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High-mass binaries in the very young open cluster NGC 6231

Implication for cluster and star formation

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Abstract. New radial-velocity observations of 37 O- and B stars in the very young open cluster NGC 6231 confirm the high frequency of short-period spectroscopic binaries on the upper main sequence. Among the 14 O-type stars, covering all luminosity classes from dwarfs to supergiants, 8 are definitively double-lined systems and all periods but one are shorter than 7 days. Several additional binaries have been detected among the early B-type stars. NGC 6231 is an exceptional cluster to constrain the scenarios of cluster- and binary-star formation over a large range of stellar masses. We discuss the evidences, based on NGC 6231 and 21 other clusters, with a total of 120 O-type stars, for a clear dichotomy in the multiplicity rate and structure of very young open clusters containing O-type stars in function of the number of massive stars. However, we cannot answer the question whether the observed characteristics result from the formation processes or from the early dynamical evolution.

Key words. galaxies: open clusters and associations: NGC 6231 – stars: binaries: spectroscopic – stars: early-type – stars: rotation

1. Introduction

Binary properties of newly formed stars in various aggregates and nearby star-forming regions have been subjected to much observing efforts in the recent years, but most of them were devoted to the study of solar-type stars. The results have been summarized by Duchêne (1999) and Mathieu et al. (1999). The binary frequency appears to be larger in loose aggregates, like Taurus-Auriga, than in high density regions, like the Orion Trapezium. However, most regions studied offer little information on the duplicity of massive stars.

Surveys of O-type stars (Gies 1987; Mason et al. 1998) have shown that the binary frequency and multiplicity are higher in open clusters and associations than in the field. If one takes also into account spectroscopic studies, we have strong observational evidences that O-type stars in open clusters are very frequently found in binary or multiple systems.

There are however few clusters close enough to allow a deep investigation of the duplicity along the main sequence from O- to solar-type objects. NGC 6231 ($\alpha_{2000} = 16^{\rm h}54\overset{\rm m}{.}2$, $\delta_{2000} = -41°48'$), in the southern part of the association Sco OB1, is certainly one of the best clusters to study the results of a fully completed star-formation process. It contains a dozen O9 stars (Garrison & Schild 1979; Levato & Malaroda 1980), many of them being double-lined binaries. The first radial velocities for 20 stars were obtained by Struve (1944), who detected six spectroscopic binaries. Orbits for 6 of them, with surprisingly short periods, had been already determined in 1974 by Hill et al. (1974), hereafter referred to as HCB. Levato & Morrell (1983), hereafter referred to as LM83, obtained further radial velocities and presented new orbital elements for 6 systems. Perry et al. (1990), hereafter referred to as PHYB, obtained 3 observations at 120 Å mm^{-1} for stars brighter than $V = 10.2$. Stickland et al. (1996, 1997) published orbital elements for two stars based on IUE spectra. Finally, Raboud (1996) investigated 53 B-type stars and also concluded that the binary frequency is larger than 50%.

NGC 6231 seems to be one of the best candidate to study directly the global products of cloud-fragmentation and star-formation processes along the main sequence in

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spite of its distance, 1800 pc (Raboud et al. 1997). On the basis of photometric CCD observations, Sung et al. (1998) and Baume et al. (1998) examined the evidence for the presence of a population of pre-main-sequence stars, which should exist due to the cluster young age, and determined the initial mass function.

The long-term goal of this study is to provide reliable data to define the characteristics of the duplicity of the O- and B-type stars in a very young open cluster just emerged from its nebulosity, namely the duplicity rate, the orbital-period- and $V \sin i$ distributions to constrain models of cluster and (binary) star formation.

2. Observations

2.1. The sample

We have undertaken a high-resolution optical spectroscopic survey of the upper main sequence stars brighter than $V = 10$ for which only low- or medium-dispersion spectra (120–40 Å mm^{-1}), or only one radial-velocity value, are available in the literature. We also selected several spectroscopic binaries (SB1 and SB2) to improve the orbital elements. The final programme contains a total of 37 stars, including 9 candidate members in the cluster outer part proposed by Raboud et al. (1997).

2.2. High dispersion spectra

The programme stars were observed at CASLEO in the optical region, between λ 3750 Å, and λ 4861 Å, at the 2.1 m telescope, equipped with a REOSC echelle spectrograph[1] with a CCD TEK 1024 × 1024 detector. We have used a grating of 400 grooves mm^{-1} as a cross disperser. This instrumental configuration gives a 2 pixel resolution of 0.30 Å. In this configuration, the echelle spectrograms cover a useful wavelength range of about 1500 Å, with a resolving power of ∼14 000. A total of 113 spectrograms for the 37 programme stars, were obtained between 1995 and 1999. Most spectra present a S/N ratio between 50 and 80 for typical exposure time of 30 min.

We have obtained the usual series of bias and flat-field frames to carry out the reduction of the images. A Th-Ar lamp was used for wavelength calibration. The pixel-to-pixel variations were removed by flat-field division and the spectra were extracted, wavelength calibrated, normalized and measured using IRAF[2] routines from version 2.10.

We also obtained spectra for standard stars from Fekel (1985, 1991) to establish the zero point correction for our observations, which we find to be negligible.

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[2] IRAF is ditributed by the National Optical Observatories which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

2.3. Heliocentric radial velocities in NGC 6231

We have measured the radial velocities for the program stars by fitting Gaussians, using splot routine in IRAF.

Mean values are presented in Table 1, described below (see Sect. 2.6) and individual observations are listed in Table 2. The latter table gives successively the identification in the system of Col. 2 in Table 1 the heliocentric Julian Day, the heliocentric radial velocities, the probable error, number of lines measured. On several occasions, line doubling was observed and radial velocities for both components are tabulated. The radial velocity of the primary component is given first.

2.4. Spectral types

We have estimated spectral types for 11 program stars lacking MK classification in the literature, using the cluster members with known spectral types as comparison, to complete the description of this sample.

2.5. Axial rotation

In order to have approximate values for the projected axial rotational velocities, we have measured on the spectra of the stars with rotational velocities published by LM83, the FWHM of the spectral lines usualy taken into account for this type of study, namely HeI λ 4026 and HeI λ 4471, and we have used the average values to obtain the coefficients of a linear regression ($V \sin i$ vs. FWHM). From these data, we have obtained new $V \sin i$ values for the program stars of luminosity classes III, IV, and V and not earlier than O9. For supergiant stars or stars of earlier spectral types, the broadening of the spectral lines is modified by turbulence. In the cases of the stars S290 and 501, we have assigned a probable value of projected rotational velocity based on the width of the HeI lines, to give an estimate of their behaviour; the first star shows broadened lines, while star 501 presents very narrow profiles. We have transformed all data to the new Sletteback system (Slettebak et al. 1975) using García & Levato (1984) calibration.

2.6. Results

Table 1 lists fundamental photometric and spectroscopic data for the stars brighter than $V = 10.40$ ($V_0 < 9.00$) in NGC 6231. The identifications are given in the first three columns: (1) the HD/CoD numbers, (2) numbers <295 are from Seggewiss (1968) and those >501 from Raboud (1996), and (3) numbers from Sung et al. (1998). Numbers larger than 853 are an extension of their numbering for the brightest stars they did not observe, as displayed in the WEBDA[3] database. The next two columns reproduce the V_0 magnitudes (4) and X colour indices (5) in the Geneva photometry from Raboud et al. (1997). Then we

[3] `http://obswww.unige.ch/webda/`

tabulate the $V \sin i$ data (6) and their sources (7). Reference 1 corresponds to this paper, Ref. 3, to LM83, Ref. 8, to Buscombe (1969), Ref. 9 to Conti & Ebbets (1977), and Ref. 10 corresponds to Killian et al. (1994). The mean radial velocities from our observations, the uncertainties and the number of spectra obtained are given in the next three Cols. (8–10). Published and new spectral types are given as well as the sources (11–12). Reference 1 corresponds to our estimates, while Ref. 2 corresponds to Levato & Malaroda (1980), Ref. 4 to Sahade (1958), Ref. 5 to Schild et al. (1971), Ref. 6 to PHYB, and Ref. 7 corresponds to Garrison & Schild (1979). Column (13) gives the magnitude differences between the star V magnitude and the magnitude on the ZAMS at the star colour. This quantity measures the vertical displacment above the ZAMS. Finally, notes describe the binary characteristics (14).

No radial velocities have been given for S28, S110, S266, S286, S253, and S312 because they are double-lined systems or binaries with large amplitudes which makes mean values meaningless.

Details about the cluster or the star members and bibliographic information can be obtained from the WEBDA open cluster database, including a map of the cluster.

3. Discussion of the individual stars

3.1. Constant radial-velocity objects

Among the members of NGC 6231 observed in the present study, twelve stars show probably constant radial velocities. However this assertion is only preliminary for S248, #723, 726, and 749, because we could obtained only one observation per star. We nevertheless note that they fall close to the mean cluster velocity.

S238 (V964 Sco) a β Cep variable, (Balona & Engelbrecht 1985). The four radial velocities obtained by LM83 varies by 20 km^{-1} over four days, but ours were constant over the same range. S238 appears as a single star in the colour-magnitude diagram.

S248. The radial velocities of PHYB and our observation favour a constant radial velocity with a mean value of $< V_{\rm r} > = -33$ km s^{-1}. This star appears to be single from the photometric analysis. Therefore, radial velocity and photometry leads to the conclusion that S248 is single.

S292 appears to be single both for the spectroscopy and the photometry. For comparison purposes, Fig. 8 shows the normalized CCD spectra, around the H_γ line, as a template of a single, slow-rotating star, which can be compared to other non-symetric line profiles.

S293 This is a O9 Ib CNO star, which has probably constant radial velocity (Levato et al. 1988). We did not reobserve it.

S309 The V magnitude published by Raboud et al. (1997) has been replaced by that of Sung et al. (1998) who resolved S309 into two components (350 + 351, with magnitudes equal to 8.72 and 9.90 respectively). Star 350 is still 0.32 mag above the ZAMS although its radial velocity seems to be constant.

S343, The observations of PHYB, LM83, and ours are constant. The star is however 0.2 mag above the ZAMS.

The stars 723, 726 and 749 were observed for the first time in the present study, and the radial velocities, although based on one observation, support their membership to the cluster.

Moreover, stars 501, 724, 774 and 810 were also observed spectroscopically in the present work by the first time. The mean radial velocities are presented in Table 1.

3.2. Probable single-lined spectroscopic binaries

S6. Our three radial velocities suggest that S6 is a spectroscopic binary. Furthermore, they differ by 30 km s^{-1} from those obtained by PHYB. The star is 0.25 mag above the ZAMS.

S34. This star raises a problem because it appears to be single in the CM diagram, but the line profiles are probably asymetric, as show by Figs. 9 and 10, which would indicate the presence of a companion. In any case, the radial velocity is variable. We assume that the variability is due to the binary nature rather than to line intrinsic variability.

S70. PHYB found a velocity dispersion of 42 km s^{-1} and a mean velocity $< V_{\rm r} > = -26$ km s^{-1}. This scatter may be due to the possible binary nature, which is supported by our observation, 20 km s^{-1} more negative. However, S70 appears to be single from the photometry.

S80. PHYB found $\Delta V = 25$ km s^{-1}, with a $< V_{\rm r} > = -26$ km s^{-1}. Our velocity is 10 km s^{-1} more negative. The stars is about 0.25 mag above the ZAMS. It could be a long period binary.

S150 (V920 Sco), a β Cep variable, (Balona 1983) appears to be 0.3 mag above the ZAMS. The scatter observed by LM83 and the fact that our mean velocity is 10 km s^{-1} more negative than the cluster velocity lead us to conclude that S150 is also a probable binary.

S272 From three observations, Levato & Morell (1983) concluded that this star is a spectroscopic binary. This suspicion is confirmed by the position of S272 in the colour magnitude diagram, about 0.65 mag above the ZAMS. Further observations are required and will be obtained.

3.3. Confirmed single-lined spectroscopic binaries

S232. Proposed as a long-period variable by Balona (1983), this star is in fact an eclipsing binary (Balona & Engelbrecht 1985). Our observations confirm the duplicity suspected from the data from LM83. It is about 0.55 mag above the ZAMS and should be detected as a double-lined binary. S232 ($V = 9.65$, $B - V = +0.23$) is a good candidate to derive a mass for a B0.5V star.

Table 1. Fundamental data for stars brighter than $V_0 = 9.0$ ($V < 10.5$) in NGC 6231

HD/CD (1)	S (2)	Sung (3)	V_0 (4)	X (5)	$V \sin i$ (6)	Ref (7)	$\overline{V_r}$ (8)	ϵ (9)	N (10)	Sp.T. (11)	Ref (12)	Phot (13)	Notes (14)
152234	290	855	3.72	0.02	150	8	−37.5	2.9	37	B0 Iab	2	—	SB2O
152248	291	856	4.58	0.00	100+80	1	−26.6	3.8	8	O7 Ib:(f) + O6.5:((f))	2	—	SB2O, EB
152249	293	857	4.78	−0.00	105	9				O9 Ib	2	—	
152233	306	858	5.08	−0.00	130	9	−30.5	1.1	4	O6 III (f)	2	—	SB1
152270	220	854	5.11	−0.02						WC6 + O	4	—	SB2O
326331	338	571	5.76	0.01						O8 III	2	—	SB2O, M?
152218	2	853	6.00	0.04	140	3	−28.9	2.8	7	O9 IV	2	0.75	SB2O
152219	254	234	6.08	0.05	160	3	−26.3	4.3	8	O9.5 III	2	0.75	SB2O
152314	161	615	6.23	0.08	65	3	−21.5	5.8	3	O8.5 III	2	1.19	SB2, triple?
−41.11037	323	862	6.29	0.04	55	3				O9 III	2	0.52	SB1O
−41.11042	224	505	6.51	0.07	130	3	−17.6	6.8	8	O9 IV	2	0.75	SB2O
−41.11029	309	350	6.91	0.09	160	1	−32.9	1.3	2	O9.5 V	1	0.32	
152200	266	206	6.97	0.06	210	3			5	O9.5 V(n)	2	0.00	SB2
326329	292	434	7.20	0.07	85	3	−45.2	5.5	3	O9.5 V	2	0.00	
		314	7.39										
	248	288	7.63	0.10	76	10	−36.1	1.8	1	B1 V	2	0.00	
	287	403	7.80	0.27	< 40	3	−70.2	1.6	1	B1 V	2	1.05	SB1
326332	343	651	7.90	0.14	32	10	−23.5	2.3	2	B1 III	1	0.24	
326327	28	113	7.94	0.16	150	3			2	B1.5 IVe+shell	2	0.33	SB2, triple?
	232	521	7.95	0.20	50	3	−70.8	4.9	3	B0.5 V	2	0.57	SB1, EB
	286	378	8.01	0.24	70	3			2	B0.5 V	2	0.69	SB2
326339	73	497	8.01	0.38						B0.5 III	6		
326333	150	712	8.02	0.17	150	3	−47.1	2.8	2	B1 V(n)	2	0.31	
326330	238	486	8.06	0.13	210	3	−29.8	0.7	2	B1 V(n)	2	0.00	
V945 Sco	253	226	8.07	0.18	100+100	3			1	B1: V + B1: V	2	0.33	SB2
−41.11048	295	349	8.07	0.24	80	3	−24.7	1.6	6	B1 V	2	0.64	SB1
−41.11032	289	353	8.08	0.15	80	3	−38.7	3.9	7	B0.5 V	2	0.12	SB1
		351	8.08										
−41.11056	110	653	8.10	0.15	190	1			2	B1 V	5	0.10	SB2
		578	8.14										
−41.11030	272	334	8.15	0.21	98	10				B1 V	2	0.42	SB1
326340	70	374	8.16	0.15	100	1	−48.8	4.9	1	B0.5 V	6	0.00	
	374	400	8.19	0.40									
	282	268	8.32	0.28	80+80	3				B2 V: + B2 V:	2	0.55	SB2
V963 Sco	80	437	8.36	0.21	170	1	−37.3	4.3	1	B0 Vn	1	0.20	
−41.11031	6	364	8.38	0.22	110	10	−22.1	5.3	3	B0 V	6	0.23	
	112	684	8.46	0.19						B1 V	5		
	312	346	8.58	0.26	<40	1	−13.6	5.1	3	B0 III	1	0.19	SB1
	330	456	8.59	0.31									
326328	34	157	8.69	0.24	120	1	−45.9	3.9	2	B1.5 V	5	0.00	SB2?
−41.11028	261	303	8.76	0.27	140	1	−32.4	3.4	1	B2 IV	6	0.07	SB:
	294	461	8.90	0.46						B1.5 V	7		
152235	501		3.10	0.06	< 40	1	−27.5	0.6	2	B1 Ia	1	—	
	723		8.88	0.52	< 40	1	−39.3	3.2	1	B3: V	1	1.29	NM?
−41.10989	724		8.52	0.26	80	1	−21.5	2.5	2	B0: IV/V	1	0.30	
−41.10990	726		8.57	0.30	90	1	−31.6	2.6	1	B1 V	1	0.40	
	745		8.26	0.24	135	1	+61.1	6.4	1	B0 V	1	0.45	SB?
	749		8.55	0.30	160	1	−38.7	3.1	1	B1.5 V	1	0.40	
−41.11051	769		7.28	0.15	145	1	−17.4	17.4	2	B0.5 V	1	0.90	SB
−41.11058	774		8.38	0.23	< 40	1	−32.2	0.4	2	B1: II/III	1	0.30	
−41.11062	810		6.95	0.19	65	1	−26.7	3.6	2	B2 V	1	1.57	NM?

S261. V946 Sco, a β Cephei variable (Balona 1983). This object was observed by PHYB and Raboud (1996); for the first authors the average of the radial velocity is -9 km s^{-1}, and for Raboud, the same value (-10 km s^{-1}), but with a dispersion of 29 km s^{-1}. Raboud proposed that this star is a spectroscopic binary. In the present study, we

Table 2. Heliocentric radial velocities in NGC 6231

S	HJD -2400000	$< RV >$ [km s^{-1}]	pe [kms^{-1}]	n
2	49910.730	−49.6	3.1	13
	49912.537	+80.3	15	6
	49914.473	−141.5	5.1	15
		+137.9	4.7	7
	49915.519	−105.1	4.3	20
	50594.809	−19.1	2.2	20
	50597.512	+16.5	4.6	12
	50598.866	−165.9	4.1	18
		+156.9	4.3	14
6	50594.794	−36.4	3.0	15
	50597.549	−20.4	2.3	15
	51361.772	−10.7	3.0	12
28	50595.694	−46.4	4.1	14
		−126.1	2.4	4
	50597.679	−29.6	3.7	13
		−115.7	3.2	6
34	50593.667	−41.4	2.7	11
	50597.665	−58.4	4.5	11
70	50598.660	−48.8	4.9	12
80	50598.622	−37.3	4.3	8
110	50595.853	−26.1	6.8	10
		−170.1	13:	6
	50597.871	−33.0	4.3	8
150	50595.760	−42.5	6.8	9
	50599.594	−49.7	5.1	8
161	50593.805	−31.5	1.6	21
		−137.7:	13	4
	50597.842	−37.6	2.7	24
	51300.738	−11.2	1.3	21
224	49912.743	+36.5	3.6	9
	49914.521	+127.5	3.2	15
	49915.538	−127.8	4.1	17
		+145.5	4.6	10
	49967.537	−94.8	4.0	22
	50594.680	+6.6	4.3	18
	50595.726	−129.2	6.0	12
		+193.0	7.8	11
	50597.827	−162.8	5.3	11
		+195.9	10:	2
	50598.811	+115.8	4.9	16
232	50594.751	−80.5	2.3	15
	50599.649	−65.8	2.1	17
	51362.593	−61.3	3.7	12
238	50594.696	−29.1	3.8	8
	50598.743	−30.5	3.1	12
248	50593.628	−36.14	1.8	21
253	50595.551	−108.9	7.5	10
		+164.7	9.1	8

Table 2. continued

Num. Id.	HJD -2400000	$< RV >$ [km s^{-1}]	pe [kms^{-1}]	n
254	49910.751	−61.6	4.9	12
	49912.721	+45.5	3.9	12
	49914.499	−132.9	4.5	18
	49915.513	+14.9	3.6	17
	50593.600	−145.2	3.9	16
		+218.0	9.2	6
	50595.536	+78.9	7.6	14
		−251.5	15	2
	50597.900	−149.9	5.2	14
		+187.2		2
	50598.792	−51.2	2.6	15
261	50599.677	−32.4	3.4	11
266	49914.565	−28.5	3.1	14
	49915.557	+62.9	4.6	18
		−124.6	6.9	15
	49967.551	−0.8	3.9	11
	50595.825	+4.1	2.8	13
		−110.6	7.4	4
	50597.639	−26.9	5.0	15
286	50593.817	−11.2	2.3	16
		−100.7	2.8	3
	50597.588	+7.5	3.0	20
		−119.9	7.5	3
287	50593.853	−70.2	1.6	18
289	49914.671	−59.8	4.4	6
	49915.611	−34.7	2.1	17
	49966.517	−33.8	3.8	11
	49967.517	−62.3	4.0	12
	50594.578	−38.2	3.7	23
	50597.615	−38.2	3.1	14
	50598.829	−26.8	3.1	13
290	49910.695	−61.9	2.2	20
	49912.501	−86.0	2.5	25
	49914.074	−69.0	2.6	22
	50593.576	+13.5	2.3	23
		−116.8	10.3:	8
	50594.549	+18.0	1.2	30
		−142.6	7.3	19
	50595.508	+23.21	2.9	20
		−145.9	8.5	11
	50597.577	+13.25	1.7	25
		−130.2	9.9	7
	51361.731	−14.0	1.3	24
		−176.6	16.2	4
	51362.545	+0.5	1.3	31
		−166.7	9.7	10

have only one measure of this star (-32.4 km s^{-1}), but it differs from the previous observations by 20 km s^{-1}, and we conclude that S261 is a binary, although it appears to be single in the CM diagram.

S287. Our observation $V_{\rm r} = -70$ km s^{-1} differs by 50 km s^{-1} from the values published by LM83 and Raboud (1996). Photometrically, it appears as a triple system, 0.25 mag above the binary ridge. We conclude that this star is another binary or multiple member of the cluster.

S289. LM83 found, from four spectrograms, a radial-velocity range of 60 km s^{-1}. We found, based on seven spectrograms $\Delta v = 40$ km s^{-1}. S289 is obviously a spectroscopic binary which also appears as a single star in the CM diagram. We have obtained a preliminary period of 8.863 days for this star (see Table 3, and Fig. 1 - Sung 353).

Table 2. continued

Num. Id.	HJD -2400000	$< RV >$ [km s^{-1}]	pe [kms^{-1}]	n
291	49910.715	+114.2	6.8	6
		−154.9	5.6	3
	49912.514	−97.6	7.5	10
	49914.463	−230.5	4.6	13
		+188.5	6.5	11
	50593.591	−183.4	3.7	11
		+144.9	3.5	12
	50594.565	−44.7	2.8	17
		−147.7	17.1	5
	50595.519	+121.4	4.3	10
		−174.2	7.7	5
	50598.518	−225.9	5.3	12
		+165.2	3.3	12
	51362.568	−49.2	5.0	12
292	50594.622	−34.4	2.8	20
	51300.812	−59.6	4.4	15
	51301.767	−47.8	2.0	17
295	49914.624	−30.6	1.9	19
	49915.576	−28.4	1.4	18
	49966.578	−23.9	1.8	20
	49967.579	−101.2	6.7	11
	50594.638	−31.5	1.8	27
	51301.809	−20.6	1.1	24
306	50594.556	−52.9	2.6	24
	51300.728	−43.7	2.3	14
	51361.745	−45.7	2.3	20
	51362.557	−45.5	2.3	17
309	50594.665	−26.8	4.5	14
	51300.783	−33.0	2.4	11
312	50597.522	−7.2	2.1	23
	50599.693	−0.8	1.6	19
	51362.646	−21.5	1.1	19
343	50595.807	−21.0	2.4	16
	50599.621	−25.9	2.0	21
501	50593.874	−28.3	1.4	23
	50597.706	−25.9	2.0	25
723	50595.606	−39.3	3.2	10
724	50595.643	−25.6	4.7	8
	50598.540	−19.2	3.5	7
726	50599.815	−31.6	2.6	12
745	50594.836	+61.1	6.4	9
749	50599.722	−38.7	3.1	14
769	50594.890	+2.7	2.1	13
	50597.758	−71.3	3.4	13
774	50597.808	−31.8	1.5	19
	50599.849	−33.9	3.1	18
810	50597.719	−31.6	3.2	14
	50598.690	−30.1	2.1	15

S295. Levato & Morrell detected a variable-radial velocity. Our spectra allow us to confirm this behaviour, although we are not able to derive orbital elements for this star. It is about 0.65 mag above the ZAMS and should be seen as a double-lined binary.

S306. HD 152233 is a blue straggler (Mermilliod 1982) and a proposed variable star (Balona 1992). Fullerton (1991) reports small radial-velocity shifts and Fullerton et al. (1996) included this object in their O-type star sample for the study of the absorption-line profile variations. These authors found −13.7, −19.9 and −27.4 km s^{-1} for the radial velocity of CIV λ5801, CIV λ5812, and HeI λ5876, respectively, observed between the JD 2446605.5 and 2446611.5. Although their data seem to be constant, their mean RV differs from the mean cluster velocity. From all published data, the star is definitely a binary and we determined a preliminary orbit (Fig. 1f), with a period of $4\overset{\mathrm{d}}{.}15$. Further observations are needed to confirm the period.

S312. This star is another SB1 system. There are some evidence of a second component, but no definitive conclusion can be derived from our spectrograms. It is 0.20 mag above the ZAMS and hence probably a binary.

R745. We have only one spectrum for this star, but the radial velocity (+61 km s^{-1}) suggests that it is a spectroscopic binary, because its photometry and spectral classification favour its membership. It is located 0.5 mag above the ZAMS, and should be a binary, if member.

3.3.1. Probable double-lined spectroscopic binaries

The stars 28, 110, 161, 253, 266, and 286 present the following characteristics in their spectra:

S28. This is V692 Sco a β Cep variable (Balona & Engelbrecht 1985). LM83 suspected the binary nature of this object. The line profile (Fig. 12) shows the presence of a broad secondary component on the left wing of the H_β line. Both spectra show the same feature. Because the velocity of the main component is close to the cluster velocity, this star should be triple. In the CM diagram, S28 is 0.3 mag above the ZAMS.

S110 This is V497 Sco, another β Cep variable star, (Balona 1983). On JD 2450595.694, we see a secondary component in the middle of the left wing. Figure 13 shows the H_β line profiles on each spectrum. The upper profile is symetric, while the lower one clearly contains a secondary component. Figure 14, plotted with a different scale, enhances the asymetry of the profile. The star is located very close to the ZAMS, which raises a problem. The velocity of the main component is close to the cluster mean velocity.

S161. Feinstein & Ferrer (1968) found that this star is variable in luminosity and Raboud et al. (1997) obtained a period of about 20 years, with a peak to peak amplitude larger than 0.1 mag. Based on the four radial velocities obtained by LM83 and our three observations, this star is clearly a binary, but the period is much shorter than 20 years. On JD 2450593.805, we detected a probable secondary spectrum on the left wing (Fig. 15). More observations are needed in order to confirm this finding. Photometrically, S161 is also clearly double, and could even be a triple system. The rather slow rotation ($V \sin i$ = 65 km s^{-1}) cannot explain the position above the binary ridge.

S253. This star was classified as SB2 by Levato & Malaroda (1980). LM83 confirmed the SB2 character, but

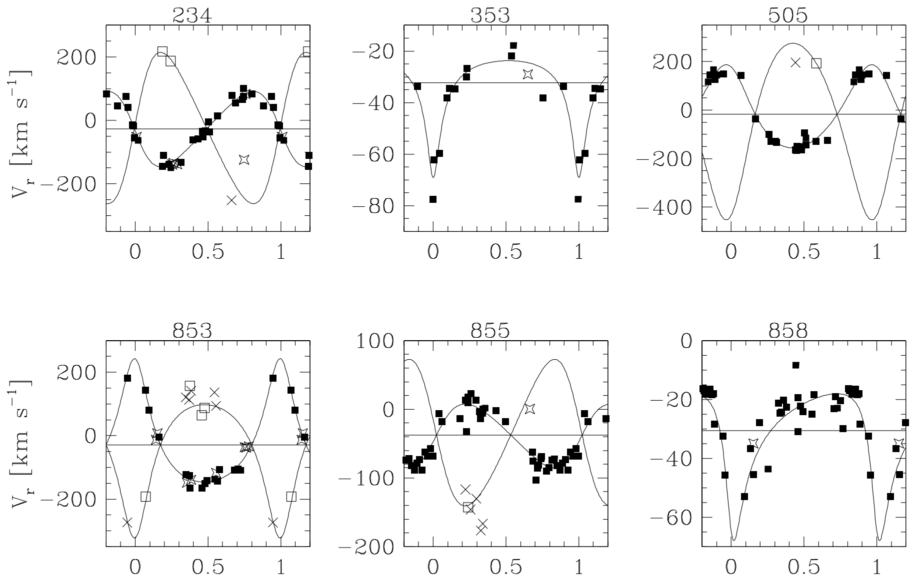

Fig. 1. Radial velocity curves for 6 spectroscopic binary systems in NGC 6231. Primary observations are indicated by filled squares, secondary, by open squares, points rejected from the solutions by diamonds or crosses

measured the velocity of the primary only. On our spectrogram, the presence of both component is evident as shown by Fig. 16. The star is 0.3 mag above the ZAMS and hence obviously double.

S266. LM83 found it to be a single-lined spectroscopic binary. On two among five spectra, we detected double lines (Fig. 17). Proposed as variable star by Feinstein & Ferrer (1968) with a range of 0.07 mag, this star appears to be single in the CM diagram.

S286. The radial-velocity difference between the observations of LM83 and later data obtained by Raboud (1996), $\Delta V_{\rm r} = 30$ km s^{-1} indicates that this star is a binary. On both of our spectra, the lines are double, as is exemplified by Fig. 18 for the HeI λ 4471 line profiles. This is in good agreement with the position in the CM diagram, about 0.7 mag above the ZAMS.

323. This star has not been reobserved. Orbital elements have been determined by HCB, and revised by LM83. The period is $P = 5\overset{\rm d}{.}74$.

R769. The radial-velocity difference between our two spectrograms amounts to $\Delta V_{\rm r} = 74$ km s^{-1} and this star is definitely a spectroscopic binary. As is shown by Fig. 11 the profiles of the Hγ line are clearly asymetric, which is probably due to the presence of the secondary. It is an obvious PHB, 0.75 mag above the ZAMS.

It is very important to note, that we have only one or two spectra for several stars of our sample. For this reason, it will be necessary to obtain additional observations to confirm our conclusions.

3.3.2. Double-lined systems with calculated orbits

The stars 2, 224, 254, 290 and 291 present well defined double-lined spectra. For these stars we have improved the periods, and estimated new orbital elements, using the code developed by Imbert at the Marseille Observatory and routinely used at the Geneva Observatory in the Coravel group.

S2 - HD 152218, O9IV This star was proposed as binary by Struve (1944). The first period obtained by HCB, was $P = 5.4$ days. LM83 proposed $P = 5\overset{\rm d}{.}5009 \pm .0003$. Stickland et al. (1997) determined a period of $P = 5\overset{\rm d}{.}6040$ by combining optical and IUE radial velocities. The combined optical observations favor a period of $4\overset{\rm d}{.}8925$. The orbital curve for all optical and IUE data for $P = 5\overset{\rm d}{.}604$ does match well all observations. The IUE observations better cover the whole cycle and better constrain the eccentricity. We give the optical period in Table 3, the RV curve is plotted in Fig. 1c. The H$_\delta$ line profiles at three different phases demonstrate the line doubling (Fig. 2).

S220 - HD 152270, WC6 + O has not been reobserved because good orbital elements have been obtained by Seggewiss (1974), with a period of $P = 8\overset{\rm d}{.}89$.

S224 - CPD $-41°7742$, O9IV The orbital elements for this star were first estimated by HCB, and by LM83. We obtained eight new observations and recomputed the orbital elements (Fig. 1b). We confirm the short period but find a higher eccentricity. Figure 3 presents the variation of the H$_\delta$ line profiles at three different phases. The secondary component is best visible on the right wing of the upper spectrum ($\phi = 0.356$). The position is the CM diagram indicates a location close to the binary ridge.

S254 - HD 152219, O9.5III Orbital elements have been published by HCB and by LM83. Our period, based on all published data and our eight additional observations is shorter by $0\overset{\rm d}{.}10$ (Fig. 1a). The presence of the secondary is seen on the line profile at phase $\phi = 0.599$ (Fig. 4, lower spectrum) and produces the enhancement of the line width. Located close to S2, this star is clearly double from the photometry.

Table 3. New orbital elements

	234 S254	353 S289	505 S224	853 S2	855 S290	856 S291	858 S306
P [d]	4.069597	8.86331	2.453087	4.892552	54.4605	5.753336	4.149995
	0.000034	0.00067	0.000012	0.000010	0.0045	0.000027	0.000030
T_0 [HJD]	4997.14	4995.19	4998.801	4995.055	5135.	4994.86	4995.828
	0.13	0.66	0.095	0.001	11.	0.20	0.081
V_0 [km s^{-1}]	−26.3	−32.3	−17.54	−28.9	−37.5	−26.6	−30.53
	4.3	2.9	6.8	2.8	2.9	3.8	1.1
e	0.218	0.62	0.205	0.398	0.183	0.133	0.57
	0.060	0.14	0.053	0.005	0.093	0.028	(fixed).
ω [°]	93.	180.	18.	4.3	259.	158.	150.0
	12.	27.	15.	0.2	78.	12.	9.0
K_1 [km s^{-1}]	118.5	22.7	171.	194.7	46.5	199.1	24.9
	7.4	3.7	11.	7.9	2.8	7.0	3.2
K_2 [km s^{-1}]	238.		364.	211.5	107.	208.0	
	22.		59.	6.1	22.	6.9	
a_1 sin$i$ [Gm]	6.47	2.16	5.665	12.01	34.2	15.61	1.16
	0.49	0.58	0.065	0.51	2.7	0.61	0.15
a_2 sin$i$ [Gm]	13.0		12.0	12.98	78.5	16.31	
	1.4		2.1	0.34	17.3	0.60	
$f(m)$ [$M_\odot$]		0.0051					0.0036
		0.0042					0.0014
σ (O−C) [km s^{-1}]	18.7	7.39	27.2	24.6	13.5	33.7	6.10
$N_{\rm obs}$	32	13	22	24	37	59	33

S282, B2V + B2V. SB2 discovered by Levato & Malaroda (1980) and confirmed by LM83. Not reobserved.

S290 - HD 152234, B0Iab. This is the brightest star in the cluster classified as a CNO-type star. It was observed by Campbell & Moore (1928), Struve (1944), LM83, and Levato et al. (1988) who proposed a period of around 27.25 days. In the present study, we confirm the binary nature of this star and propose preliminary orbital elements at $54\overset{\rm d}{.}46$, twice as long (Fig. 1d). The secondary component has been observed at several phases (Fig. 5). S290 is in addition a visual binary (AB: $0\overset{''}{.}5$).

S291 - HD 152248, O7Ib:(f) + O6.5:((f)). This star has been detected since the first observations by Struve (1944) as a double-lined system. HCB found a solution for both components. They derived a period around 5.97 days, by assuming a nul eccentricity. On the other hand, LM83 reported another solution for the orbital elements, with a period not so different from the obtained in the HCB paper (P = 5.89144 ± 4 10^{-4}) but with an eccentricity of e = 0.18 ± 0.02. Stickland et al. (1996) derived orbital elements from IUE spectra ($P = 5\overset{\rm d}{.}81$), revised by Penny et al. (1999). In the present study, we have recomputed the orbital parameters with all available observations, $P = 5\overset{\rm d}{.}75$, e = 0.13. (Radial-velocity curve not represented in Fig. 1). This star is an eclipsing binary (Mayer et al. 1992) and has a third companion, Chara 252 Aa ($0\overset{''}{.}05$), with a period estimated to 150 yr by Mason et al. (1998). The line profiles at different phases are shown in Fig. 6.

338, HD 326331, O8III. Orbital elements by LM83, with a period $P = 6\overset{\rm d}{.}42$. We have not reobserved it so far, but we shall do it.

4. Results

4.1. Average radial velocity of the cluster

To compute the average radial velocity of NGC 6231, we have included the five stars with constant velocities plus the seven binary systems with orbits. The weighted mean is $< V_{\rm r} > = -30.7 \pm 0.9$ (3.1 rms) km s^{-1}. This result is in good agreement with the value computed by Raboud (1996): −29.2 km s^{-1}, and more precise than that derived by LM83 from 8 stars: $< V_{\rm r} > = -27.3 \pm 3.5$ km s^{-1} .

4.2. New orbital elements

The new orbital elements based on combination of the literature radial velocities and our new observations are given in Table 3. For each element, Table 3 lists on the first line its values, and on the second line its errors. The orbital elements for S289 (353) and S306 (858) are first, somewhat preliminary, determinations. The radial-velocity curves are displayed in Fig. 1.

Contrary to what is observed for solar-type stars, the eccentricities are all larger than 0.10 although the orbital periods are shorter than 8 days. Similar results were obtained by Mermilliod (1996) on the basis of a larger sample of 24 O- and early B-type spectroscopic binaries in open clusters. Eccentric orbits are observed even for periods as short as 2 days.

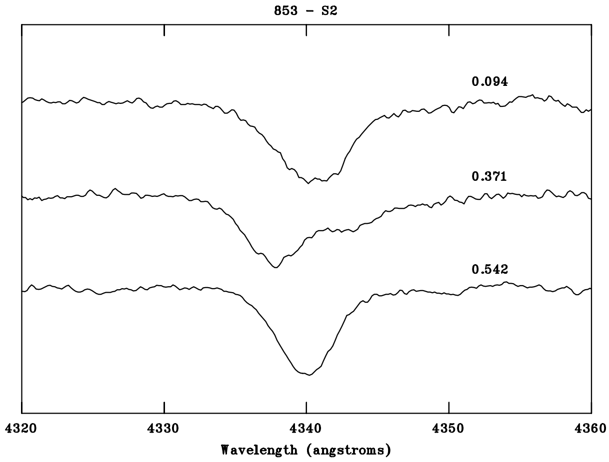

Fig. 2. H_γ profiles at various phases for S2. The double lines are evident at phase 0.371

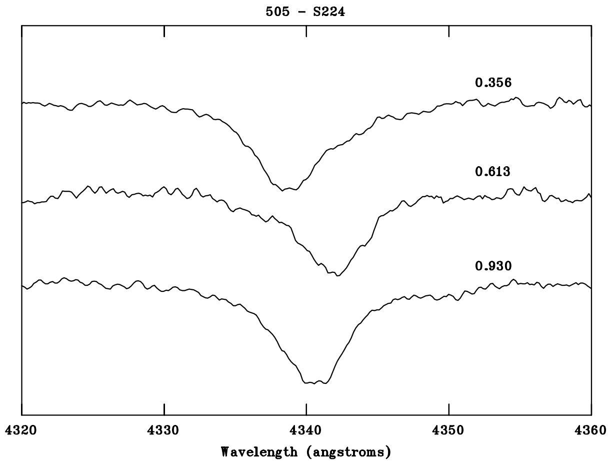

Fig. 3. H_γ profiles at various phases for S224. Asymetric wings are observed at phases 0.356 and 0.613

4.3. Percentage of binaries

The binary frequency can be estimated only on the basis of the stars in the central part of the cluster, because we have only one radial velocity per star for 9 corona candidates, which were obtained to check their membership. Indeed two are probable non-members.

Therefore, in Table 1, we count 42 member stars brighter than $V = 10.50$, i.e. $V_0 = 8.90$. But, we do not have radial-velocity observations for 8 stars, which leaves 34 stars. Among them we find 14 SB2 (8 + 6), 14 SB1 (10 + 4), 6 constant. The global binary frequency for stars mostly earlier than B1.5V is than 82% (28/34).

We have 14 O-type stars, including the brightest B0 Iab supergiant, and count 11 spectroscopic binaries, with 8 stars with confirmed double-lined spectra. The rate for the O-type stars is 79%. Star S293 (O9 Ib CNO) shows intrinsic line variability (Levato et al. 1988) and has not be included in the binary sample.

Our binary frequency is larger than that computed by LM83 (>41%) and by Raboud (1996), 52% for the stars later than B2V. However, Raboud's simulations

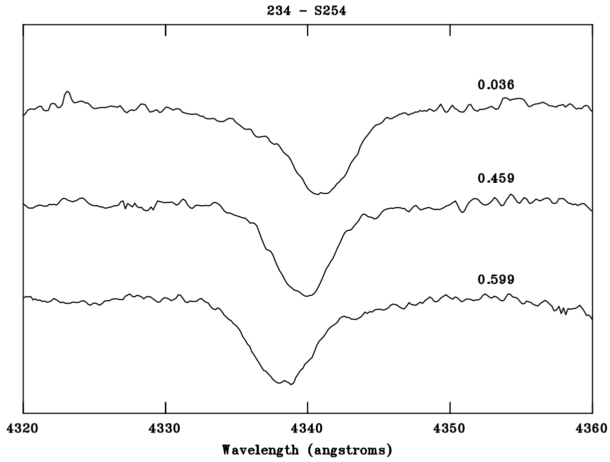

Fig. 4. H_γ profiles at various phases for S254. The change in radial velocity is quite clear, but the presence of the secondary component is not obvious

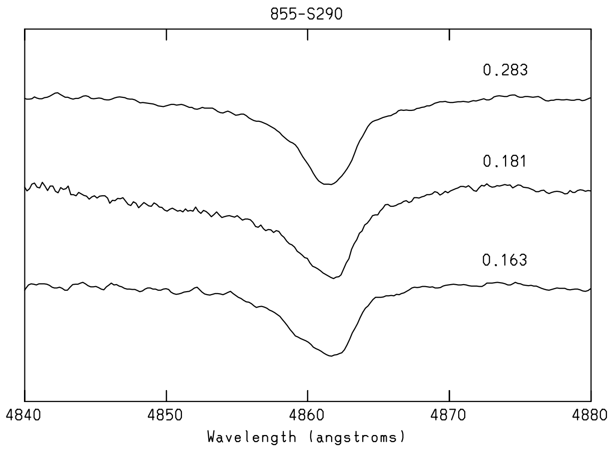

Fig. 5. H_γ profiles at various phases for S290

demonstrated that the theoretical detection percentage of about 55% of binary stars with 2 observations, separatelly 744 days; but raises to 67%, if we consider three observations, and reaches 71% with four. The large number of

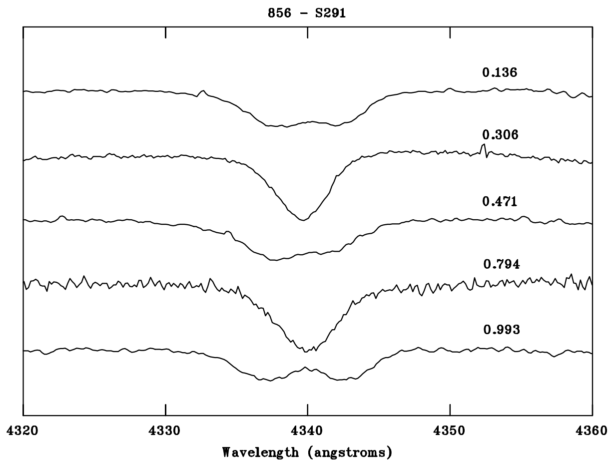

Fig. 6. H_γ profiles at various phases for S291. The double-lined nature is especially evident

observations obtained so far on the brightest stars explained the larger number of confirmed spectroscopic binaries. Further observations are needed to complete the survey of stars later than B0.

Eight O-type stars (S2, 161, 220, 254, 290, 291, 306, 338) have been observed with the CHARA speckle camera (Mason et al. 1998) and a companion has been detected only for S291.

The comparison of the location of the stars in the colour-magnitude diagram confirm in most cases the spectroscopic binary identification. We are aware of the work by Gies (1987) who showed that some O-type stars display line-profile variability due to non-radial pulsations; these variations produce apparent changes in the line profiles and radial velocities. An analysis of variance test for the interline variation could be applied to decide on the reality of the duplicity of dubious cases as Levato et al. (1988) did. But this statistical technique requires larger numbers of observations than we presently have.

4.4. Axial rotation

For those stars later than O9, and of luminosity classes III, IV and V, we derived the $V \sin i$ values. If we compare the results with the average $V \sin i$ for the field stars of the same types (Sletteback 1970; Abt 1970), the results will be a ratio $< V \sin i >/< V \sin i >_{\rm FS} = 0.67 \pm 0.04$, in the new Sletteback system, in agreement with Levato & Morrell (1983).

Fom this result, there is no doubt that the axial rotation is lower between the members of the binary systems, and NGC 6231 results in a good example due the great incidence of binary stars. Another cluster with similar characteristics is NGC 6193 (Arnal et al. 1988), with 72% of probable binary stars, and a projected axial rotation refered to field stars of similar types, of 0.67 ± 0.08.

4.5. Colour-magnitude diagram

The Geneva colours of Raboud et al. (1997) have been used to plot the (V_0, X) colour magnitude diagram (Fig. 7). X is a good temperature indicator for early-type stars, presents an interesting range and is corrected for interstellar reddening. The various symbols denote the different binaries: filled squares for SB2 and open circles for SB1. Binarity is now pretty well known down to $V_0 = 8$ ($V \sim 9.5$) and much more work remains to be done for fainter stars. The position of the double-lined binaries in the CM diagram is in good agreement with the presence of a bright companion. We note that there are only seven stars which define the single star locus, both from the photometry and spectroscopy ($V_{\rm r} = $ cte).

5. Discussion

Attention has been focused in the past years on the duplicity of solar-type- and low-mass stars in nearby associations, due to the development of speckle interferometry and adaptive optics. The interesting result is the large frequency of wide binaries, resolved in the observations. It should be noticed that the rate of spectroscopic binaries is not yet determined, and a fortiori it is not known if any of these “visual” components is itself a spectroscopic binary, producing triple systems.

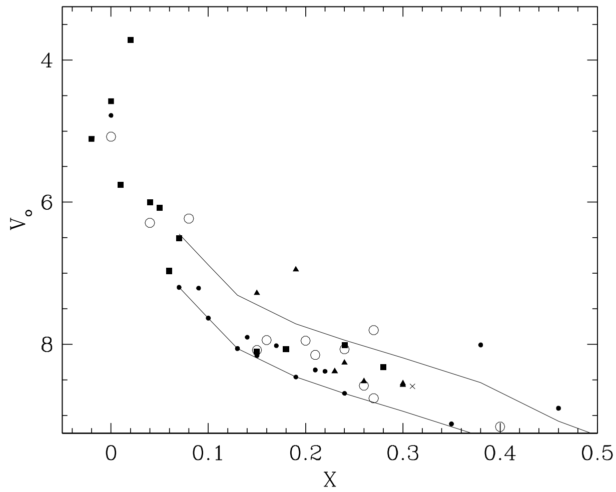

Fig. 7. Colour-magnitude diagram for observed stars in NGC 6231. Symbols are as follows: filled squares: SB2, open circles: SB1, dots: “single” stars, cross: no spectroscopic information, filled triangles: corona stars

Table 4. Binary frequency of clusters $N_{\rm O\,star} > 5$

Cluster	Number of O-stars	SBs	Frequency
IC 1805	10	8	0.80
NGC 6231	14	11	0.79
NGC 2244	6	3	0.50
IC 2944	16	7	0.44
NGC 6611	12	5	0.42
Tr 16	20	7	0.35
Cr 228	21	5	0.24
Tr 14	7	1	0.14

5.1. Binary frequency in various environnements

5.1.1. “Rich” clusters

Duplicity of massive stars in very youg clusters and associations also contains important information for the understanding of star- and cluster formation, but, probably due to technical difficulties, – the spectra are sometimes difficult to understand –, much less efforts have been put in this mass domain. In this context, NGC 6231 is an important cluster because it is outside its parent cloud and contains 14 O-type stars. To compare the characteristics of NGC 6231 with those of other clusters, we have searched the open-cluster database (Mermilliod 1995) for available information on spectroscopic binaries in other O-type clusters.

Table 5. Open clusters with one or two O-type stars in binary or multiple systems

Cluster	No	HD	Sp.T.	Binarity	Period	Visual	$N_{\rm star}$	$N_{\rm O}$	Multiplicity
NGC 2362	23	57061	O9 II	SBE	$1.^{\rm d}3$	Aa $0.''15$	5	2	Quintuple
				SB1O	$154.^{\rm d}9$	AB $8.''2$			
NGC 7380	2	215385	O6 V + O7 V	SB2OE	$2.^{\rm d}1$		2	2	SB2
NGC 6193	1	150136	O5 V + O6:	SB2O	$2.^{\rm d}7$	AB $1.''6$	5	3	Quintuple
	2	150135	O7 V	SB2?		AC $9.''6$			
NGC 1502	2	25639	O9.5 V	SB2OE	$3.^{\rm d}1$	Ba $0.''07$	6	1	Multiple
	1	25638	B0 II	SB1O	$2.^{\rm d}8$	AB $17.''9$, Aa $6.''0$			
NGC 6604	1	167791	O8 If +				3	3	Triple, A
			O5-8 V + O5-8 V	SB2E	$3.^{\rm d}3$				B: SB2
NGC 6383	1	159176	O7 V + O7 V	SB2OE	$3.^{\rm d}4$	Aa $0.''27$	5	2	Quintuple
						AB $5.''4$, Ba $0.''7$			
Tr 37	466	206267	O6	SB2O	$3.^{\rm d}7$	Aa $0.''09$, AB $1.''6$	4	1	Quadruple
Tr 24	515	152623	O7 V	SB1O	$3.^{\rm d}9$	Aa $0.''23$	3	1	Triple
NGC 6871	1	190918	WN5 + O9.5 I	SB2O	$112.^{\rm d}4$	AB $6.''6$	3	2	Triple
NGC 2264	131	47839	O7 V((f)) + O9.5 V	SB1O	23.6y	AB $2.''91$	3	2	Triple
NGC 1976	1891	37022	O6	Cte		Cc $0.''037$	>8	1	Trapezium
	1865	37020	B0	SB1E	$65.^{\rm d}4$	Aa $0.''22$			
NGC 6823	1	344782	O7 V((f))				>5	2	Trapezium
	3		O7 V((f))						
IC 1848	1	17505	O6.5 V(f)	SB2?		AG $23.''7$	4	2	Multiple
	2	17520	O8 V			Gg $0.''3$			
IC 1590	248	5005	O6.5 V((f)) + O8 Vn			AB $1.''5$, AC $3.''9$	4	3	Quadruple
	250		O9 Vn			AD $8.''9$			

The binary frequencies of 8 galactic open clusters with at least 6 O-type (primary) stars are collected in Table 4, which lists the cluster names, the number of O-type stars (counting only the primaries), the number of spectroscopic binaries and the binary frequency. This table shows that the overall binary frequency among O-type stars varies from cluster to cluster from values as high as 80% in IC 1805 and NGC 6231 to values as low as 14%, in Tr 14. In all cases the duplicity is well documented and based on extensive radial-velocity surveys, even if few orbits have been completely determined.

Among the seven O3-O9 stars in Tr 14, only one has been definitively proved to be a binary (García et al. 1998), with a period of $5.^{\rm d}03$ (Levato et al. 2000). Tr 14 has the lowest number of binaries and is the most dense clusters among those listed in Table 4.

The orbital periods, mainly determined in NGC 6231 (HCB and present study) and Tr 16 (Levato et al. 1991), are preferently shorter than 10 days.

5.1.2. "Poor" clusters

The very young open cluster NGC 6193 has also quite a large binary frequency (Arnal et al. 1988), but it contains only two O-type stars and most binaries are early-B stars. It has been included in Table 5 which presents a list of 14 very young open clusters which contain only one or two O-type stars. These clusters are considered separately from the "richer" ones because the population characteristics strongly differ between the two kinds of clusters.

In these "poor" clusters, all O-type stars, Θ^1 Ori C being the only exception, are spectroscopic binaries, often SB2, and even eclipsing. The orbital periods of 8 among 11 O-type binaries are around 3 ± 1 days and this accumulation is quite surprising. In addition, the hard binaries have other companions and the multiplicity is usually larger than 3. The overall appearance of these poor clusters is therefore quite different from that of the "rich" clusters. The systems which contains an inner short-period spectroscopic binary are in fact highly hierarchised, as deduced from the estimations of the periods for the close "visual" components computed by Mason et al. (1998). However, a few ones, like Orion and NGC 6823, form trapezium systems.

Whether the companions are optical or visual is a question which is difficult to answer with available data. Indeed, no separate photometry or radial velocity exist which could prove that the companions fall on the right place in the colour-magnitude diagram. However, companions with separations less than a few arcsec are certainly physical, while in the case of separations of the order of 15 to 20 arcsec, the question of the gravitational link may be raised, especially in a cluster. In Table 5, each O-type spectroscopic binary has at least one close companion and is therefore a triple or a quadruple system. Even if companions with larger separations are not physically associated but are simply cluster members, nearly all systems have a multiplicity larger than 2. It should be mentioned that some young and dense open clusters, like NGC 1502, 2264 and 6871, have been improperly included in the

ADS catalogue with 10 or even 20 components. A plot of these stars just reproduces the cluster map.

No information on periods are unfortunately available for the O-type stars in NGC 6823 and in IC 1590 and 1848. These clusters are listed at the bottom of Table 5 because the O-type stars are part of multiple- or trapezium systems. Further open clusters have not been included in Table 5 because of the lack of information on the binarity and multiplicity of their O-type stars (e.g. Tr 27, St 16, NGC 6514, NGC 6618).

A list of 37 galactic open clusters with 1 to 7 O-type stars has been published by Mermilliod & García (2000). It would be important to observe the O-type stars and determine their binary and multiplicity status to extend the present statistics. However, only 4 additional clusters have more than 5 stars, and the sample of clusters presented in Table 4 cannot be increased significantly.

5.2. Cluster structure

We have at present two evidences that there may be a causal link between cluster density and binary frequency. On the one side, wide binaries seem to be more numerous in loose aggregates (i.e. in Taurus-Auriga) than in more dense clusters (i.e. in Orion) as demonstrated by Duchêne (1999) and Mathieu et al. (1999). On the other side, Penny et al. (1993) have proposed that the higher than normal density in the central part of Tr 14 is due to the lack of binaries. One can therefore wonder whether the cluster density is governed by the binary population or if the binary population depends on the cluster density. It is probably valid for wide binaries, but we are here dealing with short-period spectroscopic binaries and the condition of survival are not the same. A dense central region would have a tendency to destroy binaries and to become more dense. If few binaries are initially formed, the process of cluster formation could directly form a dense cluster. But, in light of the results on duplicity reported in the present paper, we can wonder if single massive stars are ever formed in cluster environment.

In rich clusters with many O-type stars, the massive O stars have characteristics similar to those of the other main sequence stars: they appear to be single or double, but the rate of multiple system seems to be low, they are found over most cluster area, as in IC 1805. On the contrary, in clusters which contain only few massive stars, but may contain many low-mass stars, like the Orion Trapezium cluster, the O-type stars are members of multiple or trapezium systems which are very often located close to the cluster center. The observed multiplicity is generally higher than 3.

The question is: do dense clusters destroy their binaries or is there any coupling producing different binary populations in different environnements: few binaries in very dense clusters (Tr 14), many binaries in rich, less dense, clusters (NGC 6231, Tr 16, Cr 228), more multiple systems in less rich clusters (Orion cluster, NGC 2264) and wide

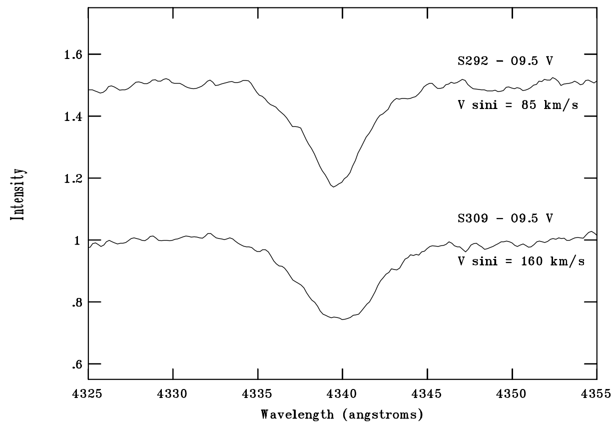

Fig. 8. Normalized CCD observations for S292 and S309, in H_γ region

binaries in poor aggregates (Taurus-Auriga)? This result is to be also considered in light of the correlation found by Abt & Sanders (1973) between the binary frequency and the ratio of the mean rotational velocities between the cluster and field stars.

It has been proposed that the binary fraction decreases with the time (Ghez et al. 1993; Patience et al. 1998), or that the physical conditions of the cloud, from which the cluster was born, are the responsables of the incidence of binary systems. Durisen & Sterik (1994) proposed that the binary fraction is established during the formation process, without many later disruptions. They pointed out that a natural prediction of both cloud- and disk-fragmentation models is that the binary fraction is higher in colder star-formation regions. Moreover, they proposed that the cloud temperature could also influence the orbital-period distribution.

The observational evidences we have collected show that we have a clear difference in structure and multiplicity characteristics between "rich" and "poor" clusters. But we agree that, due to the available data, we have considered only the two extreme cases. Observations of the clusters listed by Mermilliod & García (2000) would be very important to complete the overall picture.

Consequently the overall structure and, probably, the evolutionary history of these clusters are different.

6. Conclusion

By combining new high-resolution spectroscopic observations of 37 stars with those available in the literature for the members of NGC 6231, we got the following results:

- We have confirmed the binary nature for 28 members of the cluster;
- The orbital elements of 7 SB systems were calculated, three of them for the first time;
- We found a global binary frequency of 82% for the stars earlier than B1.5V;

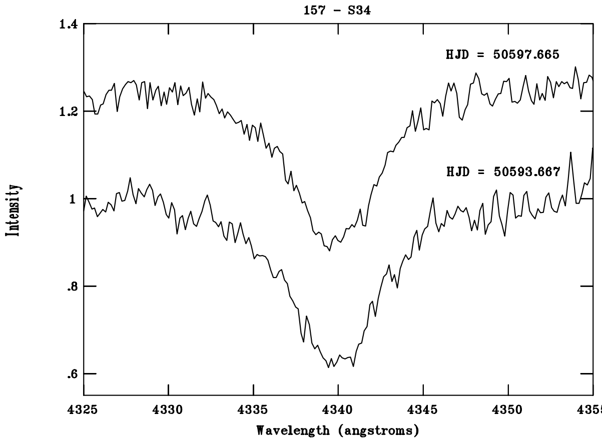

Fig. 9. Same as Fig. 8 for S34

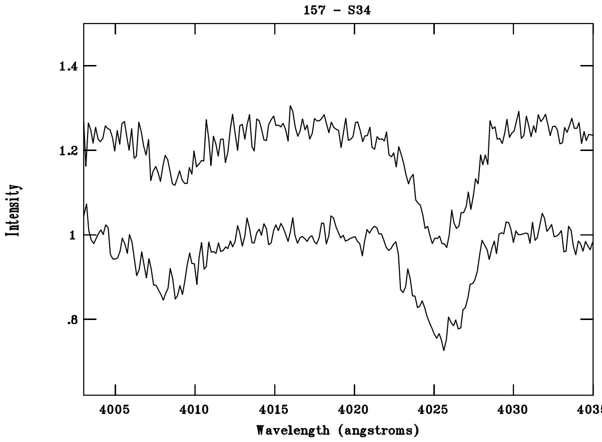

Fig. 10. Same as Fig. 8 for S34, in HeI $\lambda 4026$ region

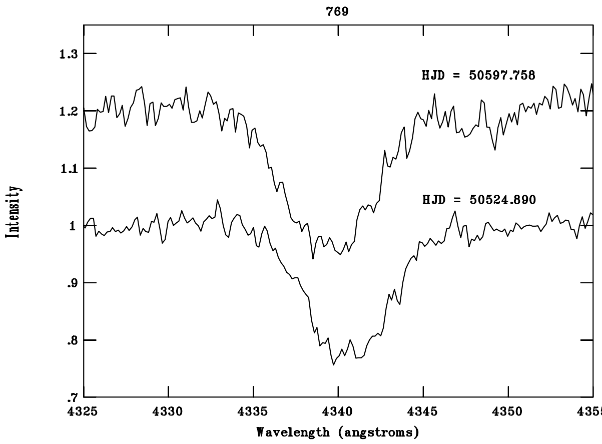

Fig. 11. Same as Fig. 8 for 769

- 79% of the O-type stars, are binary systems, and among the binaries, 86% are double-lined objects;
- The average baricentric velocity we obtain, -30.7 ± 0.9 km s^{-1}, is in agreement with previous studies;
- The average ratio between the rotation of the cluster members and field stars is 0.67 ± 0.04;
- The percentage the binaries with periods lower than 100 days, fits fairly well on the Abt & Sanders (1973) correlation. This result contributes to demonstrate that the overall axial rotation is lower in clusters rich in binary systems (see Morrell & Levato 1991, Fig. 4);
- It is also remarkable that all except one periods in NGC 6231 O-type binaries are less than 10 days, with non-zero eccentricities.

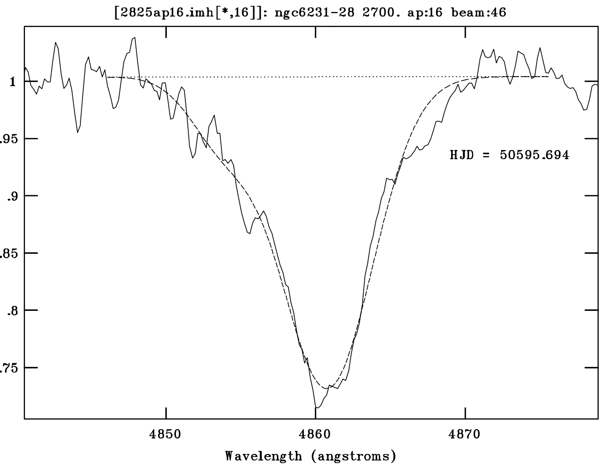

Fig. 12. Radial velocity components for S28, in H_β region

From the comparison with other very young open clusters containg O-type stars, we distinguish two different scenarios: either the clusters have many (more than 6) O-type stars which are distributed over the cluster field and are mostly binaries or "single" or they have one or two O-type stars, which form a double-lined spectroscopic binary, belonging to herarchical triple or quadruple systems, or to trapezia, with a period close to 3 days and are often located at the cluster center. In the latter case, most of the mass is strongly concentrated in the central multiple system.

The similarity of the value of the periods of the inner spectroscopic binary, around $P \sim 3$ days, is quite striking. We can wonder what are the reasons for such a similarity and if the short 3 days periods result from the formation of the O-type binaries or from the early evolution of the multiple systems or inner part of the clusters. Due to the very small ages of these clusters, we are inclined to conclude that the observed difference must result, for a large part, from the formation processes, rather than from early dynamical evolution inside the molecular cloud, but appropriate simulations will be necessary to settle the question.

Raboud & Mermilliod (1998) found mass segregation among the cluster members and between binaries and single stars in NGC 6231, although this cluster is likely still not dynamically relaxed. The massive stars occupy a much smaller volume than the less massive stars. The present study contributes to prove, by spectroscopic methods, the binary nature of several stars, which was based so far mostly on photometric criteria. Radial-velocity observations are especially important in the upper part of the main sequence where the seqeunce is nearly vertical. For most clusters listed in Table 5 the massive multiple systems are located close to the cluster center.

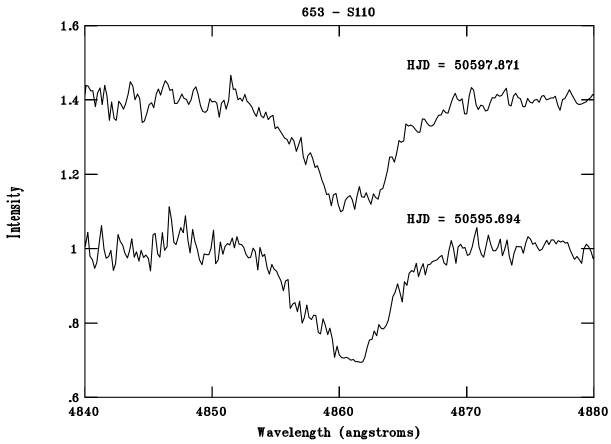

Fig. 13. Same as Fig. 8 for S110

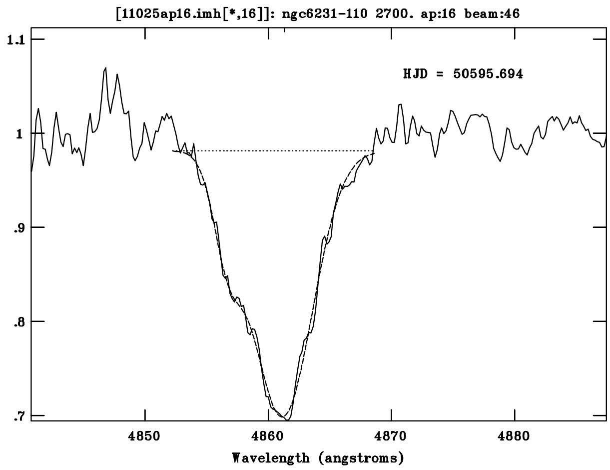

Fig. 14. Radial velocity components for S110, in H_β region

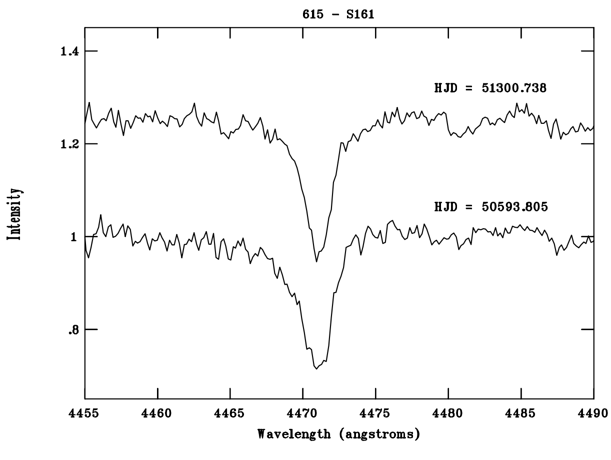

Fig. 15. Same as Fig. 8 for S161, in He I λ4471 region

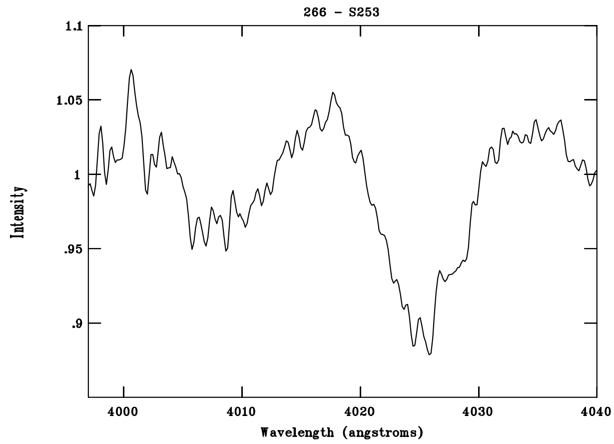

Fig. 16. Same as Fig. 8 for S253, in HeI λ4026 region

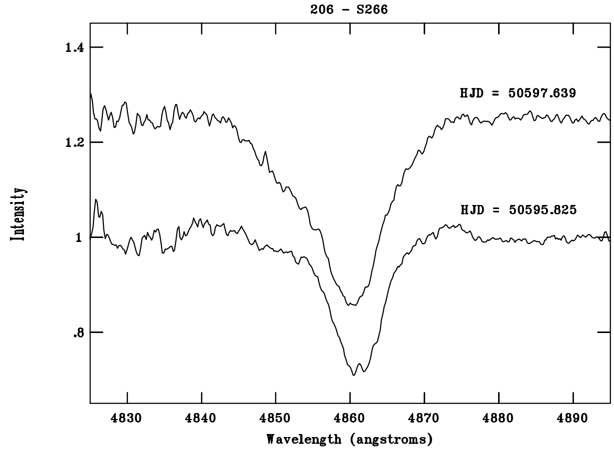

Fig. 17. Same as Fig. 8 for S253, in H_β region

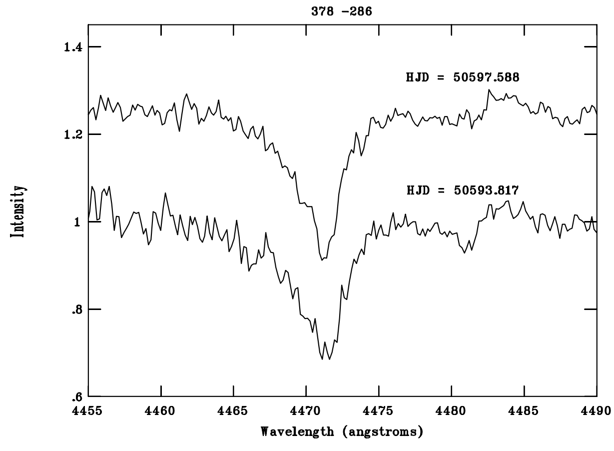

Fig. 18. Same as Fig. 8 for S286, in HeI λ4471 region

In this study, we tentatively conclude that the cluster density depends on the duplicity rate for rich clusters with many O-type stars. But in less rich clusters, O-type stars belongs to multiple systems which may be massive enough to ensure the stability of the surrounding clusters. The overall structure and the evolutionary history of these clusters are probably different.

NGC 6231 is an exceptional cluster because of its young age ($\log t = 6.75$) and the rich stellar content. Multi-fiber spectrographs mounted on large telescopes will permit to study the duplicity and rotation of stars all along the main sequence to describe the characteristics of a very young open cluster just emerged from its parent cloud.

Further spectroscopic observations, as well as a search for “wider” components with adaptive optics or speckle interferometry, of O-type stars in more very young open clusters would help confirming and understanding the differences found in this paper.

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