RADIAL VELOCITIES AND BINARITY IN OPEN CLUSTERS

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ABSTRACT. Radial and rotational velocities have been determined with the CORAVEL scanners for F5-K0 stars in the nine open clusters closer than 300 pc in both hemispheres. The total number of stars observed is larger than 1000. For most open clusters, these data sets form the only systematic long-term surveys made up to now in this spectral-type range. The aim was to study the membership, find new member stars, discover spectroscopic binaries and determine their orbital elements. As a by-product, we have access to the rotational velocities, as measured by the half-width of the cross-correlation function. Coravel observations of X-ray sources in the southern-hemisphere open clusters (NGC 6475, IC 2391 and 2602) confirm the membership of many candidates. The rotational velocities of the Hyades and Praesepe in the F5-K0 domain do not support the explanation of Praesepe X-ray anomaly in terms of different rotation.

1. Introduction

Open clusters, and especially the young ones, are the direct results of star formation processes. The precise knowledge of their characteristics is important to describe with enough details the products of star-formation processes and the evolution with time of properties like rotation, activity, and so on. Extensive descriptions of young open clusters are crucial to constrain the various scenarios of star- and cluster formation. This represents a major observational effort that has so far not been fully realised. Ideally, one would wish to address the following topics:

- the number of stars of various masses formed (IMF),
- the percentage of binaries formed along the main sequence,
- the distribution of their parameters (P, e, q),
- the initial distribution of stellar rotation,
- the physical characteristics of the stars,
- the sequence of star formation,
- the existence and importance of age spread,
- the cluster extent (radial distribution),
- the importance of initial mass segregation.

If we have presently numerous determinations of the luminosity- or mass functions, the question of binaries is far from being satisfactorily settled. The comparison of duplicity in several stellar groups (Bouvier et al. 1997) shows that the binary frequency may depend on the cloud mass. Questions like the dependence of the binary frequency on the primary masses or the distribution of the secondary masses along the main sequence have not been answered so far because no cluster has been completely and systematically observed. This obviously raises complex observational problems which may be solved with the new instruments installed on large telescopes. The membership list is probably not yet complete for any cluster because proper-motion surveys have not covered the complete surface out to the tidal radius and down to faint enough magnitudes. The Hyades are the only exception, because several large surveys have been performed (see for example Reid 1992, 1993) to identify faint members.

The nearby clusters form the best sample we have to study the main sequence properties down to low or very low mass stars. Table 1 recalls their names and parameters. The distances quoted are the direct determinations obtained from the discussion of Hipparcos parallaxes (Mermilliod et al. 1997). Available data have been compiled for some clusters by various peoples, but they have been systematically collected in the Database for Stars in Open Clusters (BDA) (Mermilliod 1995). The bibliography on these clusters from 1969 to present days may be accessed from our World Wide Web service at http://obswww.unige.ch/bda/.

Tab. 1 - Nearby clusters

Cluster	RA	Dec	dist [pc]	m-M [mag]	EBV [mag]	logt	ST	z [pc]	D ['arc]
Hyades	4 24.0	15 45	46	3.33	0.00	8.85	A2	-15	330
Coma Ber	12 22.6	26 23	88	4.73	0.00	8.66	A0	78	120
Pleiades	3 44.0	23 58	116	5.33	0.04	8.00	B5	-49	120
IC 2602	10 41.4	-64 08	147	5.83	0.04	7.46	B0	-12	100
IC 2391	8 38.8	-52 53	148	5.84	0.01	7.46	B3	-18	60
Praesepe	8 37.2	20 10	177	6.24	0.00	8.85	A0	84	70
α Persei	3 18.5	48 26	184	6.33	0.09	7.72	B3	-20	300
Blanco 1	0 01.7	-30 13	252	7.01	0.02	7.85	B5	-235	70
NGC 6475	17 50.6	-34 48	289	7.30	0.06	8.11	B8	-18	80

2. Observations

The radial-velocity survey of dwarf stars in nearby open clusters have been done with the CORAVEL radial-velocity scanners (Baranne et al. 1979) at two telescopes: in the Northern hemisphere, we have used the Swiss 1m-telescope at the Haute-Provence Observatory (OHP, France) and in the Southern sky we have used the Danish 1.54m-telescope at La Silla (ESO, Chile). The programm was started in fall 1978 in the north and later (1983) in the south. Because the cluster distances are similar, the main body of the survey contains mostly stars in the range F5 to K0. The limiting magnitude reaches

B = 12.5 for routine observations at the Haute-Provence Observatory and 14.5 at La Silla because of the larger telescope and lower detector noise. Integration times range from 5 to 20 min. per star, depending on the magnitude and stellar rotation.

The total number of measurements obtained for this program is 7429 (North: 6379, South: 1050). The main difference in the practical realisation is that we operate the Swiss telescope full time, while the observations in the South depend on the attribution of ESO time, which represented in the best case a week per period. This explains the lower number of velocities obtained in the South. Fortunately, Danish time could also be used thanks to the collaboration of J. Andersen (Copenhagen).

2.1. Northern sample

Table 2 presents the summary of the Northern sample. For each cluster it gives the number of stars included in the survey, the number of members found, of binaries detected and the number of orbits determined. The information in the column "Zone" indicates which part of the clusters (core or halo) the survey refers to, when the information is relevant. The column "Remarks" gives the source catalogue for member lists.

For sake of completeness, I have added the information on the extensive surveys realised by Latham and collaborators in M67 and the Hyades. Observations on NGC 752 are made in collaboration with his group. Orion is a southern cluster, but it has mainly been observed from OHP. Generally two observations per star were obtained in the Hyades primarily to determine the rotational velocities.

Tab. 2 - Dwarf Sample I. North

Cluster	Zone	Obs	Mem	SB	Orb	Remarks
Orion	Brun	36	13	2	2	Brun (1935)
α Persei		63	42	6	3	Heckmann et al. (1956)
Pleiades	Core	100	98	14	12	Hertzsprung (1947)
	Halo	83	56	5		van Leeuwen et al. (1986)
	Halo	101	30	4		Artjukhina & Kalinina (1970)
NGC 7092		23	24	2		
Coma Ber		64	24	5	5	
Praesepe	Core	90	85	29	23	Klein-Wassink (1927)
	Halo	116	48	11	7	Artjukhina (1966a, 1966b)
Hyades		156	148			2 meas/star
Total		832	568	78	52	
NGC 752		120	115		24	Obs. with Latham
Hyades		212	200		42	Obs. by Latham group
M67		400	400		23	Obs. by Latham group

Fig. 1 shows the colour-magnitude of Praesepe and the fraction of the main sequence covered by our survey. It also clearly demonstrates that such a survey should be extended

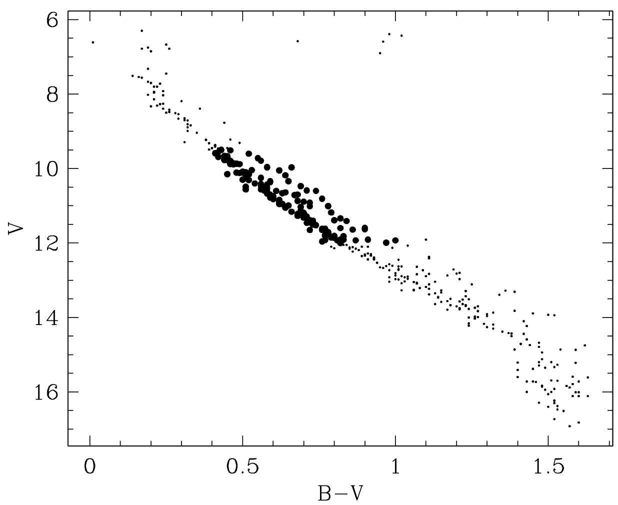

Fig. 1. Colour-magnitude diagram of Praesepe which shows the fraction of the main sequence covered by our observing program (large dots).

to main-sequence stars fainter by at least 3-4 magnitudes, which is not feasible with our instrumentation. The same is also true for the α Persei and Pleiades clusters.

2.2. Southern sample

The lists of candidate stars were more difficult to establish for the southern clusters for which the main sequence was limited to stars brighter than $V \sim 10.5$ - 11.0. The membership of dK stars was largely unknown before ROSAT observations. The samples were based on existing photometry for most clusters and search for candidates in available catalogues. NGC 6475 sample has been extended with stars selected from an unpublished proper motion study (Constantine et al. 1969).

Selection of candidates for Blanco 1 was first based on the photographic study of Abraham de Epstein & Epstein (1985) and completed with candidates selected from Platais' (1996) proper motions. According to the high success rate obtained, proper motion represents an efficient selection criterion in this cluster. The observing lists were lately up-dated to include the X-ray emission stars in NGC 6475 (Prosser et al. 1995), IC 2391 (Patten & Simond 1996) and 2602 (Randich et al. 1995). One or two observations could be secured so far for stars within the capabilities of the southern CORAVEL, to provide a second epoch to those published in the above quoted papers. Two older clusters, NGC 3680 and IC 4651, have been observed by Nordström & Andersen (Copenhagen). Result for the former have already been published (Nordström et al. 1996, 1997). The exploitation of the southern CORAVEL has been stopped. The instrument will be replaced by CORALIE, the southern twin of ELODIE (Baranne et al. 1996) which is running at OHP.

Tab. 3 - Dwarf Sample II. South

Cluster	Zone	Obs	Mem	SB	Orb	Remarks
IC 2391		30	25	7	2	
IC 2602		35	26			
NGC 6475		75	61	9		
Blanco 1		149	74	7	1	
Total		289	186	23	3	
NGC 3680		109	44	22	1	Nordström et al. (1996, 1997)
IC 4651						Nordström & Andersen

2.3. Publication status

Due to the size of the total program and the interest in determining orbital elements, such a program obviously needs quite a long time to be completed. Analysis of the observations on the Pleiades have been published for the halo (Rosvick et al. 1992a, 1992b; Mermilliod et al. 1997) and for the binaries (Mermilliod et al. 1992). The discussion of the central part (Hertzsprung area) together with that of the cluster structure is in press (Raboud & Mermilliod 1997a). Data for Praesepe's halo have been published (Mermilliod et al. 1990), as well as the analysis of three triple systems (Mermilliod et al. 1994). The discussion of the orbits of 18 spectroscopic binaries is in preparation and the analysis of the central zone (Klein-Wassink area) has been submitted (Raboud & Mermilliod 1997b).

The observations for most clusters have now been completed and I hope to be able to publish the results for the other clusters within the next two years.

CORAVEL radial velocity system is being compared with that defined by the observations made with the ELODIE spectrograph at the Haute-Provence Observatory, to check for a residual ($\sim$0.3 km/s) zero point systematic difference and a possible small colour dependence. This however does not affect the conclusions drawn from CORAVEL observations.

3. Results

3.1. New results on the Pleiades

The analysis of the structure of the Pleiades (Raboud & Mermilliod 1997a) shows that the diameter of the cluster increases with decreasing mass of the stars (Fig. 2) and confirms the importance of the corona. It also shows that the spectroscopic binaries are more centrally concentrated than single stars (Fig. 3). These two points are important to bear in mind when computing statistics on star clusters.

The mass function is depending on the size of the area investigated, because a large fraction of the faint members is located in the cluster corona. The binary frequency is strongly biaised towards the cluster center due to the existence of a clear mass segre-

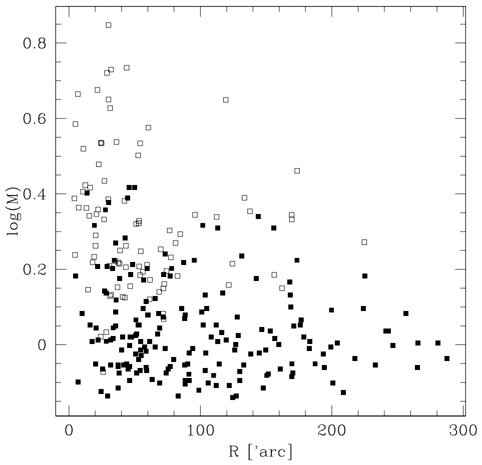

Fig. 2. Radial distribution of Pleiades stars in function of their mass. Open squares denotes binaries. There is a clear correlation between the mass and the maximum radius at a given mass.

gation effect. Therefore, one should be very cautious with results based on deep but spatially limited samples.

One interesting point, which needs to be confirmed by observations of other clusters or associations, is that the mass function of the primaries of binaries is different from that for the single stars. It has also been observed in Praesepe (Raboud & Mermilliod 1997b). It may results from the binary-star formation processes, but also from the dynamical evolution of the binaries by exchange of stars during three-body or binary-binary encounters.

3.2. Binary frequency

The binary frequency, estimated from the figures given in Table 2, is twice larger in Praesepe (29 / 85 = 34%) than in the Pleiades (14 / 98 = 15%) and in α Persei (6 / 42 = 15%). Part of the difference may be attributed to incomplete discovery of long period binaries in the Pleiades or α Persei, but it does certainly not explain the entire difference. Does it results from initial differences in binary properties or from different dynamical evolution? The Hyades (Griffin et al. 1985; Latham 1992) are also known to present a large frequency of binaries.

3.3. The (eccentricity - log period) diagram

The first result from this systematic survey has been the discovery of a well-marked cut-off period in the (eccentricity, log period) diagram. Presently 78 orbits are used to plot this diagram, including those published by Griffin and collaborators for the Hyades. This plane has been much discussed at the Bettmeralp meeting (Duquennoy et al. 1992;

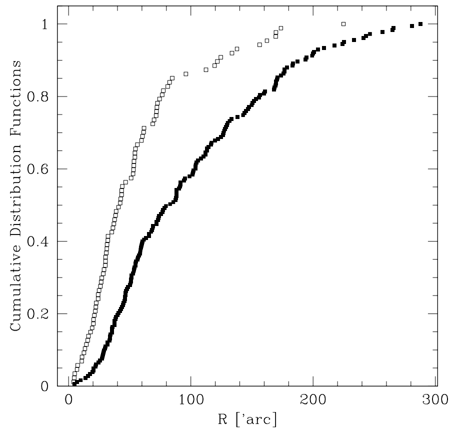

Fig. 3. Mass segregation between the spectroscopic binaries (upper curve) and the single stars (lower curve).

Mathieu et al. 1992) and the analysis will not be reproduced here. The important points are:

- Most periods shorter than P = 8 days are circular (e = 0),
- A lack of orbits with an eccentricity smaller than 0.10 for log P > 1,
- The eccentricity distribution presents a broad maximum for e $\sim$ 0.3.

From the paper of Zahn & Bouchet (1989) the cut-off period at 8 days is understood in terms of the circularization during the pre-main sequence phase. This explains why the cut-off period is nearly the same for most clusters up to the age of the Hyades. For older clusters, tidal interaction extends the circularization to binaries of longer periods, as shown by the example of M67, where the cut-off period is equal to 12.4 days, (Latham et al. 1992). The cut-off period reaches 18.7 days for the very old population of halo binaries (Torres et al. 1992).

3.4. Binaries in the colour-magnitude diagram

The results on spectroscopic binaries provide a good confirmation of the interpretation of the main sequence scatter (Fig. 4). However there is no one to one correlation between the photometric analysis of the colour magnitude diagram and the spectroscopic binary detection. Although the detection by both methods agrees in many cases, several spectroscopic binaries are not detected by photometry because the secondary is too faint to contribute significantly to the total light. However, use of red colours like R-I or V-I reveals more companions (Mermilliod et al. 1990) because the fainter secondary is usually brighter at longer wavelength. Conversely, several binaries are detected in the photometric analysis but not by spectroscopy. Infrared imaging, as obtained by Bouvier

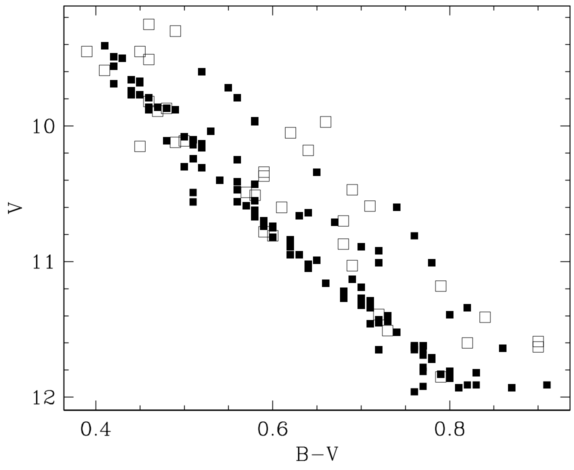

Fig. 4. Distribution along Praesepe main sequence of the spectroscopic binaries (open squares) with respect to the "single" stars (filled squares). The binary ridge at 0.75 mag above the ZAMS is well marked. The star clearly above this limit at (V = 9.97, $B - V$ = 0.66) is the triple (SB3) system KW 495 (Mermilliod et al. 1994). This diagram shows that spectroscopic binaries are located all across the main sequence band.

et al. (1997) in the Pleiades, offers a natural answer. It directly shows double systems with separations between 0.1 and 1.0 arc seconds. Therefore many systems not detected in radial velocity are simply long period binaries with amplitude below the detection threshold, which is about 3-4 km/s with our number of observations.

The photometric analysis of the colour-magnitude diagram detects only about 50% of the real binaries. This is another point that should be kept in mind in the discussion of distant clusters for which only CCD observations are available. One cannot exclude that all stars have a companion (Kroupa & Tout 1992), which is probably an excessive statement, provided the secondary is too faint for photometric detection, or too light for spectroscopic detection.

3.5. Rotation

The determination of projected rotational velocities is a by-product of radial-velocity observations. It is related to the half-width of the cross-correlation function. Due to the size of the velocity interval observed (120 km/s), the significant $V \sin i$ values are limited to rotation smaller than about 50 km/s. An extensive discussion of the rotational velocities in the Pleiades is in preparation (Queloz et al. 1997). The data obtained for the Hyades and Praesepe (Fig. 5) do not support the explanation of the difference in X-ray fluxes in terms of difference in rotation (see Barrado y Navascues et al. 1997). If any, the difference between the Hyades and Praesepe would be in the sense of a slightly larger rotation in Praesepe. This could be accounted for by the effect of $\sin i$ or larger errors in the observations of Praesepe, because the stars are about 3 mag. fainter at a given $B - V$ colour than Hyades stars. In Fig. 5, open squares denote the spectroscopic

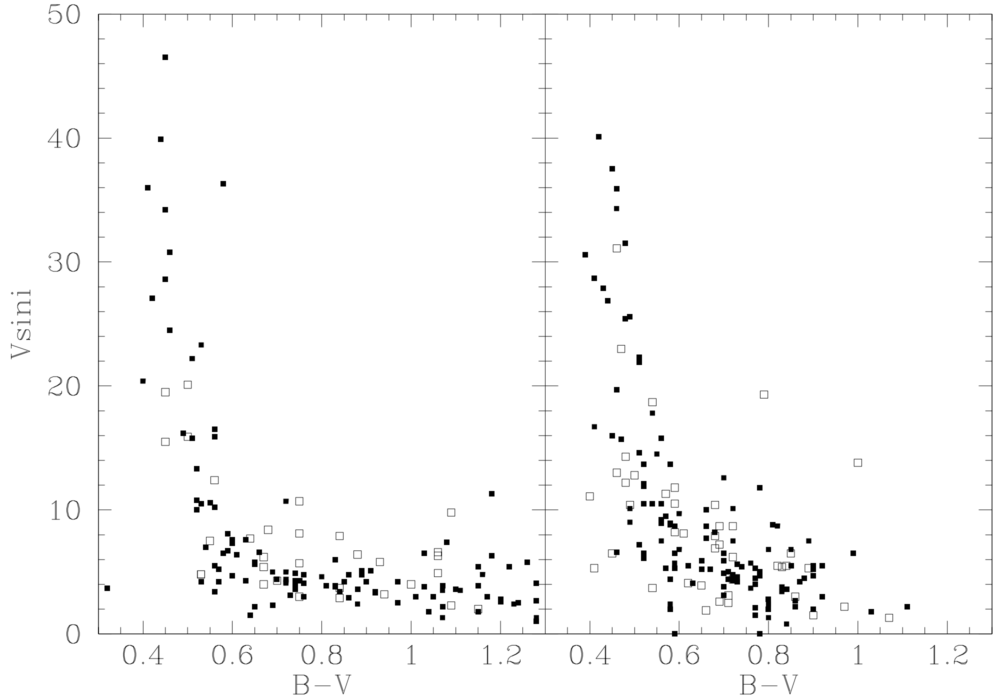

Fig. 5. Comparison of the Vsini distribution for the Hyades (left) and Praesepe (right).

binaries and filled squares, the single stars.

4. Red giants

A large observing program devoted to the study of membership and binarity of red giants in open clusters has also been undertaken. I shall give here some information on this program because the analysis of the ROSAT observations of several intermediate-age and old clusters, NGC 752 (Belloni & Verbunt 1996), NGC 6940 and IC 4651 (Tagliaferri & Belloni 1997) and M67 (Belloni et al. 1993), has shown that several sources identified in these clusters were red giant binary members. A first discussion of the material has been presented at the Bettmeralp workshop (Mermilliod & Mayor 1992).

4.1. The sample

A large sample of ∼1200 stars in about 180 open clusters has been observed from OHP and La Silla in the same conditions as the dwarfs were. The limiting magnitudes are B = 13. at OHP and B = 15. at La Silla. This sample represents now about 30% of the red giants in cluster fields known from photometric studies, most others are fainter than these limits. Systematic surveys have also been done in NGC 188 and 7789 at Victoria. An orbit is presently known for 100 red giants:

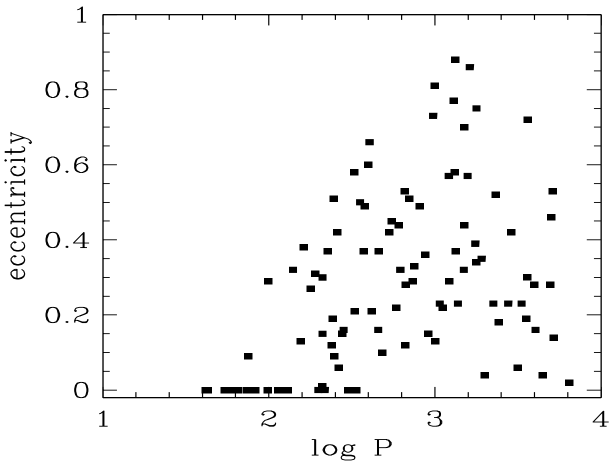

Fig. 6. (e, log P) diagram for 100 spectroscopic binaries with a red giant primary in open clusters.

- 87 orbits from CORAVEL,
- 9 orbits in M67 (Mathieu et al. 1990),
- 2 orbits in NGC 6705 (Lee et al. 1989),
- 1 orbit in the Hyades (Griffin & Gunn 1977),
- 1 orbit in Coma Ber (VinterHansen 1940).

Two papers (Papers II and VI) have been devoted to the discussion of twenty orbits (Mermilliod et al. 1989; Mermilliod et al. 1997), but 30 other orbits have been published within the discussion of the parent clusters. References to first papers of this series may be found starting from Paper VII (Mermilliod et al. 1997).

The first result has been the (e, log P) plot (Fig. 6) which shows also a clear separation between circular and eccentric orbits. This version is based on 100 orbits. Mermilliod & Mayor (1996) have shown that the cut-off period depends on the red-giant primary masses which govern the size of the Roche lobe at the red giant tip. This size defines the longest period at which a spectroscopic binary will still get in contact and hence follow a different evolution. The theoretical estimate, computed for a mass ratio q = 0.9, agrees rather well with the observed points.

No periods shorter than 40 days have been observed. This limit is again related to the radius of the star at the red giant tip and is in good agreement with the predictions made from evolutionary models. The smallest radius is observed for 2 $M_\odot$ stars which have the shortest path on the ascending giant branch. This limit also means that all main sequence stars with periods shorter than 40 days will get in contact during their evolution off the main sequence. Because of this situation, the estimation of the ratio of the number of red giants to main sequence stars is strongly influenced by this loss, which depends on the binary properties of the cluster.

5. Conclusion

The CORAVEL survey of dwarf stars in nearby open clusters resulted in the determination of orbital elements for 55 spectroscopic binaries and of rotational velocities. Main results have been briefly presented in this paper. Improvements to the present data can be made by extending the systematic survey to fainter stars, including the halo stars, which cannot be made with the telescopes used for this work because we have reached the very limits of the instruments. Systematic IR imaging would be important to find double stars that cannot be detected with radial velocities because of their too large separation. High precision radial-velocity surveys would also be very important to discover lower mass companions (down to brown dwarfs or giant planets) and improve the mass-ratio distribution for values of $q \leq 0.3$.

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