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The Castor moving group

The age of Fomalhaut and Vega*

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Abstract. We have recomputed the kinematic properties of several of dozens nearby stars, to try to verify if Castor (α Gem) indeed has a cohort of stars sharing the same space motion and age. We used kinematics, the location of the stars in Color-Magnitude Diagrams, their lithium abundances, and their activity, to establish that the moving group seems to be real and to reject several stars which were believed to be part of this group. Of the initial 26 stars, we show that probably only 16 stars are physically associated.

The moving group contains several A spectral type stars. Among them, Vega and Fomalhaut, two of the prototypes of the β Pic type stars. If these stars are coeval, their different levels of IR emission suggest that the time scale for the formation of planets is not universal. Due to the age of the group, these IR excesses would appear as a consequence of collisions and sublimation of larger bodies and they would not arise from protoplanetary structures.

Since this association includes several late spectral type stars, we used their properties to estimate their age and, therefore, the age of the group and that of Vega and Fomalhaut. Our estimate for that age is 200$\pm$100 Myr.

Key words: stars: individual: HD 216956 – stars: individual: HD 172167 – Galaxy: open clusters and associations: general

1. Introduction

It was realized a few years ago (Anosova & Orlov 1991) that the multiple system ADS 6175, which contains three spectroscopic binaries (Castor A, Castor B and YY Gem), could be just the most prominent members of a moving group. This moving group would include about 18 stars, having spectral types between A1 V and M6 Ve, including one of the prototypes of the β Pic stars.

The β Pic type stars show IR excesses, which are associated the the presence of circumstellar dusty disks. The prototypes for this class of stars are β Pic, Vega and Fomalhaut. As a result of their proximity and brightness, these three stars have been studied in great detail, and estimates of the mass, radial distribution and structure, dust-grain properties of their disks have been made (e.g., Backman & Paresce 1993). It is generally believed that these circumstellar dusty disks are either the direct descendents of T Tauri disks or the secondary products of the planet formation process. Knowledge of the ages of β Pic stars is therefore one of the keys to understand the formation and evolution of their disks. However, there is only a handful of estimates of the ages of these systems, and no member of this class has yet been detected with certainty in an open cluster (although see Backman, Angelova & Stauffer 1998). All three prototypes are A stars, and estimates from their post-ZAMS evolution give approximate ages of 100, 200, and 400 Myr for β Pic, Fomalhaut and Vega, respectively (Backman and Paresce 1993). Recently, Barrado y Navascués et al. (1997a) estimated an age of 200$\pm$100 Myr for Fomalhaut, based on a number of properties (X-ray emission, rotation, lithium abundance, isochrones) of its physical companion GL879. Another relevant star belonging to this class, HR4796A, has been studied in a similar way by Stauffer et al. (1995). These authors derived an age of 8$\pm$2 Myr. Lately, Holland et al. (1998) have imaged the thermal emission from the disks of the three prototypes at submillimeter wavelengths. They concluded that any Earth–like planet must have already formed. Moreover, the central holes found by Holland et al. (1998) in the orbit of Fomalhaut and by Jayawardhana et al. (1998) and Koerner et al. (1998) in the case of HR4796A, support the idea of the early formation of planets.

In this paper, we examine the proper motions of several nearby stars. Based on Hipparcos data, we show that, indeed, Castor shares its Galactic motion with other stars, including Fomalhaut and Vega and several late spectral type stars. This fact allows us to derive the age of the group.

2. The selection of the sample

A few years ago, Barrado y Navascués et al. (1997a) determined the age of one of the prototypes of the β Pic class, Fomalhaut,

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* Based on observations collected by the Hipparcos satellite

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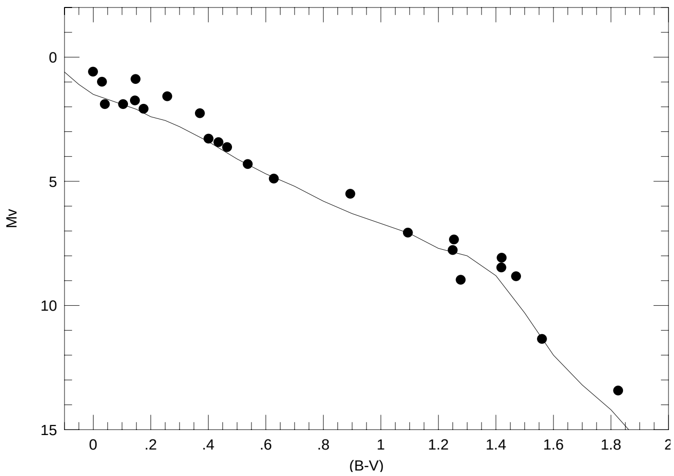


Fig. 1. Color-Magnitude Diagram for the initial sample of proposed members of the Castor moving group. The Schmidt-Kaler ZAMS is included as a solid line.

based on the properties of a physical late spectral type companion, GL879. They noted that Anosova & Orlov (1991) had suggested that both stars could be part of a moving group which would include Castor AB and YY Gem. However, uncertainties at that time were too large to derive any firm conclusion. The wealth of data obtained by Hipparcos allows a more precise determination of distances, positions, and proper motions. Using these new values, we have recomputed the Galactic velocities for the Anosova & Orlov (1991) sample, to try to verify whether there is a moving group or not.

In addition to the 18 possible members studied by Anosova & Orlov (1991), we have included several stars from two different sources. The first source provides the kinematics of several types of cool dwarfs in the solar neighborhood (Soderblom 1990). The second source is a large study which searched for kinematic groups in the solar neighborhood (Agekyan & Orlov 1984). These latter authors computed the Galactic velocities for more than 1,000 stars selected from the Gliese Catalog, and suggested the existence of several moving groups. From these two sources, we have selected a total of 26 stars, and we have re-analyzed their kinematic properties. Table 1 lists our sample of stars. The first column contains the common name for well known stars, whereas the other three columns provide the numbers in the Gliese, HD and Hipparcos/Tycho catalogs, respectively.

A Color-Magnitude Diagram of the whole sample is shown in Fig. 1, where the absolute visual magnitude is plotted versus the (B–V) color index. A Schmidt-Kaler (1982) Zero Age Main Sequence (ZAMS) is also included as a solid line. The group includes eight A stars with different levels of IR emission, as well as five dF, two dG, three dK and seven dM. Note that we have not performed a systematic search for possible members (either using the whole Gliese Catalog or taking advantage of the Hipparcos database) and, therefore, our sample is not complete and may be biased.

Table 1. Candidates of the Castor moving group.

Name (1)	GL (2)	HD (3)	HIP (4)
κ Phe	20	2262	2072
14 Lep	217.1	38678	27288
	226.2	–	29067
	255AB	–	33451
Castor A+B	278AB	60179/8	36850
YY Gem	278C	60179	–
	351A	–	46651
	426 AB	98736	55486
	466	–	60661
	521.2A	119124	66704
α^2 Lib	564.1	130841	72622
α^1 Lib	563.4	130819	72603
	696	162283	87322
Vega	721	172167	91262
	755	181321	95149
AU Mic	803	197481	102409
Alderamin	826	203280	105199
	842.2	–	108467
ι Peg	848	210027	109176
	879	216803	113283
Fomalhaut	881	216956	113368
EQ Peg	896AB	–	116132

Table 2 contains additional information about the sample. We list the apparent and absolute visual magnitudes, (B–V) and (V–I) –cousin– colors and, when available, the equivalent width of Hα –EW(Hα)–, X-ray luminosity and lithium abundance.

3. Membership in the moving group

3.1. The kinematic criterion

Based on the positions, parallaxes, and proper motions provided by the Hipparcos database, and the radial velocities (SIMBAD database and references therein), we have computed the kinematic properties of our sample of stars. Table 3 shows the numbers in the Gliese Catalog, the positions, parallaxes, proper motions, radial velocities, and the Galactic velocities (U, V and W), with their associated errors for all these quantities. Galactic velocities and errors were computed following the description provided by Johnson & Soderblom (1987) and follow the right-handed coordinate system (positive toward the Galactic center, Galactic rotation and North Galactic Pole). Since the time span for the Hipparcos mission was short, the proper motions based on Hipparcos data might be not accurate. For this reason, we have also computed the Galactic velocities using the proper motion values from the PPM (Roeser & Bastian 1988; Bastian & Roeser 1993; Roeser & Bastian 1994), and the Hipparcos positions and parallaxes. Except in very few cases (e.g. GL351, GL521.2, Castor itself), the discrepancies do not affect the conclusions. However, we note that the differences between the Hipparcos and the PPM proper motions differ by more than the quoted uncertainties for all stars in the sample. Narayanan

Table 2. Photometry and other data for the Castor moving group.

Gliese number	Sp. Type	m_V	Mv	(B-V)	(V-I)c	H(alpha) (Å)	Log Lx (erg/s)	Log N(Li)	References
20	A7 V	3.93	2.072	0.175	0.20	–	–	–	
217.1	A2Vann	3.55	1.886	0.104	0.105	–	–	–	
226.2	K8 V	9.75	7.767	1.250	(1.41)	–	–	–	
255 A	F8 IV-V	6.795	3.618	0.465	0.53	–	–	–	
255 B	–	7.209	4.032	–	–	–	–	–	
278 A	A1 V	1.98	0.986	0.03	–	–	–	–	
278 B	A2 Vm	2.88	1.886	0.04	–	–	–	–	
278 C	M1 Ve	9.07	8.076	1.42	1.87	1.95/0.72	29.03	0.11	4,5,8
351 A	F2IV	3.60	2.258	0.371	0.43	–	–	–	
426 A	G5	7.996	5.500	0.894	(0.94)	–	–	–	
426 B	K6.5	10.999	8.503	–	–	–	–	–	
466	M0 V	10.34	7.337	1.254	1.440	–	–	–	
521.2	F7.7V	6.31	4.30	0.537	(0.61)	–	–	–	
546.1	A3 IV	2.75	0.879	0.147	0.155	–	–	–	
563.4	F3 V	5.15	3.280	0.401	0.48	–	–	3.20	1
696	M0V	10.17	8.468	1.419	1.769	-0.53	–	–	2,5
721	A0V	0.03	0.582	-0.001	-0.005	–	–	–	
755	G1/G2V	6.48	4.886	0.628	0.685	–	–	–	
803	M1Ve	8.81	8.82	1.470	2.10	1.56	29.83/29.38	–	3,4,5
826	A7IV-V	2.45	1.575	0.257	(0.26)	–	–	–	
842.2	M0	10.56	8.964	0.742	(1.61)	–	–	–	
848	F5V	3.77	3.419	0.435	(0.51)	–	–	–	
879	K4 V	6.48	7.065	1.094	1.205	-0.77	28.3	0.60	5,9
881	A3 V	1.17	1.741	0.145	0.080	–	–	–	
896 A	M4 V +	10.32	11.34	1.56	(2.54)	4.26	28.62	-0.05	2,5,6,7,10
896 B	M6 V	12.40	13.42	1.825	(2.84)	5.11	28.84	–	2,4,5,7

References: Spectral type and photometry from SIMBAD and Hipparcos/Tycho database and Bessel (1990). Other data: 1. Duncan (1981), 2. Stauffer et al. (1986), 3. Doyle (1989), 4. Güdel et al. (1993), 5. Panagi & Mathioudakis (1993), 6. Schmitt et al. (1995), 7. Fleming et al. (1995), 8. Barrado y Navascués (1996), 9. Barrado y Navascués et al. (1997a), 10. Zboril et al. (1997).

& Gould (1998) have shown that Hipparcos proper motions are consistent with its parallaxes (at least in the direction toward the Hyades), an indication that there are not systematics errors due to the short baseline. The derived V component of the Galactic velocities also differ by more than the nominal uncertainties in 30% of the sample. This fact indicates that some stars catalogued as members of the moving group could be spurious members.

We have made a special effort to use the most accurate radial velocities. Primarily, we selected the values from the WEB catalog (Duflot et al. 1995), a compilation of three different works (Wilson 1963; Evans 1978; Batten et al. 1989). We also provide other values quoted in the literature. Only in three cases (GL426, GL564.1 and GL842.2), there are disagreements between these values. For GL426 and GL842.2, the kinematics and other information seem to indicate that they are not associated with the moving group. The case of GL564.1 is discussed below.

Figs. 2a and 2b allow us to identify possible members based on their kinematic properties (V against U and W, respectively, from Hipparcos data). Soderblom & Mayor (1993) pointed out that the components of a stellar kinematic group must have the same motion in the direction of the Galactic rotation (the V component). Visual inspection indicates that the velocities are clustered around (-10,-8,-10). The dispersions of these velocities are rather small, in particular for the the 7 A spectral type stars (note that Castor is itself composed of two pairs of spectroscopic binaries, but we have counted them as one star). However, there are several stars which have velocities in disagreement with these average values.

In particular, the Galactic velocities (specifically, using the V component as a criterion) seem to indicate that GL426AB, GL466 and GL696 are probable non-members of the moving group, and that GL803 and GL842.2 are possible non-members (indicated with the labels “N” and “N?” in the second column of Table 4). The table also indicates if the stars are probable or possible members (“Y” and “Y?”, respectively).

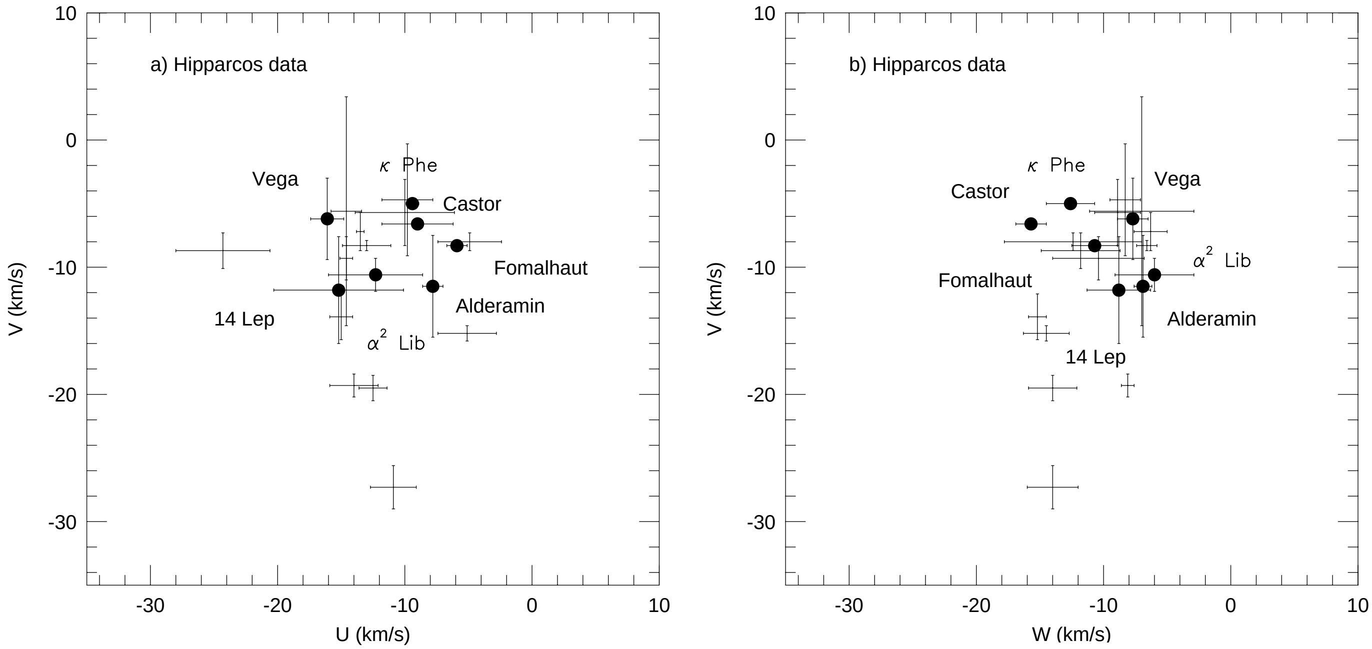
GL564.1 (α^2 Lib) deserves special attention. It is physically associated to GL563.4 (Poveda et al. 1994). The WEB value of the radial velocities of both stars leads to a a similar value of the V component of the Galactic velocity, but Poveda et al. (1994) provide a radial velocity in large disagreement with the WEB value. We have preferred to keep this last value. On the other hand, the U component of the velocity of GL563.4 is quite different from the average of the group. The only relevant difference between both stars is the radial velocity and this could

Table 3. Coordinates and velocities for the Castor moving group.

GL	alpha	delta	parallax	μ_α	μ_δ	ref	RV	U	V	W
	(1950.0)		(mas)	(mas/yr)				(km/s)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
20	0:23:44.92	−43:57:25.6	42.51±0.69	106.14±0.48	32.83±0.57	HIP	10.9±2.0	−9.4±0.5	−5.0±0.4	−12.6±1.9
″	″	″	″	″	″	″	11.3±2.0	−9.3±0.5	−5.0±0.4	−13.0±1.9
″	″	″	″	108.0±6.7	10±6.8	PPM	11.3±2.0	−8.4±0.9	−7.3±0.8	−12.3±1.9
217.1	5:44:41.31	−14:50:21.0	46.47±0.68	−14.84±0.63	−1.18±0.45	HIP	21.1±7.0	−15.2±5.1	−11.8±4.2	−8.8±2.5
″	″	″	″	″	″	″	20.0±5.0	−14.4±3.6	−11.1±3.0	−8.4±1.8
″	″	″	″	−16.0±0.5	−1±0.7	PPM	20.0±5.0	−14.4±3.6	−11.1±3.0	−8.5±1.8
226.2	6:02:36.80	67:59:05.3	40.12±1.78	−48.32±1.03	−112.31±1.15	HIP	1.6±5.0	−10.0±3.9	−5.7±2.6	−8.9±1.8
255	6:55:30.20	−35:26:22.6	23.15±0.56	−40.38±0.50	19.58±0.53	HIP	10.1±5.0	−9.8±2.0	−4.7±4.4	−8.3±1.2
″	″	″	″	−36.7±2.9	19±3.3	PPM	10.1±5.0	−9.5±2.1	−5.0±4.4	−7.6±1.4
278	7:31:24.66	32:00:00.8	63.27±1.23	−206.33±1.60	−148.18±1.47	HIP	3.0±3.0	−9.0±2.8	−6.6±0.4	−15.7±1.2
″	″	″	″	″	″	″	2.0±0.9	−8.1±0.8	−6.5±0.3	−16.1±0.5
″	″	″	″	−171.7±0.4	−99±0.4	PPM	2.0±0.9	−7.0±0.8	−3.7±0.2	−12.7±0.4
351	9:28:43.53	−40:14:48.3	53.89±0.70	−147.14±0.58	48.65±0.78	HIP	8.8±2.0	−12.9±0.2	−8.8±2.0	−4.5±0.3
″	″	″	″	−193.5±5.5	64±5.4	PPM	8.8±2.0	−16.8±0.5	−8.8±2.0	−6.3±0.6
426	11:19:12.33	18:27:56.1	31.68±1.55	−151.10±1.97	−95.73±1.33	HIP	−4.1±2.0	−12.5±1.1	−19.5±1.0	−14.0±1.9
″	″	″	″	″	″	″	−9.0±1.7	−11.4±1.1	−18.0±0.9	−18.5±1.6
″	″	″	″	−149.4±2.6	−102±2.9	PPM	−4.1±2.0	−11.9±1.1	−20.2±1.1	−14.1±1.9
466	12:23:26.29	8:20:25.9	25.08±1.85	−129.11±2.16	−110.85±1.48	HIP	−5.0±2.0	−10.9±1.8	−27.3±1.7	−14.0±2.0
521.2	13:38:24.36	50:46:16.2	39.64±0.71	−124.73±0.58	57.86±0.62	HIP	−11.7±4.0	−14.6±0.5	−9.3±1.7	−10.4±3.6
″	″	″	″	″	″	″	−10.8±2.0	−14.7±0.3	−9.0±0.8	−9.6±1.8
″	″	″	″	−190.5±2.5	59±2.5	PPM	−10.8±2.0	−20.8±0.5	−13.7±0.9	−8.1±1.8
564.1	14:48:06.45	−15:50:06.5	42.25±1.05	−105.69±0.87	−69.00±0.62	HIP	−10.0±5.0	−12.3±3.7	−10.6±1.3	−6.0±3.1
″	″	″	″	″	″	″	−46.7±5.0	−39.5±3.7	−0.9±1.3	−28.6±3.1
″	″	″	″	−105.3±0.3	−67±0.4	PPM	−10.0±5.0	−12.4±3.7	−10.5±1.3	−5.9±3.1
563.4	14:47:55.07	−15:47:26.0	42.26±1.04	−135.93±0.94	−59.47±0.62	HIP	−23.0±5.0	−24.3±3.7	−8.7±1.4	−11.8±3.1
″	″	″	″	−98.2±0.4	−66±0.6	PPM	−23.0±5.0	−21.5±3.7	−6.4±1.3	−14.2±3.1
696	17:47:53.27	− 6:02:07.4	45.67±2.06	−26.05±2.16	−131.40±1.36	HIP	−21.0±2.0	−14.0±1.9	−19.3±0.9	−8.1±0.5
″	″	″	″	″	″	″	−26.2±1.0	−18.8±1.0	−21.1±0.6	−9.1±0.4
″	″	″	″	−25.4±2.7	−139±3.0	PPM	−21.0±2.0	−13.7±1.9	−19.9±0.9	−8.6±0.6
721	18:35:14.67	38:44:09.7	128.93±0.55	201.02±0.57	287.46±0.60	HIP	−13.8±3.7	−16.1±1.3	−6.2±3.2	−7.7±1.2
″	″	″	″	″	″	″	−13.9±0.9	−16.1±0.3	−6.3±0.8	−7.7±0.3
″	″	″	″	202.4±0.3	286±0.3	PPM	−13.9±0.9	−16.1±0.3	−6.3±0.8	−7.8±0.3
755	19:18:11.62	−35:04:37.3	47.95±1.28	78.88±4.08	−108.93±2.50	HIP	−10.2±2.0	−13.0±1.9	−8.3±0.4	−6.6±0.8
″	″	″	″	93.3±3.0	−89±3.6	PPM	−10.2±2.0	−13.4±1.9	−6.0±0.4	−7.2±0.8
803	20:42:03.79	−31:31:05.6	100.59±1.35	280.37±1.58	−360.09±0.98	HIP	2.0±3.0	−5.1±2.3	−15.2±0.6	−14.5±1.8
″	″	″	″	″	″	″	1.2±2.0	−5.7±1.6	−15.4±0.4	−14.0±1.2
″	″	″	″	281.3±2.9	−363±2.9	PPM	1.2±2.0	−5.7±1.6	−15.5±0.4	−14.0±1.2
826	21:17:23.18	62:22:23.8	66.84±0.49	149.91±0.49	48.27±0.45	HIP	−10.8±4.1	−7.8±0.8	−11.5±4.0	−6.9±0.7
″	″	″	″	″	″	″	−10.8±5.0	−7.8±0.9	−11.5±4.8	−6.9±0.8
″	″	″	″	151.6±0.3	49±0.3	PPM	−10.8±5.0	−7.9±0.9	−11.5±4.8	−6.9±0.8
842.2	21:57:58.27	75:20:55.8	47.95±1.08	231.83±1.23	22.60±1.08	HIP	−11.0±2.0	−15.0±0.9	−13.9±1.8	−15.2±0.7
″	″	″	″	″	″	″	−19.7±0.5	−11.8±0.5	−21.6±0.5	−17.7±0.4
848	22:04:40.83	25:06:00.7	85.06±0.71	296.73±0.56	26.93±0.69	HIP	−4.0±10.0	−14.6±1.2	−5.6±9.0	−7.0±4.1
″	″	″	″	″	″	″	−5.5±0.9	−14.7±0.2	−7.0±0.8	−6.3±0.4
″	″	″	″	298.8±0.4	25±0.5	PPM	−5.5±0.9	−14.8±0.2	−7.0±0.8	−6.5±0.4
879	22:53:37.44	−31:49:50.5	130.94±0.92	330.53±1.00	−159.86±0.75	HIP	8.5±6.0	−4.9±2.5	−8.0±0.7	−12.7±5.4
″	″	″	″	″	″	″	6.70±0.1	−5.7±0.1	−8.2±0.1	−11.1±0.1
″	″	″	″	″	″	″	6.0±5.0	−6.0±2.1	−8.3±0.6	−10.4±4.5
″	″	″	″	336.4±3.0	−158±3.1	PPM	6.0±5.0	−6.2±2.1	−8.3±0.6	−10.5±4.5
881	22:54:53.53	−29:53:15.8	130.08±0.92	329.22±1.05	−164.22±0.73	HIP	6.1±2.0	−5.9±0.8	−8.3±0.3	−10.7±1.8
″	″	″	″	″	″	″	6.5±0.9	−5.7±0.4	−8.2±0.1	−11.0±0.8
″	″	″	″	292.61±0.4	−165±0.6	PPM	6.5±0.9	−4.7±0.8	−7.9±0.3	−10.1±1.8
896	23:29:19.52	19:39:43.3	160.06±2.81	554.40±2.03	−62.61±1.60	HIP	0.0±2.0	−13.5±0.3	−7.2±1.5	−6.3±1.3

be due to the orbital motion as well as to uncertainties in the measured values. Therefore, we do not rule out the possibility that it indeed belongs to the moving group.

Fig. 3c displays the velocities computed with the PPM data. The agreement in the kinematics of these stars also suggest a common origin. However, when computed from the PPM values, Castor has a V component of the velocity quite different from the average of the moving group, with a difference much larger than the quoted uncertainties. Therefore, it would be possible that these system would not be a member of the moving



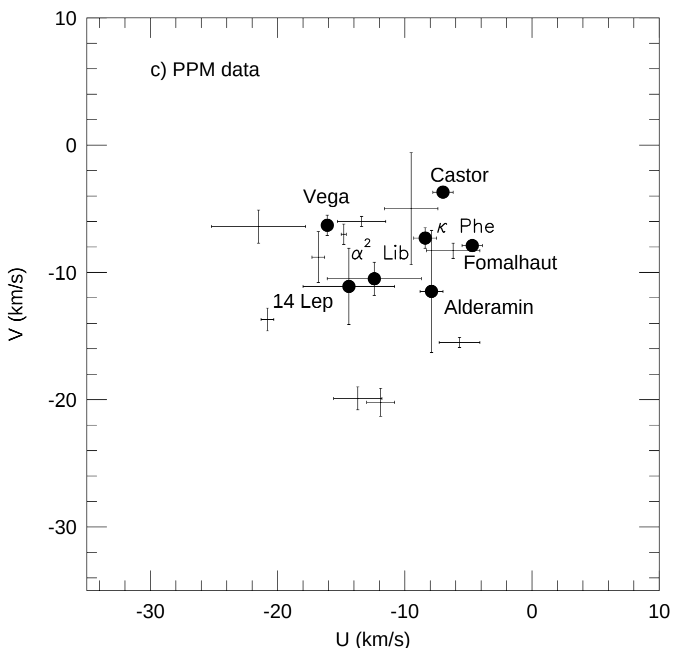


Fig. 2a–c. Kinematics of the whole sample. The seven proposed members of A spectral type are indicated with filled circles and labels. The **c** panel shows the data obtained using the PPM data

group (and the association should be called Vega moving group). In fact, if a very restricted definition would be used, this figure indicates that there could be 2 different groups; one including Vega, Fomalhaut and κ Phe and another with 14 Lep and α^2 Lib. Alderamin could be in either of them, due to its large error bars. However, the data based on Hipparcos and the evidences provided below seem to indicate that, indeed, all of them share a common origin.

3.2. Color-magnitude diagrams

Further information on the membership can be obtained from Color-Magnitude Diagrams. Fig. 3a displays the absolute visual magnitude against the (B–V) color, whereas Fig. 3b has $(V–I)_c$ in the x-axis. The initial sample of late spectral type stars are shown as circles. Filled symbols indicate final members and open symbols those stars rejected as physically associated (see Sect. 3.4). Both figures include the D'Antona and Mazzitelli (1994) isochrones for the ages 3, 10, 35 and 70 Myr (top to bottom, dashed lines). The solid line is the ZAMS. Details concerning the convertion between theoretical values ($T_{\rm eff}$ and luminosity) and the observational plane can be found in Stauffer et al. (1995) and Barrado y Navascués et al. (1997a).

We have selected those stars located below the 35 Myr isochrone and above the ZAMS as possible members and indicated this in the third and fourth columns of Table 4.

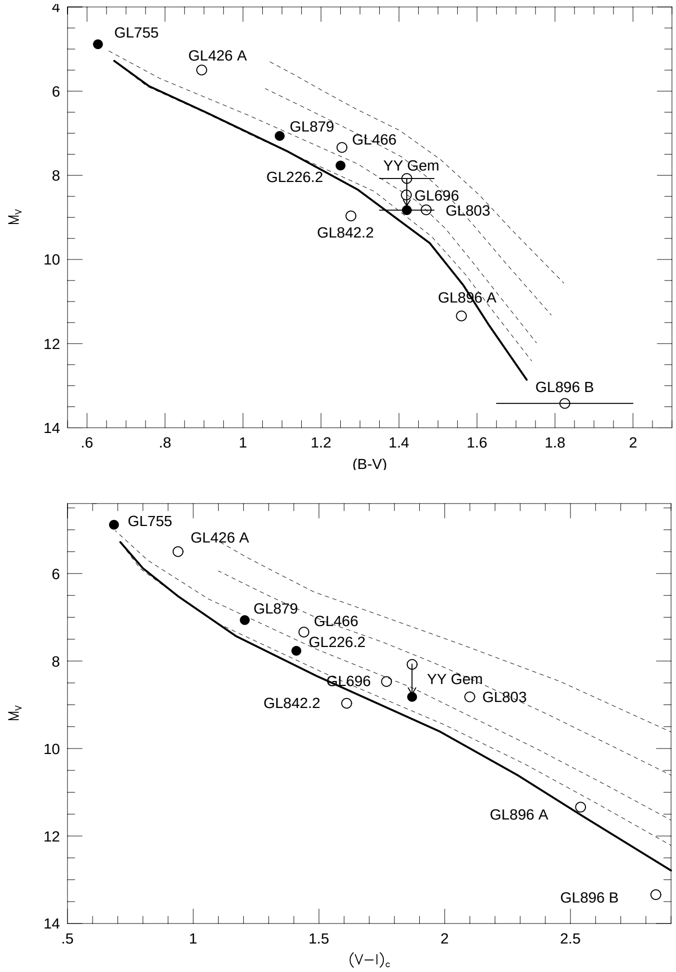


Fig. 3a and b. Color-Magnitude Diagrams for the late spectral type candidates. The isochrones (3, 10, 35, 70 and ZAMS) are those from D'Antona & Mazzitelli (1994). Final members are indicated as filled circles, whereas rejected members appear as open circles. **a** Mv against (B–V). **b** Mv against (V–I)$_c$.

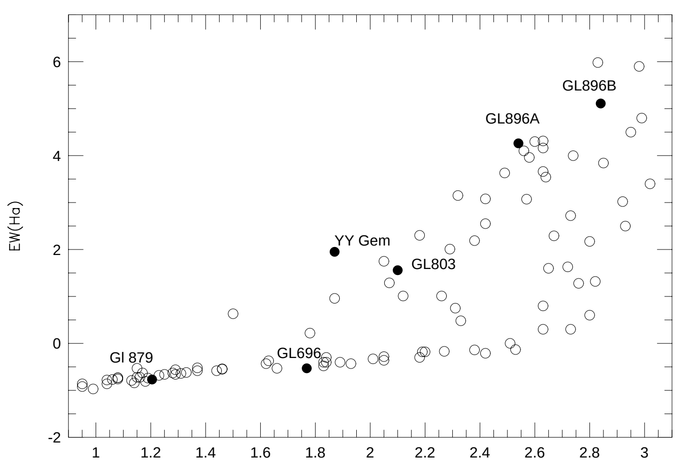


Fig. 4. Hα equivalent width against (V-I) color. Proposed members of the moving group are shown as filled circles. Hyades members appear as open circles.

Table 4. Membership in the Castor moving group.

Gliese number (1)	Criterion: Kinematic (2)	Mv–(B-V) (3)	Mv–(V-I) (4)	Lithium (5)	Final memberhip (6)
20	Y	–	–	–	Y
217.1	Y	–	–	–	Y
226.2	Y	Y	Y	–	Y
255 A	Y	–	–	–	Y
255 B	Y	–	–	–	Y
278 A	Y	–	–	–	Y
278 B	Y	–	–	–	Y
278 C	Y	Y	Y	Y	Y
351	Y	–	–	–	Y
426 A	N	N	N	–	N
426 B	N	–	–	–	N
466	N	N	N	–	N
521.2	Y	–	–	–	Y
546.1	Y	–	–	–	Y
563.4	N?	–	–	Y	Y?
696	N?	Y	Y	–	N?
721	Y	–	–	–	Y
755	Y	Y	Y	–	Y
803	Y?	N	N	–	N
826	Y	–	–	–	Y
842.2	Y?	N	–	–	N
848	Y?	–	–	N	N?
879	Y	Y	Y	Y	Y
881	Y	–	–	–	Y
896 A	Y	N	–	N?	N?
896 B	Y	Y?	–	–	N?

3.3. Stellar activity

Fig. 4 compares the equivalent width of Hα for our sample of stars (filled circles) with the Hyades (open circles). This graph can be used to support rejection of several candidates or to accept them as members: GL696 presents a minimum value in its Hα absorption (it is a very inactive star), so it seems to be older than the Hyades and a non-member of the moving group. GL896A, GL896B and GL803 are very active stars. Their activity is similar to the most active Hyades stars, an indication that they could be younger. However, Barrado y Navascués et al. 1998) have shown that some dM Praesepe stars have larger activity than equivalent Hyades stars (both clusters are coeval). Therefore, these stars could be as old as 600-800 Myr. The spectroscopic binary YY Gem is a BY Dra system, whose rotational period is synchronized with its orbital one, phenomenon which produces an enhanced stellar activity, not related with the age of the system. Its location on the plot cannot provide any information about its membership to the moving group. Similar conclusions can be reached if the coronal activities are compared.

3.4. A list of members

We have combined the information provided by the kinematics and the CMD to select a list of members. We have also taken into account the lithium abundance and the Hα equivalent width when that information is available. We find that there is a good agreement between these criteria (if the kinematics are different from the average value, then the location in the CMD usually desagree with membership).

Column six in Table 4 provides our final classification for the membership. The hotter stars are classified as members based only on the kinematic. However, they are relatively young, and the probability of having several stars of A spectral type, leaving the Main Sequence, with the same spatial velocity, and not having been born at the same time, is quite low. We have a total of 16 probable members and another star which could be part of the group (α^1 Lib).

3.5. Are these stars physically associated?

A significant fraction of the stars studied here fulfill the Soderblom & Mayor (1993) definition of a stellar kinematic group. The most restrictive requirement is that of having identical V component of the Galactic velocity. In our case, there are 8 stars with V within 1 sigma of the average of the final members. This group includes Castor, Vega and Fomalhaut. Although we do not rule out the possibility of having a spurious kinematic group, we believe that the data presented here provide strong indications for a common origin of, at least, the majority of the sample. However, the membership of individual stars cannot be known without doubt. In fact, Whitmire et al. (1992) studied the kinematics of several A stars in the solar vicinity, including several stars in common with our study, namely, GL20, GL217.1, GL278, GL564.1, GL721, GL826 and GL881. Although they discussed the possibility of a common origin for several of these stars, they concluded that the small velocity dispersion is due to an observational selection. Their model implies an interaction with an interstellar cloud, a phenomenon which could enhance the circumstellar disks. However, not all A stars in our sample display IR excesses, a subproduct of the disks. In any case, some caveats about particular membership should be kept in mind.

4. Estimating the age of the moving group

4.1. Age and kinematics

Palouš & Piskunov (1985) have shown that there is a relation between the kinematic properties and the age of B and A stars. Based on their Table 3, it is possible to constrain the age of the hot members of the Castor moving group. They have average values of the velocities of $<U>=-10.7\pm3.5$, $<V>=-8.0\pm2.4$ and $<W>=-9.7\pm3.0$ km/s, leading to ages of 100–400, 200-600 and 50-100 Myr, respectively. These ages are indicative, since the velocity dispersion components in the Palouš & Piskunov (1985) study are quite large and, in the last case, the W component of the velocity of the Castor group is slightly out the range of velocities examined by Palouš & Piskunov (1985). A combined age would be 100-400 Myr, in good agreement with the values derived for the late spectral type stars (see below).

4.2. Age from the isochrone fitting

Figs. 3a and 3b can provide an estimate of the age of the association. The final set of members lies below the 35 Myr isochrone and above the 70 Myr. Both the proximity to the ZAMS and the unknown metallicity of the group do not allow an accurate determination of the age. However, it seems that these stars are clearly above the ZAMS. Then, they would be Premain sequence (PMS) objects, still approaching at the MS. We believe that due to the errors in the conversion from the theoretical plane to observational plane, together with the errors associated with the observational data (very small in most cases), the two color-magnitude diagrams put only a lower limit to the age, of 35 Myr.

On the other hand, the hotter real members of the moving group should be close to the end of their lives in the Main Sequence (in particular, Castor A and B, and α^2 Lib). This particular evolutionary status allows for the possibility of isochrone fit. Again, uncertainties in the individual actual distances – negligible, see Table 3, magnitudes and colors are too large to provide accurate ages. Backman & Paresce (1993), by fitting isochrones, derived ages close to 400 and 200 Myr for Vega and Fomalhaut, respectively, with uncertainties of 30%. For our data set, we use Meynet et al. (1993) set of evolutionary tracks. We find that Fomalhaut is too close to the MS to fit an isochrone. The location of Vega, hotter than Fomalhaut, in the CMD is completely compatible with the turn-off position of the open cluster NGC 6494, and provides an age close to 300 Myr. In any case, it seems that at least some stars, including the Castor system, YY Gem, Fomalhaut and Gl 879, are physically associated and, for this reason, they have the same age.

The common origin and age of these stars would have important implications. In particular, YY Gem, an eclipsing binary, is one of the two M dwarfs with accurate measurements of radii and temperatures. Chabrier & Baraffe (1995), using new evolutionary models, fit isochrones to both components of the system (either in the radii-mass or the $T_{\rm eff}$-mass planes), and concluded that the system has to be on the late Pre-main Sequence contraction phase. They estimated an age of $\sim$100 Myr. We note that if it is really slightly a PMS system, then it should not be used as a calibrator of theoretical models (unless one can accurately correct for its PMS nature or accurately know its age).

4.3. The lithium–Teff plane

The lithium abundance of late spectral type stars can be used as a membership criterion, as well as a statistical method to estimate the age of an association of stars, since the lithium abundance depends on both age and mass (e.g., Balachandran 1994). Figs. 5a and 5b depict the abundance against the effective temperature for those stars with published values (crosses). In the first case (Fig. 5a), we have included data corresponding to Hyades stars (filled circles) and Pleiades stars (open circles). These two clusters have standard ages of 600-800 and 70-80 Myr, respectively (see Stauffer et al. 1998 for a new determination of the age of the Pleiades, which yields 125$\pm$5 Myr, based on the position of the

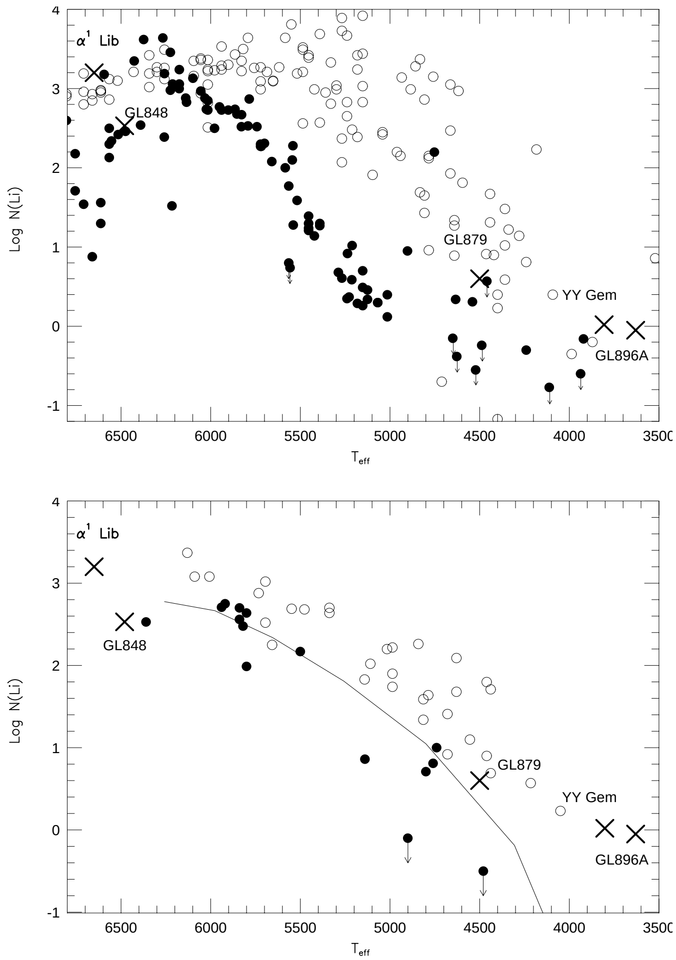


Fig. 5a and b. Lithium abundances against effective temperatures. Crosses represent the proposed members of the moving group. **a** Pleiades and Hyades data (open and filled circles). **b** M34 and UMa Group data (open and filled circles).

lithium boundary for very low mass stars and brown dwarfs). The second figure contains data from the M34 cluster (open circles) and the UMa moving group (filled circles), which are 200 and 300 Myr old, respectively. Fig. 5b also includes a 300 Myr lithium depletion isochrone from Chaboyer (1993). The sources of the lithium data for all four associations can be found in Barrado y Navascués et al. (1997a).

The comparison between the lithium abundances of cluster stars of different ages and GL879, a physical companion of Fomalhaut, was used by Barrado y Navascués et al. (1997a) to establish that these stars are younger than 300 Myr, probably in the range 100-300 Myr. Figs. 5a and 5b indicates that the lithium abundance of α^1 Lib is compatible with this age (see our caveats about the membership based on the kinematic, Sect. 3.5). GL848 seems too old to be part of the moving group, whereas GL896A is too young.

The case of YY Gem is more complex. It is well known that it is a very close SB2 eclipsing binary. Its rapid rotation (v sini=40 kms^{-1}) causes significant for the important spectral line blending. Moreover, since the system is composed of 2 similar stars (M=0.62 and 0.57 M$_\odot$, Bopp 1974), lines arising from both components appear in the spectrum. For the particular observation used to derive the lithium abundance (phase=0.21, Barrado y Navascués 1996), the LiI6708.8 Å doublets of each component were well detached. The final abundance is Log N(Li)=0.02±0.20, in the customary scale where Log N(H)=12. However, close binaries in clusters (Barrado y Navascués & Stauffer 1996 in the case of Hyades, and Ryan & Deliyannis 1995 in the case of M67) and chromospherically active binaries, such as YY Gem (Barrado y Navascués et al. 1997b) inhibit partially the lithium depletion, probably due to mixing related to rotation. Therefore, this binary is not a good candidate to be used to estimate the age of the Castor moving group, although it is very well established that there is a physical connection between these stars.

4.4. The age of the association

All these comparisons, which are compatible with the well determined age of GL879 and Fomalhaut, allows us to conclude that, indeed, the Castor moving group has an age of 200±100 Myr. Note that at this point, we have assumed that the stellar kinematic group is real and that these stars are members of it. However, as mentioned before, the group, as found in open clusters, could contain spurious members, and even the possibility of having a sample with the same kinematic properties and compatible CMD and a different origin cannot be rejected.

If these stars do have a common origin, as it seems, the same age derived for them is a very relevant fact, since the group has several A stars with different infrared excesses (or none at all), indicating that, at least at this age, the evolution of the protoplanetary disks does not depend on their age.

5. Summary

We have used data provided by Hipparcos to select several stars as possible members of the Castor moving group. Additional information, such as the position in Color-Magnitude Diagrams, isochrones, lithium abundances, stellar activity, was used to add new constraints to the membership and to estimate the age of the association, which is 200±100 Myr.

The moving group contains seven A spectral type stars with different IR excesses. This fact could indicate that, at this stage, the evolution of these excesses, when present, does not depend on age, and that, therefore, the time scale of the formation of planetary does not seem to be universal. The excesses would be produced by collisions and sublimation of large bodies and not from protoplanetary disks.

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References

Agekyan T.A., Orlov V.V., 1984, Astron. Zh. 61, 60

Anosova J.P., Orlov V.V, 1991, A&A 252, 123
Backman D.E., Paresce F., 1993, In: Levy E.H., Lunine J. (eds.) Protostars and Planets III. University of Arizona Press, Tucson, USA
Balachandran S., 1994, In: Caillault J-P. (ed.) Eighth Cool Stars, Stellar systems and the Sun. ASP Conf. Ser. 64, p. 234
Barrado y Navascués D., 1996, PhD Thesis, Universidad Complutense de Madrid, Spain
Barrado y Navascués D., Stauffer J.R., 1996, A&A 310, 879
Barrado y Navascués D., Stauffer J.R., Hartmann L., Balachandran S., 1997a, ApJ 475, 313
Barrado y Navascués D., Fernández-Figueroa M.F., García–López R., de Castro E., Cornide M., 1997b, A&A 326, 780
Barrado y Navascués D., Stauffer J.R., Randich S. 1998, ApJ in press
Bastian U., Roeser S., 1993, Astronomisches Rechen-Institut, Heidelberg
Batten A.H., Fletcher J.M., Mac Carthy D.G., 1989, Publ.D.A.O. XVII,1
Bessel M.S., 1990, A&AS 83, 357
Bopp B.W., 1974, ApJ 193, 389
Chaboyer B.C., 1993, PhD Thesis, Yale University, USA
Chabrier G., Baraffe I., 1995, ApJ Letters 451, L29
D'Antona F., Mazzitelli I., 1994, ApJS 90, 467
Doyle J.D., 1989, A&A 218, 195
Duflot M., Figon P., Meyssonnier N., 1995, A&A SS 114, 269
Duncan D.K., 1981, ApJ 248, 651
Evans D.S., 1978, Bull. Inf. CDS 15, 121
Fleming T.A., Schmitt J.H.M.M., Giampapa M.S., 1995, ApJ 450, 401
Güdel M., Schmitt J.H.M.M., Bookbinder J.A., Fleming T.A., 1993, ApJ 415, 236
Herbst W., Miller J.R., 1989, AJ 97, 891
Holland W.S., et. al., 1998, Nat 392, 788
Jayawardhana R., Fisher S., Hartmann L., et al., 1998, ApJ Letter, in press
Johnson D.H., Soderblom D.R., 1987, AJ 93, 864
Koerner D.W., Ressler M.E., Werner M.W., Backman D.E., 1998, ApJ Letter 503, 83
Meynet G., Mermilliod J.-C., Maeder A., 1993, A&AS 98, 477
Narayanan V.K., Gould A., 1998, ApJ submitted
Palouš J., Piskunov A.E., 1984, A&A 143, 102
Panagi P.M., Mathioudakis M., 1993, A&AS 100, 343
Poveda A., Herrera M.A., Allen C., Cordero G., Lavalley C., 1994, Rev. Mex. Astron. Astrof. 28, 43
Roeser S., Bastian U., 1988, A&ASS 74, 449
Roeser S., Bastian U., 1994, A&ASS 105, 301
Ryan S.G., Deliyannis C.P., 1995, ApJ, 453, 819
Schmidt-Kaler T., 1982 In: Schaifers K., Voig H.H. (eds.) Landolt–Börnstein, Vol. 2b. Springer, Heidelberg
Schmitt J.H.M.M., Fleming T.A., Giampapa M.S., 1995, ApJ 450, 392
Soderblom D.R., 1990, AJ 100, 204
Soderblom D.R., Mayor M., 1993, AJ 105, 226
Stauffer J.R., Hartmann L., Barrado y Navascués D., 1995, ApJ 454, 910
Stauffer J.R., Schultz G., Kirkpatrick J.D., 1998, ApJ Letters 499, L199
Whitmire D.P., Matese J.J., Whitman P.G., 1992, ApJ 388, 190
Wilson R.E., 1963, Carnegie Institution of Washington Publication, 601
Zboril M., Byrne P.B., Rolleston W.R.J.R., 1997, MNRAS 284, 685