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THE AGE OF β PICTORIS[1]

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ABSTRACT

We have reanalyzed data for the proposed moving group associated with β Pictoris in order to determine if the group (or part of it) is real and, if so, to derive an improved age estimate for β Pic. By using new, more accurate proper motions from PPM and *Hipparcos* and a few new radial velocities, we conclude that on kinematic grounds, most of the proposed members of the moving group are not, in fact, associated with β Pic. However, two M dwarfs—or three, actually, since one of them is a nearly equal mass binary—have space motions that coincide with that of β Pic to within 1 km s^{-1} with small error bars. Based on a color-magnitude diagram derived from accurate photometry and *Hipparcos* parallaxes, these two possible proper-motion companions to β Pic are very young; we derive an age of ~20 Myr by comparison with theoretical tracks from F. D'Antona & I. Mazzitelli. In fact, the proposed β Pic companions comprise two of the three youngest M dwarfs in the sample of 160 dM stars for which we have data. The chromospheric and coronal activities of these two stars also confirm that they are quite young. We argue that the probability that two of the three youngest nearby M dwarfs would accurately share the space motion of β Pic by chance is quite small, and therefore we believe that β Pic and the two M dwarfs (GL 799 and GL 803) were formed together. The estimated age for β Pic is then 20 $\pm$ 10 Myr, where the uncertainty in the age arises primarily from possible errors in the pre–main-sequence isochrones and in the conversion from color to effective temperature. This young age for β Pic supports the contention that the IR excess for the Vega-like stars is age dependent.

Subject headings: circumstellar matter — stars: individual (β Pictoris) — stars: kinematics

1. INTRODUCTION

This Letter is the fourth paper in a series devoted to the ages of Vega-like stars. This is achieved by finding late-type stars physically associated with them. Then several time-dependent properties are analyzed, and an age is derived. Stauffer, Hartmann, & Barrado y Navascués (1995) studied the secondary component of HR 4796, a conspicuous Vega-like star discovered by Jura (1991). They concluded that the binary is remarkably young (8 $\pm$ 2 Myr). More recently, Barrado y Navascués et al. (1997) focused on Fomalhaut. The physical association with the late-type star GL 879 served to constrain the age to 200 $\pm$ 100 Myr. The realization of the fact that Fomalhaut shares its Galactic movement with other stars, including Castor and Vega, produced another independent determination of the age, 200 $\pm$ 100 Myr (Barrado y Navascués 1998).

Vega-like stars show large IR excesses originating in dusty circumstellar disks, which are thought to be the remnants of the T Tauri disks or a consequence of the formation of planets (see Backman & Paresce 1993). Until the discovery of the first extrasolar planet by Mayor & Queloz (1995), they provided some of the best evidence for the presence of planetary systems outside of our own. There has been much recent progress on these systems in terms of understanding the structure of their disks (Jura et al. 1998; Jayawardhana et al. 1998; Koerner et al. 1998; Greaves et al. 1998; Schneider et al. 1999), spectral distribution (Zuckerman & Becklin 1993; Holland et al. 1998; Fajardo-Acosta, Telesco, & Knacke 1998; Schneider et al. 1999), and evolution (Zuckerman, Forvelle, & Kastner 1995; Thakur et al. 1997; Song et al. 1998). However, it is still true that accurate ages for these systems are still in considerable short supply. In this Letter, we provide what we believe to be an accurate age for β Pictoris.

2. A COMMON ORIGIN BASED ON THE KINEMATIC PROPERTIES

Following Barrado y Navascués (1998), we have selected an initial list of possible β Pic companions from Agekyan & Orlov (1984), which provides an extensive search of kinematic groups. We also included stars from Soderblom (1990), Poveda et al. (1994), and Tokovinin (1997). Then we computed the Galactic components of these stars using equatorial coordinates, parallaxes, proper motions (the *Hipparcos* [ESA 1997] and PPM [Roeser & Bastian 1994; Bastian & Roeser 1993] catalogues), and the radial velocities (RVs) (Duflot, Fignon, & Meyssonnier 1995). For β Pic itself, we used the values derived by Lagrange et al. (1995) and Jolly et al. (1998), based on *Hubble Space Telescope*/Goddard High-Resolution Spectrograph spectra of narrow absorption lines of Fe and CO (thought to be the result of stationary circumstellar gas but external to its disk). Of the initial stars selected, only six have space motions within 2 σ of that of β Pic to be plausible companions. Tables 1 and 2 provide various data for these stars and the dynamics. The *UVW* components of the Galactic velocity were computed following Johnson & Soderblom (1987), using PPM proper motions. Similar results can be computed with *Hipparcos*. We have used these data for two different purposes. First, we have tried to verify if indeed these stars are physically

[1] Based on observations collected by the *Hipparcos* satellite.

TABLE 1
PHOTOMETRY AND OTHER DATA FOR THE β PIC MOVING GROUP

Gliese Number	Spectral Type	V	M_V	$(B-V)$	$(V-I)_C$	log L_X[a] (ergs s^{-1})	EW(Hα)[b] (Å)	Other Names
219	A3 V	3.85	2.425	0.171	0.18	...	...	HD 39060, β Pic
97	G2 V	5.19	3.485	0.608	0.68	29.60	...	HD 14802, κ For
601A	F2 III	2.83	2.38	0.30	0.36	...	...	HD 141891, β TrA
781.2	K3/K4 V	9.75	7.241	1.137	1.249	...	...	HD 191285
799AB	M4.5e + M4.5e	10.27	10.97[c]	1.550[c]	2.90[c]	29.55[c]	4.10	HD 196982, AT Mic
803	M1 Ve	8.81	8.82	1.470	2.10	29.74	1.56	HD 197481, AU Mic
824	K2	7.88	6.84	1.020	1.11	27.76	−0.91	HD 202575

NOTE.—Spectral type and photometry from the *Hipparcos* and Tycho Catalogues and Bessel 1990.
[a] L_X values from Hünsch et al. 1999.
[b] From Panagi & Mathioudakis 1993.
[c] Values for each individual component.

associated. Second, using several properties of the late-type stars, we have estimated the age of the moving group.

The V component imposes the strongest constraint for determining whether or not a group of stars are associated (Soderblom & Mayor 1993). V should correspond to a drift rate that would lead to a secular increase in separation between two given stars (as opposed to U or W components, where a difference in current velocity may not matter because stars oscillate in those directions). Since 2 km s^{-1} is about 2 pc Myr^{-1}, two stars whose space motion differed by that amount would separate by 40 pc in 20 Myr (our final estimation of the age of β Pic). Therefore, they could not both have been born in the same place 20 Myr ago and now both be within 20 pc of the Sun. Given the accuracies to which we can estimate the space motions of our selected stars, we believe that GL 97 can be rejected as a possible companion to β Pic. If we use the PPM proper motions, it has too large a difference in the V component; if, instead, we adopt the *Hipparcos* proper motions, then the U velocity differs by an amount (>8 km s^{-1}) that is too large. There are other spectroscopic reasons to believe also that GL 97 is too old to be a possible companion to β Pic (Pasquini, Liu, & Pallavicini 1994). We also choose to exclude GL 601 from further consideration because we have no observational data that allow us to estimate its age usefully. In the next section, we will examine age estimates for β Pic and for the four remaining stars in order to try to establish whether any of these stars appear to be coeval.

3. THE AGE OF β PIC

3.1. *Isochrone Fitting for β Pic Itself*

Isochrone fitting for β Pic has been previously attempted, yielding an age of 100 Myr (Backman & Paresce 1993). Lanz, Heap, & Hubeny (1995), using the same procedure, concluded that an age around 12 Myr or larger than 300 Myr would be possible, although they judged the first value as the most likely. From Figure 2 of Brunini & Benvenuto (1996), which represents evolutionary tracks, an age between 20 and 40 Myr could be inferred. Finally, Crifo et al. (1997), using *Hipparcos* data, confirmed that the star is very close to or on the zero-age main sequence (ZAMS), and it is older than 8 Myr. All these studies show that this technique is not very reliable and that the age of β Pic remains uncertain.

3.2. *Isochrone Fitting for Possible Companions of β Pic*

The photometry of late-type stars can provide accurate ages, if they are cool and young enough to be in the pre–main-sequence (PMS) phase, by comparison with isochrones. We have compared the four candidate β Pic companions with PMS isochrones from F. D'Antona & I. Mazzitelli (1997, private communication [hereafter DM97]), where we have used a color-temperature conversion based on requiring the 125 Myr isochrone by DM97 to coincide with the main-sequence locus of stars in the Pleiades (cf. Stauffer et al. 1995; Stauffer 1998). In order to place our four candidate β Pic companions in con-

TABLE 2
COORDINATES AND VELOCITIES FOR THE β PIC MOVING GROUP

GL	α (1950.0)	δ (1950.0)	Parallax (mas)	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})	RV (km s^{-1})	U (km s^{-1})	V (km s^{-1})	W (km s^{-1})
219	5 46 05.93	−51 05 01.8	51.87 ± 0.51	9.4 ± 4.2	79 ± 4.3	20.0 ± 0.5[a]	−10.6 ± 0.4	−16.3 ± 0.5	−8.7 ± 0.4
						21.0 ± 1.0[b]	−10.7 ± 0.4	−17.1 ± 0.9	−9.2 ± 0.6
97	2 20 15.23	−24 2 36.2	45.60 ± 0.82	197.34 ± 0.77[c]	−4.39 ± 0.51[c]	18.6 ± 1.0[d]	−19.3 ± 0.4	−16.9 ± 0.3	−10.4 ± 0.9
				200.0 ± 0.6	−62 ± 0.8		−15.5 ± 0.4	−21.5 ± 0.3	−10.8 ± 0.9
601	15 50 42.96	−63 16 42.7	81.24 ± 0.62	−192.2 ± 0.9	−398 ± 1.0	0.4 ± 1.0[d]	−15.3 ± 0.8	−17.8 ± 0.6	−10.7 ± 0.2
781.2	20 06 47.92	−14 26 00.2	31.49 ± 1.58	81.3 ± 2.1	−85 ± 2.1	−12.3 ± 3.0[d]	−12.5 ± 2.5	−14.4 ± 1.5	−10.1 ± 1.4
799AB	20 38 43.71	−32 36 33.8	97.80 ± 4.65	274.2 ± 2.9	−351 ± 3.0	−3.5 ± 1.0[d]	−9.7 ± 0.9	−16.1 ± 0.8	−11.2 ± 0.8
803	20 42 03.79	−31 31 05.6	100.59 ± 1.35	281.3 ± 2.9	−363 ± 2.9	−4.89 ± 0.02[e]	−10.5 ± 0.1	−16.6 ± 0.3	−10.4 ± 0.2
824	21 14 05.39	09 11 09.3	61.83 ± 1.06	143.6 ± 2.2	−121 ± 2.1	−13.2 ± 1.0[d]	−8.3 ± 0.5	−16.2 ± 0.8	−7.0 ± 0.5

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] From Lagrange et al. 1995.
[b] From Jolly et al. 1998.
[c] From *Hipparcos*, all others from PPM.
[d] From Duflot et al. 1995.
[e] From X. Delfosse 1999 (private communication).

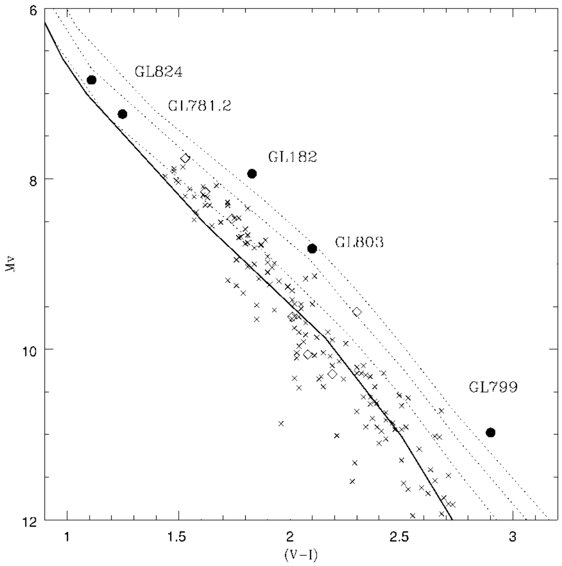

FIG. 1.—Color-magnitude diagram for the late spectral type candidates. The isochrones (20, 30, 50, and ZAMS) are those from DM97. The stars from Leggett (1992) are shown as crosses. The open diamonds represent the combined photometry of binaries.

text, we also include in Figure 1 all of the nearby M dwarfs for which Leggett (1992) has compiled accurate photometry and for which we have parallaxes from *Hipparcos* with $\sigma(\pi)/\pi < 0.10$. For binary stars where it is known that the two components are nearly equal in brightness (including GL 799), we have added 0.75 mag to the M_V in order to correct the binarity effect; for known binaries with unknown mass ratios, we plot the star as an open diamond symbol but do not correct the M_V. Clearly, GL 799 and GL 803 are among the brightest stars, compared with stars of the same color, in the solar neighborhood. That is, they are very young. In fact, the three youngest objects in Figure 1 are GL 182, GL 799, and GL 803. GL 182 is known to be a very young dMe star (Favata et al. 1998); its kinematics indicate that it is not, however, moving with the same space motion of GL 799 and 803, so we do not consider it further. Within the errors, the locations of GL 799 and 803 in Figure 1 are consistent with their having the same age (20 Myr). GL 781.2 and GL 824 appear to be older, with ages formally consistent with being 40 Myr. However, because they are higher mass objects and their displacement above the ZAMS is less, their locations in Figure 1 are actually consistent with any age up to several hundred megayears, given uncertainties in their photometry and metallicity and the placement of the isochrones into the observational plane. We provide evidence in the next section that GL 824, at least, is quite old (>600 Myr), and unlikely to be physically connected to β Pic.

3.3. *Stellar Activity*

Stellar activity, a consequence of the presence of magnetic fields in late-type stars (due to the combination of the rotation and convection or to the dynamo effect), is a well-studied phenomenon. Because of main-sequence angular momentum loss, the rotation rates of low-mass stars decline with age, and hence activity levels also decline with age (e.g., Stauffer 1988). Therefore, we can use measures of stellar activity as proxies for age in an attempt to identify which of our candidate stars might be coeval with β Pic. Figure 2 depicts the X-ray luminosity against $(B-V)$. In the left panel of Figure 2, the crosses represent *ROSAT* all-sky data (Hünsch et al. 1999) for the Gliese stars. In the right panel of Figure 2, Pleiades and Hyades stars appear as open and filled symbols, respectively. Clearly, the X-ray luminosity of GL 824 is relatively low, even compared with that of the stars in the Hyades (with an age of ~600 Myr); we infer from this that GL 824 is older than the Hyades. Based on its location in a color-magnitude diagram, β Pic cannot be as old as 600 Myr, and therefore the X-ray data provide strong evidence that GL 824 is older than β Pic. On the other hand, the activity of GL 803 and GL 799 is very high, consistent with the young ages deduced from their position in the color-magnitude (CM) diagram. Unfortunately, there is no published

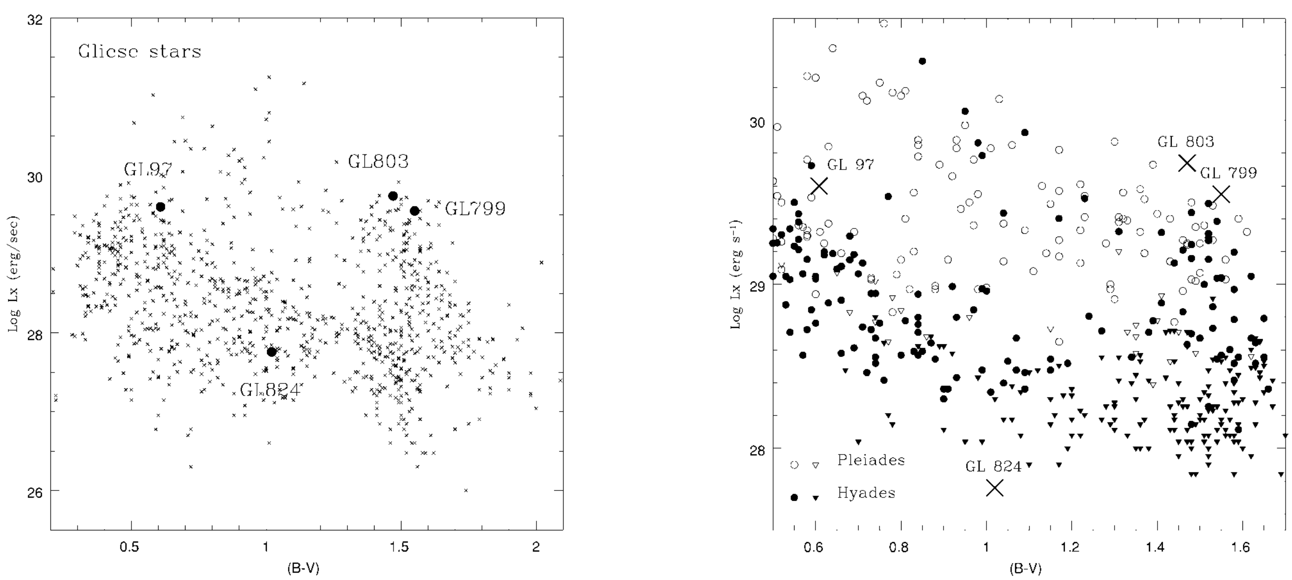

FIG. 2.—X-ray luminosities plotted vs. the $(B-V)$ color indices. *Left panel*: Gliese stars. *Right panel*: Pleiades and Hyades members. The triangles indicate upper limits.

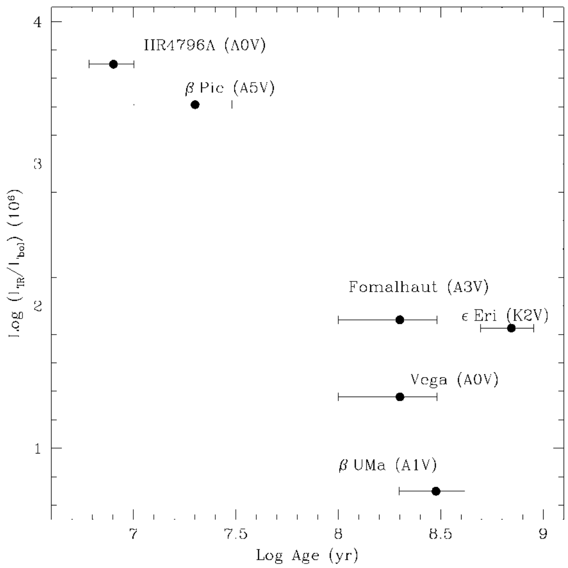

FIG. 3.—Fractional infrared luminosity vs. age

X-ray for GL781.2, and we cannot further constrain its age at this time.

3.4. *Summary of Age Constraints*

Using the best available data, analysis of the location of β Pic in a CM diagram only allows one to conclude that its age is somewhere between a few million and a few hundred million years. Of the four late-type stars whose kinematics match that of β Pic, GL 824 is removed from contention because its activity indicates it is much older than the maximum age for β Pic. GL 781.2 is essentially unconstrained in its age because of a lack of activity data and because of its early spectral type (precluding an accurate H-R diagram age). However, the other two candidates have a well-constrained age from their location in a CM diagram, have activity levels consistent with that age, and share the motion of β Pic to within 1 km s^{-1}. We believe, therefore, that the age derived for these stars from PMS isochrones (20 $\pm$ 10 Myr) is the best estimate for the age of β Pic. The spatial location of the three stars is compatible with this age and the derived relative space motions. We note that Poveda et al. (1994) has previously identified GL 799 and GL 803 as being likely siblings—we are now simply adding β Pic as their bigger brother.

4. CORRELATION OF INFRARED EXCESS AND AGE FOR β PIC STARS

In their comprehensive review of the Vega phenomenon, Backman & Paresce (1993) described specifically the evolutionary status of the three prototypes, β Pic, Vega, and Fomalhaut, estimating their ages as 100, 200, and 400 Myr, respectively. Several studies have tried to relate these ages with different properties that appear as a consequence of the presence of circumstellar disks, in order to see if there is an evolutionary sequence. For instance, Figure 2 of Holland et al. (1998) suggests a dependence with the age of the total amount of dust in the disk. Our results support this type of dependence (Fig. 3). The inferred rapid decline in dust mass supports the hypothesis that the Vega phenomenon is a normal stage in the early life of intermediate-mass and solar-like stars.

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