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Research Note

Investigation of the Pleiades cluster⋆,⋆⋆

III. Additional corona members

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Abstract. The analysis of CORAVEL radial velocities of 93 stars selected on the basis of their proper motion and Geneva CCD photometric observations for 57 stars have permitted to identify 25 new members in the outer part of the Pleiades. Several spectroscopic binaries have been discovered, but their membership is not clear. Two orbits with short periods have been determined, but both stars are probably non-members. The total number of member stars in the outer part of the Pleiades in the spectral range F5-K0 (0.45 $< B-V <$ 0.90) is now 81 which is comparable to the number of stars known in Hertzsprung's central area (88 stars) in the same spectral domain. Therefore at least 48 % of the F5-K0 main-sequence stars are located in the outer part of the cluster. And the census is probably still incomplete.

Key words: clusters: open: Pleiades – stars: binaries: spectroscopic – techniques: radial velocity

1. Introduction

In an effort to enlarge the sample of Pleiades members in the outer part of the cluster, we have observed a new sample of stars selected from the proper motion study by Artjukhina & Kalinina (1970, hereafter referred to as AK). In the first paper of this series (Rosvick et al. 1992a, paper I), we have observed 83 stars in the corona of the Pleiades selected on the basis of the proper motions and Walraven photometry published by van Leeuwen et al. (1986). Our radial velocities, obtained with the CORAVEL scanner (Baranne et al. 1979), enabled us to confirm the cluster membership of 56 F5-K0 main-sequence stars. We realised that we had not included the stars proposed by AK, of which the list extracted from van Leeuwen's paper was only a sub-sample. The reason is that AK published only (x,y) position which makes the identification of the stars on the sky more difficult. Stauffer et al. (1991) published new proper motions for faint stars in the Pleiades and gave coordinates for many AK stars. This enabled us to compute an initial set of coordinates for all AK stars and then to match the AK stars up with HST GSC stars. We used the GSC facilities developed at the Geneva observatory to get for each star a detailed map and better coordinates.

The evidences for the existence of a corona around open clusters have been developed in the introductory section of paper I, as well as the importance to identify the stars individually and not statistically. In the present paper we consider the area covered by Hertzsprung's (1947) study as the inner part of the Pleiades (out to 1° of the cluster center) and everything outside this zone as the outer part. This subdivision will be refined in the next paper of this series which will be devoted to the study of the structure of the Pleiades (Raboud et al. 1996).

This paper discusses the new radial-velocity observations made for the present sample and the CCD observations in the Geneva photometric system which were obtained for candidate members. We thus have all data at hand to examine the membership of these stars to the Pleiades.

2. Observations

2.1. The sample

The present sample contains 107 stars from Artjukhina & Kalinina's (1970) table 4 that were not already contained in the sample discussed in paper I, which is based on the list of van Leeuwen et al. (1986). In two cases (AK Ib-148 and IV-793), two stars were

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⋆ based on observations collected at the Haute-Provence Observatory (France) and La Silla Observatory (Chile)

⋆⋆ Table 2 is available only in electronic form at the CDS via anonymous ftp to cds.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html found at the given position and both were observed. The two stars are identified by 'a' and 'b' respectively in Tables 1 and 2. After each star received a first radial velocity observation, the most probable members, taking also into account possible binaries, were observed photometrically, because no data, except the AK photographic magnitudes or those given in the GSC, were previously known for these stars. The AK identification and the coordinates for epoch 2000 from the GSC are given in Tables 1 (member stars) and Table 3 (non members). Pels identifications are given for a few stars. They correspond to the numbering system used by van Leeuwen et al. (1986). For stars without other sources of photometric data the magnitude from the GSC is quoted. Table 3 is available only in electronic form at the CDS via anonymous ftp. Identification charts for the stars observed can be obtained from the first author (JCM).

2.2. Coravel observations

The observations were obtained with the CORAVEL radial-velocity scanner (Baranne et al. 1979) installed on the Swiss 1-m telescope at the Haute-Provence Observatory (OHP). The radial velocities were corrected for zero-point difference to place them in the system defined by the southern CORAVEL. Between September 1991 and Decembre 1994, as a rule two to three observations per star were obtained. In total, 288 radial-velocity measurements of 93 stars were made. AK Ib-590, III-153, III-909 and V-151 have spectral types earlier than F5 and could therefore not be observed with CORAVEL; AK III-158 and III-419 have not been observed and ten stars were tested but did not produce any correlation dip. These 10 stars are identified by the remark "no dip". Four double-lined and six single-lined spectroscopic binaries were discovered. Two of them appeared to have short periods and were more intensively monitored until orbital elements could be determined.

The mean radial velocities and errors in km s^{-1} and number of measurements are displayed separately for the members and non-members in Tables 1 and 3. As mentionned above, Table 3 is available only in electronic form.

2.3. Photometric observations

Photometric observations were obtained by (PB) with a CCD camera and Geneva filters (Bratschi & Blecha 1996) mounted on the 70-cm Swiss telescope at La Silla (Chile). Most observations were obtained in a single run in November 1994, although some measurements were already obtained in October 1992. Ten stars in common between both periods show a good agreement in their magnitudes. A second observation of 8 stars has been made in January 1996 to check their identifications and magnitudes. The V magnitudes and Geneva [B-V] colour indices are given in Tables 1 and 3. $(B-V)$ indices in the Johnson system have been computed with the relation given by Meylan & Hauck (1981): $(B-V)_J = 0.788\ [B-V] + 0.776$. For four stars (AK Ib-683, Ib-770, V-019 and V-437) the V magnitudes and Johnson $B-V$ colours given have been computed from the observations in the Walraven system published by van Leeuwen et al. (1986) and no Geneva $[B-V]$ are given.

3. Results

3.1. Membership

Radial velocity and proper motion are strong membership criteria, but photometry is nevertheless needed to define the final membership. As shown in paper I, the large dimension of the cluster over the sky induces a geometric effect due to the projection of the space velocity along the line of sight. We have taken this effect into account to determine the membership from radial velocities. With the value for the cluster parameters adopted in paper I ($V_r = 5.85 km\ s^{-1}$, $\mu = 0.''047\ yr^{-1}$, and $d = 130$ pc) and the convergent point given by Rosvick et al. (1992b) (α = 92.°97, δ = -48.°32 (1950)) we computed the expected radial velocity according to the position of the stars within the cluster field. The computed velocities range from 3.3 to 7.3 km s^{-1}. The apparent velocity dispersion produced by the geometric projection is thus much larger than the expected internal velocity dispersion. We retained those stars which have a radial velocity within ± 4 km s^{-1} of the expected value. The computed values of the radial-velocity (V_c) and the differences in the sense observed minus computed ($O-C$) are given in Tables 1 and 2.

The stars were then plotted in a colour-magnitude diagram (Fig. 1) with different symbols to distinguish between the candidate members (filled squares) and non-members (crosses). The main sequence defined by the members is clearly visible, as well as several stars with a radial velocity appropriate for membership, but located well below the main sequence. To prove that the position of the sequence corresponds to that of the Pleiades, we have plotted in a similar diagram (Fig. 2) the Geneva colours (Rufener 1989) of the stars in the central part of the Pleiades (open squares) and the present sample (filled squares). The new members fall on the same sequence, with a somewhat larger scatter. The latter may arise from observational errors, but also, as stated in paper I, from the depth effect. The Pleiades are some 23 pc across which produces magnitude differences up to 0.3 mag. This diagram shows that most of the stars selected for having similar proper motions and a radial velocity close to the cluster velocity are located at the same distance as the Pleiades. We therefore assume that they are *bona fide* members of the Pleiades and populate the outer part of the cluster, i.e. the corona.

Confirmation of our analysis is afforded by the proper-motion membership probabilities published by Stauffer et al. (1991). They unfortunately covered the central part only, i.e. zones Ia and Ib, which limits the number of star in common. Our members have predominently high membership probabilities, and, conversely, most stars rejected as non-members have low (well below 50%) membership probabilities.

Stars AK II-293, III-391 and III-679 are well located on the colour-magnitude diagram, but their velocities differs by 3.7, 3.1 and 3.4 km s^{-1} respectively from the computed value. AK III-391 and III-679 have small values of P(χ^2) and are possible

Table 1. Observational data for new members of the Pleiades

A-K	R.A. (2000)	Dec.	V	[B-V]	B-V	Vr	ϵ	n	ΔT	P(χ^2)	V_c	$O-C$	P	Remarks
Ia 317	3 54 21.6	24 04 33	9.75	-0.32	0.54	4.3	3.7	1			5.8	-1.5	.96	
Ib 038	3 40 50.4	23 25 07	10.84	-0.10	0.70	4.6	0.2	3	1066	0.487	5.5	-0.9	.97	
Ib 055	3 41 27.8	23 42 31	11.20	0.01	0.78	4.9	0.2	3	1066	0.937	5.4	-0.5	.94	
Ib 078	3 42 27.6	25 02 50	12.66	0.38	1.07	5.2	0.5	3	1066	0.001	4.8	0.4	.54	
Ib 146	3 43 50.6	25 16 08	9.63	-0.32	0.52	10.1	0.5	2	1179	0.000	4.8	5.3	.15	SB2
Ib 199	3 44 43.9	25 29 58	12.19	0.25	0.97	5.4	0.2	3	1066	0.966	4.7	0.7	.69	Pels 41
Ib 205	3 44 53.0	26 08 32	12.45	0.39	1.08	4.1	0.3	3	1067	0.153	4.4	-0.3	.98	Pels 137
Ib 288	3 46 09.5	26 08 20	11.88	0.35	1.05	4.1		7	717	0.000	4.5	-0.4	.17	SB2
Ib 590	3 51 06.3	25 35 41	9.11	-0.42	0.44						4.9		.92	BD +25°626, HD 24086, F2
II 293	3 36 17.6	21 53 39	10.96	-0.11	0.69	9.7	0.2	3	1066	0.766	6.0	3.7		M?
II 359	3 37 34.9	24 14 12	10.59	-0.21	0.61	5.0	0.2	3	1065	0.588	4.9	0.1		
III 059	3 28 40.5	25 36 28	11.75	0.08	0.84	4.7	0.2	3	1064	0.253	3.9	0.8		
III 079	3 29 25.4	25 39 08	9.43	-0.39	0.47						3.9			BD +25° 555, F5, no dip
III 153	3 31 15.9	25 15 20	8.10	-0.66	0.26						4.2			BD +24° 503, HD 21744, A3
III 391	3 36 01.0	24 15 58	11.29	-0.01	0.77	8.2	0.4	3	1065	0.006	4.9	3.3		M?, SB?
III 419	3 36 08.4	27 20 36	9.35	-0.25	0.58						3.4			BD +26° 579, G0
III 679	3 40 21.9	26 04 20	12.20	0.28	1.00	0.8	0.4	3	1074	0.021	4.2	-3.4		M?, SB?
III 700	3 40 35.9	26 09 05	11.14	-0.08	0.71	3.8	0.3	3	1065	0.147	4.2	-0.4		
III 909	3 45 15.0	26 53 29	8.58	-0.61	0.29						4.1			BD +26° 608, HD 23323, A5
IV 131	3 50 21.4	27 08 40	11.33	0.05	0.81	4.0	0.2	3	1064	0.932	4.2	-0.2		
IV 314	3 54 08.9	24 20 02	12.49	0.31	1.02	6.4	0.5	2	1067	0.011	5.7	0.7		
V 088	3 53 02.4	21 39 39	10.72	0.04	0.81	8.5	0.2	3	1064	0.256	6.9	1.6		
V 151	3 54 57.8	20 52 54	9.17	-0.42	0.44						7.3			BD +20°660, F0
V 198	3 56 12.2	21 02 28	10.86	-0.08	0.71	6.2	2.2	11	1064	0.000	7.2	-1.0		SB2
V 308	3 58 21.6	21 15 28	11.46	0.06	0.82	7.3	0.2	3	1064	0.609	7.3	0.0		

Table 3. Observational data for stars with contradictory membership criteria

A-K	R.A. (2000)	Dec.	V	[B-V]	B-V	Vr	ϵ	n	ΔT	P(χ^2)	V_c	$O-C$	P	Remarks
Ib 148	3 43 43.2	25 44 00	11.25	-0.21	0.61	4.2	0.3	3	1066	0.058	4.5	-0.3		a
Ib 174	3 44 11.8	25 23 54	12.26	-0.02	0.76	3.4	0.2	3	1066	0.749	4.7	-1.3	.98	
Ib 574	3 50 34.9	24 54 19	11.19	-0.19	0.63	7.4	0.6	2	1066	0.001	5.2	2.2	.92	HII 2736
II 046	3 31 24.0	20 56 45	11.41	-0.22	0.60	8.9	0.3	3	1065	0.080	6.1	2.8		
III 031	3 27 32.5	25 54 00	9.24	-0.14	0.67	5.3	0.1	27	1189	0.000	3.6	2.2		SB, orbit, BD +25°547

binaries. All three stars are considered as possible members (remark M?).

Five stars could not be observed successfully with Coravel because they are too hot (AK III-79, III-153, III-419, III-909 and V-151). They all fall nicely on the Pleiades main sequence and are considered as probable members. It would however be useful to get radial velocities for them to more firmly confirm their membership.

Five stars (AK Ib-148a, Ib-174, Ib-574, II-46 and III-31) have a radial velocity in close agreement to be classified as members, but are rejected on the basis of the colour-magnitude diagram. They are listed in Table 3. The first three are located at least one magnitude below the ZAMS, while III-31 is about 1.5 mag above the ZAMS. Additional photometric observations obtained in January 1996 confirm the identification and the previous photometry within a few percents. In the case of Ib-174 and Ib-574, both the radial velocities and the proper motion membership probabilities (.98 and .92 respectively) are in favour of the membership to the Pleiades and it would be interesting to make independant identifications and observations of these stars to confirm their status. The only possibility to have member stars below the main sequence is the presence of a bright white dwarf companion that makes the B-V colour bluer. A few cases exist in the Hyades, all are known spectroscopic binaries.

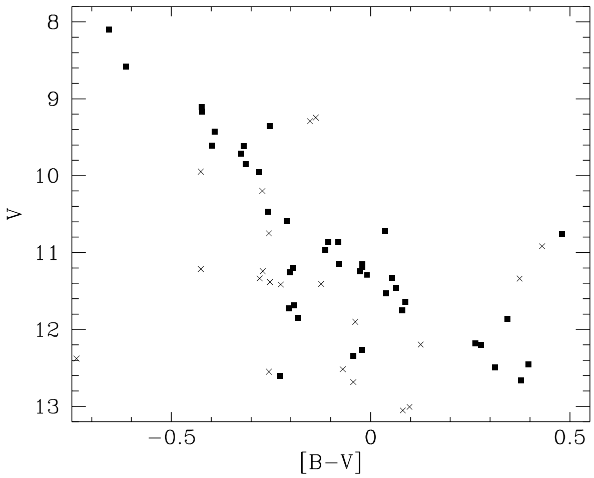

Fig. 1. Colour-magnitude diagram for the present sample. Filled squares indicate radial velocity members, while crosses stand for non-members.

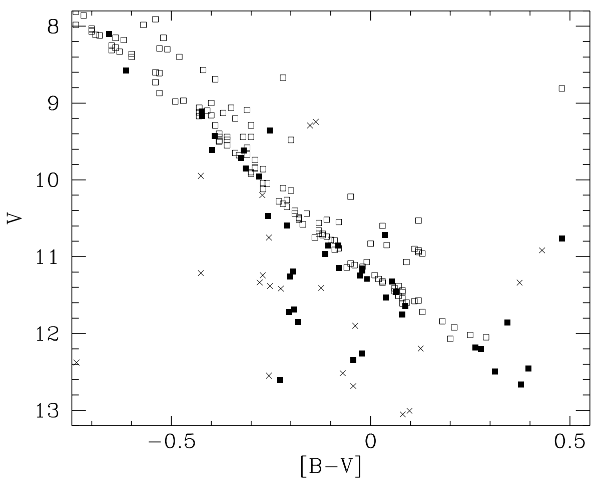

Fig. 2. Colour-magnitude diagram for the present sample and stars in the central region. Filled squares indicate radial velocity members, crosses stand for non-members and open squares denote the Hertzsprung (1947) stars.

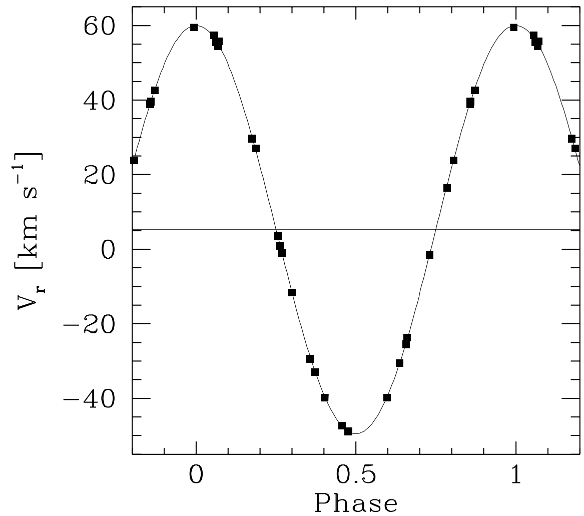

Fig. 3. Radial-velocity curve for AK III-031

Table 4. Orbital elements of two spectroscopic binaries

Element	AK III-31	AK III-416
P [d]	5.00433	10.9366
	.00003	.0005
T [HJD-2440000]	9998.859	9998.73
	.005	.07
e	0.00	0.172
	.002	.005
γ [km s^{-1}]	5.25	-9.89
	.09	.09
ω [°]		281.3
		1.7
K [km s^{-1}]	54.76	24.15
	.13	.13
f(m) [$M_\odot$]	0.0853	0.0153
	.0006	.0003
a sini [Gm]	3.768	3.58
	.009	.02
$\sigma(O-C)$ [km s^{-1}]	0.45	0.32
n_{obs}	27	17

3.2. Binarity

With two or three radial velocity observation in three years we cannot pretend to have detected all spectroscopic binaries. We have nevertheless detected 4 double-lined and 6 single-lined binaries, most of them showed up already at the second measurements. Orbital elements have been obtained for two of them (Table 4). AK III-031 (Fig. 3) has the right velocity to be a member, but lies rather far above the main sequence band. AK III-416 (Fig. 4) is clearly a non-member.

A double dip has been seen in the correlation function for AK Ib-146 on the third observation only which is not enough to determine its systemic velocity. It is considered as a possible member and a few more observations are needed to definitively settle its membership. AK Ib-288 has been observed as a double-lined system on several occasions and the systemic velocity quoted in Table 1 has been determined by Wilson's (1941) method and is around 4.1 km s^{-1}. In addition, it is located about 0.75 mag. above the ZAMS in the colour-magnitude diagram (Fig. 1), which is another strong argument for its membership. AK V-198 is another double-lined binary. Its systemic velocity, also determined by Wilson's (1941) method, is close to 6. km s^{-1}. There is a slight discrepancy between the mass ratio (close to 0.9), the dip depth and the position within the main sequence. If both components are of nearly equal masses, the star should be brighter than observed.

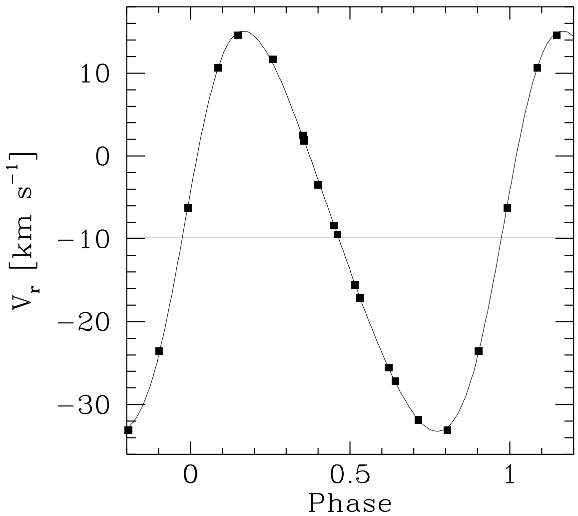

Fig. 4. Radial-velocity curve for AK III-416

Among the other spectroscopic binaries, AK Ia-351 is a triple system, with a fixed component around +32 km s^{-1} and a variable component. This system is therefore non-member.

3.3. Statistics

These 25 new members extend the previous sample of 56 corona members identified in paper I. The total number of F5-K0 members (the domain of completeness is limited to $0.45 < B-V < 0.90$) identified in the corona amounts now to 81 and represents nearly 50% of the total number of Pleiades stars already known (88 + 81) in this spectral interval. We are approaching the figures estimated by Artjukhina & Kholopov (1966) who stated that the corona of the Pleiades and Praesepe clusters could contain as much as 60% of the total number of stars. There is a possibility that when the degree of completeness of the population in the outer part of the Pleiades will be higher, more late-type dwarfs will be found in the outer part than in Hertzsprung's (1947) area.

The study of the structure of the Pleiades and discussion of mass segregation in light of the observations accumulated for the inner and outer parts of the Pleiades will be presented in the next paper (IV) of this series (Raboud et al. 1996).

4. Discussion and conclusion

The radial velocity observations and photometric data obtained for this new sample of stars in the wide surrounding of the Pleiades confirmed the membership of some 25 new stars. There are a few ambiguous cases: the membership evidences from radial velocity and photometry are contradictory. The rate of success (25/93) is much less than in the previous sample (56/83), which can be explained by two factors: (1) the first sample was selected on the basis of proper motions and photometric data, while the second one is based only on proper motions because no photometric data were available; (2) the data from Artjukhina & Kalinina (1970) have larger errors and many field stars appear (in their data) to have proper motions close to that of the Pleiades. The proper motion of the Pleiades represents usually a very selective criterion for membership (Schilbach et al. 1995). But because of the larger errors, it is also possible that real Pleiades members have not been selected in the member list due to their proper motion being beyond the limiting criterion, while many field stars have been considered erroneously in the candidate list. It is therefore quite probable that the sample of corona members is still not exhaustive.

Complementary radial-velocity observations are suggested for a few probable members that we cannot observe with CORAVEL because they are hotter than F5 and it would be useful to get independent observations of several stars with contradictory membership assignements from the kinematics and the photometry. It would be also very important for the study of the Pleiades and the understanding of the structure of the cluster to search for the Pleiades members in the magnitude range $9.5 < V < 15$ (or even to fainter magnitudes, if possible), corresponding to the G- and K-type dwarfs out to about 6° from the cluster center.

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