	20	3.919	3.966	565	693	693
50241	AB	A7 IV	1.1	0.126	0.175	0.998	2.788	230	3.938	3.686	501	664	890
71155	AB	A0 V	0.062	−0.007	0.158	1.026	2.896	130	4.013	4.205	50	169	266
74956	AB	A1 V	0.22	0.034	0.151	1.087	2.876	85	3.979	3.857	372	390	403
78045	AB	Am	0.03	0.077	0.188	0.960	2.871	40	3.928	4.184	50	427	610
91312	AB	A7 IV	0.093	0.121	0.208	0.850	2.821	135	3.922	4.191	50	414	647
95418	AB	A1 V	0.0062	−0.006	0.158	1.088	2.880	40	3.991	3.883	335	358	369
99211	AB	A0 V	0.012	0.117	0.194	0.894	2.822	145	3.925	4.069	392	600	684
102647	A	A3 V	0.012	0.043	0.211	0.973	2.899	120	3.958	4.299	...	50	331
125162	AB	A0sh	0.042	0.051	0.183	0.999	2.894	100	3.966	4.188	50	313	451
135379	A	A3 V	0.24	0.043	0.200	1.011	2.914	60	3.949	4.281	50	166	378
139006	AB	A0 V	0.023	−0.001	0.146	1.058	2.871	135	4.008	3.952	267	314	322
159492	A	A7 V	0.094	0.102	0.204	0.883	2.858	80	3.927	4.322	...	50	419
161868	AB	A0 V	0.068	0.015	0.173	1.051	2.898	220	4.011	4.199	50	184	277
172167	AB	A0 V	0.013	0.003	0.157	1.088	2.903	15	3.987	4.031	267	354	383
172555	AB	A7 V	0.9	0.112	0.200	0.839	2.839	175	3.942	4.376	...	...	50
178253	A	A0/A1 V	0.064	0.018	0.184	1.060	2.889	225	4.008	4.112	164	254	316
181296	AB	A0 Vn	0.14	0.000	0.157	1.002	2.916	420	4.133	4.898	...	...	50
192425	A	A2 V	0.067	0.028	0.188	1.024	2.920	160	3.987	4.354	...	50	166
216956	AB	A3 V	0.046	0.037	0.206	0.990	2.906	100	3.957	4.291	50	156	344
218396	AB	A5 V	0.22	0.178	0.146	0.678	2.739	55	3.868	4.166	50	732	1128

TABLE 2

NEW A-TYPE VEGA-LIKE CANDIDATES

HD NUMBER	OTHER NAME	SPECTRAL TYPE	r_v 12 μm	r_v 25 μm	REMARK
2262	κ Phe	A7 V	3.8	3.3	
6961	33 Cas	A7 V	3.7	3.6	
18978	11 Eri	A4 V	3.9	3.5	
20320	13 Eri	A5m	4.1	3.1	SB
78209	15 UMa	A1m	5.0	3.7	
87696	21 LMi	A7 V	3.4	3.3	
103287	γ UMa	A0 V	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	A8 IV	4.0	4.0*	
141003	β Ser	A2 IV	5.0	4.0	Double
192696	33 Cyg	A3 IV–Vn	5.7	4.7	SB
203280	α Cep	A7 IV	10.2	5.5	
214846	β Oct	A9 IV–V	7.1	5.8	

NOTE.—SB: spectroscopic binary. Asterisk (*) indicates 100 μm excess, $r(v) = 1.9$ for 25 μm excess.

measurements is difficult because, for most of the cases, stellar photospheric flux dominates in comparison to any excess at these wavelengths; thus a slight error in the photospheric flux calculation results in a large error in f-values. For this reason, we have not taken these stars into account in our consideration of f versus age relation (see below).

The photospheric flux calculated from the Plets & Vynckier (1999) empirical relation between the visual magnitude and the *IRAS* 12 μm 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 Vega-like stars falls below the 3 σ threshold when Plets & Vynckier 's method is used. Therefore, these 14 new candidates have to be treated with care. We considered two different sets of Vega-like stars: (1) using all proposed Vega-like stars (case A, $N = 26$) and (2) using only the bona fide stars (case B, $N = 20$). 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–zero-age main-sequence (ZAMS) stars. We make that assumption because of simple timescale arguments (the ratio of less than 10 Myr old stars to the number of 100–300 Myr old stars should be of order less than 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 Habing 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, $f \equiv (L_{\rm IR}/L_*)$, 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 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-value (Table 3). Clearly, the younger A-type Vega-like stars have higher f-values compared to those of the older ones (case-independent). However, we cannot more accurately quantify this relation because the uncertainties in $T_{\rm eff}$ and log g are large.

TABLE 3

AGES AND f-VALUES OF VEGA-LIKE STARS

Case	Age Range	Number 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

4. SUMMARY AND DISCUSSION

In an attempt to determine the ages of A-type Vega-like stars, we have used a technique involving $uvby\beta$ photometry and theoretical log $T_{\rm eff}$–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 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.

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

We thank the referee, Ralf Napiwotzki, for his useful suggestions and for kindly providing his FORTRAN code to extract $T_{\rm eff}$ and log g. I. S. and J. P. C. acknowledge the support of NASA through grant NAG 5-6902. D. B. N. has been partially supported by Spanish Plan Nacional del Espacio, under grant ESP 98-1339-CO2. We have used SIMBAD and Vizier databases.

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