Astron. Astrophys. 336, 953–959 (1998)

ASTRONOMY AND ASTROPHYSICS

The HR-diagram from Hipparcos data. Absolute magnitudes and kinematics of Bp - Ap stars⋆

A.E. Gómez[1], **X. Luri**[1,2], **S. Grenier**[1], **F. Figueras**[2], **P. North**[3], **F. Royer**[1], **J. Torra**[2], **and M.O. Mennessier**[4]

[1] Observatoire de Paris-Meudon, D.A.S.G.A.L., URA 335 du CNRS, F-92195 Meudon Cedex, France
[2] Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Avda. Diagonal 647, E-08028, Barcelona, Spain
[3] Institut d'Astronomie de l'Université de Lausanne, CH-1290 Chavannes des Bois, Switzerland
[4] Université Montpellier II, Groupe de Recherche en Astronomie et Astrophysique du Languedoc, URA 1368 du CNRS, F-34095 Montpellier Cedex 5, France

Received 22 January 1997 / Accepted 6 May 1998

Abstract. The HR-diagram of about 1000 Bp - Ap stars in the solar neighbourhood has been constructed using astrometric data from Hipparcos satellite as well as photometric and radial velocity data. The LM method (Luri, 1995; Luri, Mennessier et al., 1996) allows the use of proper motion and radial velocity data in addition to the trigonometric parallaxes to obtain luminosity calibrations and improved distances estimates.

Six types of Bp - Ap stars have been examined: He-rich, He-weak, HgMn, Si, Si+ and SrCrEu. Most Bp - Ap stars lie on the main sequence occupying the whole width of it (about 2 mag), just like normal stars in the same range of spectral types. Their kinematic behaviour is typical of thin disk stars younger than about 1 Gyr.

A few stars found to be high above the galactic plane or to have a high velocity are briefly discussed.

Key words: stars: chemically peculiar – stars: distances – stars: fundamental parameters – stars: Hertzsprung-Russell (HR) diagram – stars: kinematics

1. Introduction

Bp - Ap stars constitute one of the classical groups of chemically peculiar stars of the upper main sequence. They show abnormal enhancement of one or several elements in their atmosphere (see Jaschek & Jaschek, 1987 for a detailed discussion). In the present paper the following categories of Bp - Ap stars (He-rich, He-weak, HgMn, Si, Si+ and SrCrEu) are considered and their position in the HR-diagram and kinematic characteristics are obtained using Hipparcos data, radial velocity and Geneva photometry complementary data.

Since the release of Hipparcos parallaxes, the mean absolute magnitude for the different kinds of CP stars has been obtained by North et al. (1997). In that work only stars with a trigonometric parallax relative error ≤ 0.14 were considered, thus considerably reducing the number of stars in each sample. The main result of that study is that, as far as the mean luminosity is concerned, CP stars are main sequence stars. In this paper the approach is different: the LM statistical method (Luri, 1995; Luri, Mennessier et al., 1996) is applied to the different samples. This method allows the use, for each star, of all the available astrometric data (whatever the quality of the parallax is) as well as radial velocity data. It is well suited to treat inhomogeneous samples. Consequently, the problem of possible misclassifications is partly overcome and, on the other hand, the final results rely on larger samples. It also provides the kinematic characteristics of the samples.

The paper is organized as follows:

– The description of the selected samples and the corresponding available data are given in section 2.
– A summary of the LM method is presented in section 3.
– The presentation and discussion of the results on the absolute magnitudes, the spatial distribution and the kinematical behaviour of the groups are given in sections 4 and 5. In particular, the results are compared with those obtained for non-peculiar stars of the same spectral range. The existence of high- velocity Ap stars is also emphasized.

2. Sampling

In order to minimize misclassifications, the samples were selected from different sources by comparing the spectral classifications. First, all the stars in Renson's catalogue (Renson et al., 1991) observed by Hipparcos were retained. This first list was cross-correlated with the Catalogue of Stellar Groups (Jaschek & Egret, 1981) and the Michigan catalogues: Houk & Cowley (1975), Houk (1978), Houk (1982) and Houk & Smith-Moore (1988). After that, the stars with discrepant

Send offprint requests to: A.E. Gómez

⋆ Based on data from the ESA Hipparcos astrometry satellite and photometric data collected in the Geneva system at ESO, La Silla (Chile) and at Jungfraujoch and Gornergrat Observatories (Switzerland). Tables 3 and 4 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. Samples of Bp-Ap stars

Sample	N	Sp. range	$T_{\rm eff}$ range
He-rich	14	B2	18000 - 23000 K
He-weak	58	B4 - B8	13000 - 17000 K
HgMn	76	B8 - A0	10000 - 14000 K
Si	440	B7 - A2	9000 - 14000 K
Si+	87	B8 - A2	8000 - 13000 K
SrCrEu	378	A0 - F0	7000 - 10000 K

spectral classifications were excluded. Table 1 gives the number of stars in the samples selected (N) and the spectral type and effective temperature ranges. The sample named Si+ contains intermediate types like SiCr and SiEu. The satellite performed a survey (Turon et al., 1992) complete up to an apparent V-magnitude that depends on the spectral type and the galactic latitude. In the case of the spectral range covered by Bp - Ap stars, all the stars brighter than apparent magnitude 7.9 were observed. Our samples contain not only survey stars but also fainter stars observed by the satellite.

For each star, astrometric data (parallax and proper motion components) as well as photometric data and their corresponding errors were taken from the Hipparcos Catalogue (ESA, 1997). Radial velocity data come from different sources: Barbier-Brossat & Figon (1998), Duflot et al. (1995), Grenier et al. (1998), Levato et al. (1996) or from Coravel obtained by one of us (P. North). When a star had more than one radial velocity source, a mean weighted value was adopted. Effective temperatures ($T_{\rm eff}$) were evaluated using Geneva photometry for all the stars with the exception of He-rich stars. In this case, the values given in Zboril et al. (1997) were used.

Absolute magnitude determinations may be affected by the presence of binaries. The selected samples were then scrutinized for companions. Different sources from the literature were taken into account, the main ones being the Hipparcos Catalogue, which provides duplicity or multiplicity information (ESA, 1997), and the “Bright Star Catalogue” (Hoffleit & Warren Jr, 1991), which gives indications on spectroscopic binaries or variable radial velocity stars. In those cases where the difference of magnitude between the components was known the star was retained and its apparent magnitude was corrected, otherwise it was rejected. Consequently, the number of stars in the final samples was reduced to 44, 415, 66 and 353 stars in the samples HgMn, Si, Si+ and SrCrEu, respectively.

Fig. 1 gives the histogram of the relative errors on the trigonometric parallax for the final samples. Notice that in the LM method, all the available parallax data can be used, whatever the quality of the parallax is.

Finally, the effect of the interstellar absorption on the apparent magnitude was taken into account using the tridimensional model of Arenou et al. (1992), which is included in the LM algorithm.

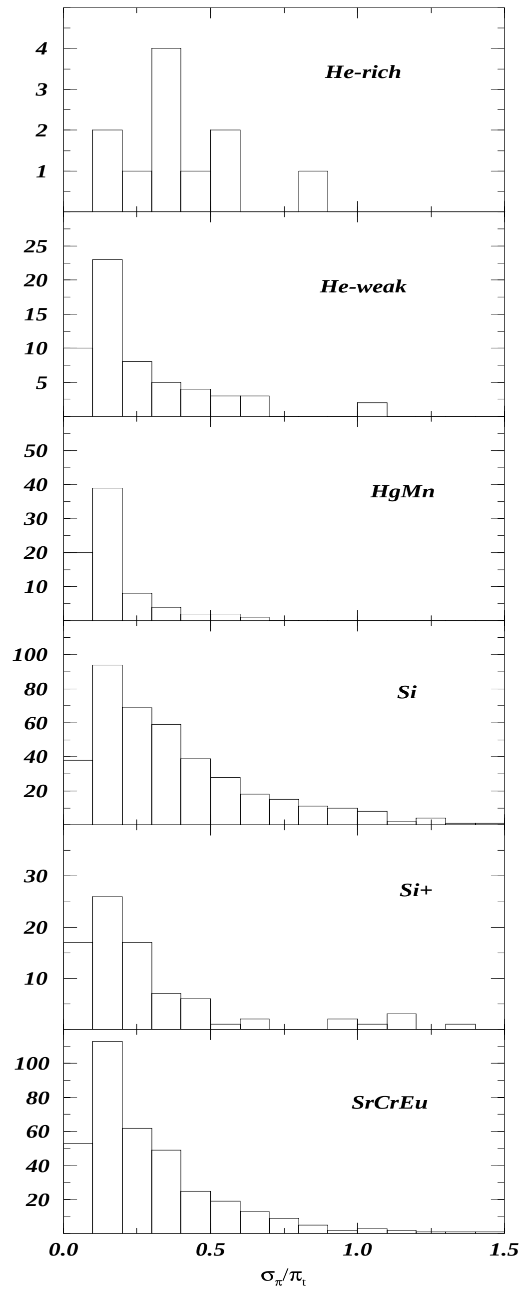

Fig. 1. Distribution of relative trigonometric parallax errors in the samples. A few stars have relative trigonometric parallax errors greater than 1.5 (in groups Si, Si+ and SrCrEu) or smaller than 0.0 (in groups He-rich and Si)

3. The LM method

The LM method (Luri, 1995; Luri, Mennessier et al., 1996) is based on a Maximum-Likelihood (ML) algorithm which allows the simultaneous determination of the luminosity, kinematic characteristics and spatial distribution of a sample of stars using all the available information: apparent magnitudes, galactic coordinates, trigonometric parallaxes, proper motions, radial velocities and any other measured parameter related to luminosity such as colour indices or atmospheric parameters ($T_{\rm eff}$, $\log\, g$, metallicity, etc.).

The method allows the treatement of non homogeneous samples and takes into account the effects due to the sample selection, the interstellar absorption, the galactic differential rotation and the errors in the observables. Each sample is assumed to be a mixture of stars coming from several groups, each one being characterized by the following probability density functions: a normal distribution for the absolute magnitude (M_0, σ_M), a Schwarzchild ellipsoid velocity distribution $(U_0, V_0, W_0, \sigma_U, \sigma_V, \sigma_W)$ and an exponential-disk spatial distribution (Z_0 being the scale height in the direction perpendicular to the galactic plane). U, V and W are directed towards the galactic center, the galactic rotation and the north galactic pole, respectively. Furthermore, in the Hipparcos Catalogue there is a selection in apparent magnitude which affects our samples. This effect has been modeled by a selection function which is uniform up to a certain magnitude m_c (determined in the process of ML estimation) and then decreases linearly up to the limiting magnitude of the sample. The application of the LM method to a given sample provides not only the mean absolute magnitude for the groups identified but also individual absolute magnitude and distance estimates for the sample stars. For stars with high relative errors on the parallaxes, the method allows us to improve the estimation of the individual absolute magnitude because the estimate is not biased and its variance is reduced due to the use of all the available information for each star (see Brown et al., 1997 for a detailed discussion).

The number of different groups composing each sample (n) is not usually known. It is obtained by applying the Wilk's test to the ML estimations performed assuming n and n+1 groups (n = 1, 2, ...). Once the estimation has been obtained, the stars of the sample can be classified into the groups identified. The *a posteriori* probability of a given star of belonging to each group is calculated and the star is assigned to the group with the highest probability. Notice that since this procedure is probabilistic, some misclassification may occur. Furthermore, the same *a posteriori* probability is an indicator of the reliability of the classification of the stars.

The method is completely implemented using numerical procedures. In this way a greater flexibility is achieved and analytical approximations are avoided. More details on the LM method and its application are given in the above cited papers and in Gómez et al. (1997a), Luri et al. (1997) and Luri et al. (1998).

4. Results

The LM method was applied to the different samples and for all of them, with the exception of the He-rich and He-weak samples, two groups were identified. Table 2 gives the results obtained for the main groups (containing the largest number of stars). The entries are self-explanatory: M_0 and σ_M correspond to the visual magnitude expressed in magnitudes. The kinematic parameters (U_0, V_0, W_0, σ_U, σ_V and σ_W) are given in km s^{-1}. Z_0 is expressed in pc. The errors were estimated using Monte-Carlo simulations. The percentage of the total sample belonging to the main group is indicated. The last row gives the total number of stars (N) in the used samples.

As explained above, the LM method provides individual absolute magnitude estimates. Table 3 gives for each star of the main groups the apparent V-magnitude, the absolute magnitude estimate, the estimated individual distance with the corresponding error as well as the probability of belonging to the group. The spectral classification is also indicated. The secondary groups differ from the main groups in luminosity or in kinematics. These groups seem to be rather inhomogeneous, containing high-velocity stars and possible misclassified objects. Table 4 lists the stars in the secondary groups (about 30) with their estimated probability of belonging to the group.

As we are interested in comparing the position in the HR-diagram of Bp - Ap stars with respect to those of normal stars of the same $T_{\rm eff}$, individual bolometric absolute magnitudes M_{bol} have been calculated. For magnetic Bp - Ap stars the bolometric correction of Stępień (1994) has been applied, otherwise the values of Flower (1996) have been used. It has to be noted that not every star has $T_{\rm eff}$ data available. Fig. 2 displays the HR-diagram ($M_{bol}, \log_{10}\, T_{\rm eff}$) for the main groups stars in the different samples. The results obtained for normal stars (Gómez et al. 1997a) are represented. Finally, the isochrones of Schaller et al. (1992) for solar metallicity are also plotted.

5. Discussion

5.1. Bp - Ap main groups

As shown in Fig. 2, Bp - Ap stars are main sequence stars occupying the whole width of the sequence. The width reaches up to 2 mag., a similar result to that obtained for non-peculiar stars of the same spectral range (Gómez et al., 1997a). The intrinsic dispersion in absolute magnitude is rather large, varying from 0.6 to 0.8 mag for most types. In the case of He-rich stars, the intrinsic dispersion is about 1.2 mag, reflecting that these stars spread over a large range in luminosities, from about -0.2 $\pm$ 0.4 to -6.2 $\pm$ 0.8 mag. As the sample is very small, further classification in different groups has no statistical meaning.

The results given in Table 2 may be compared with those obtained by North et al. (1997) using small samples of Bp - Ap stars selected with a relative error smaller than 14 % on the trigonometric parallax. These last values need to be corrected for the sample bias (although the corrections are small because the stars have very precise parallaxes) while in the LM method the sample bias is taken into account in the estimation process. The intrinsic dispersions obtained by North et al. (1997) are large and similar to ours. Due to the large value of the intrinsic dispersions, the sample mean absolute magnitude provides a rough estimate for an individual star and should be used only in those cases where the only available information is its spectral type. Individual absolute magnitudes as given in Table 3 are preferred. Notice that for stars with less accurate parallaxes (relative errors $>\ 0.14$) the absolute magnitude estimate has been improved.

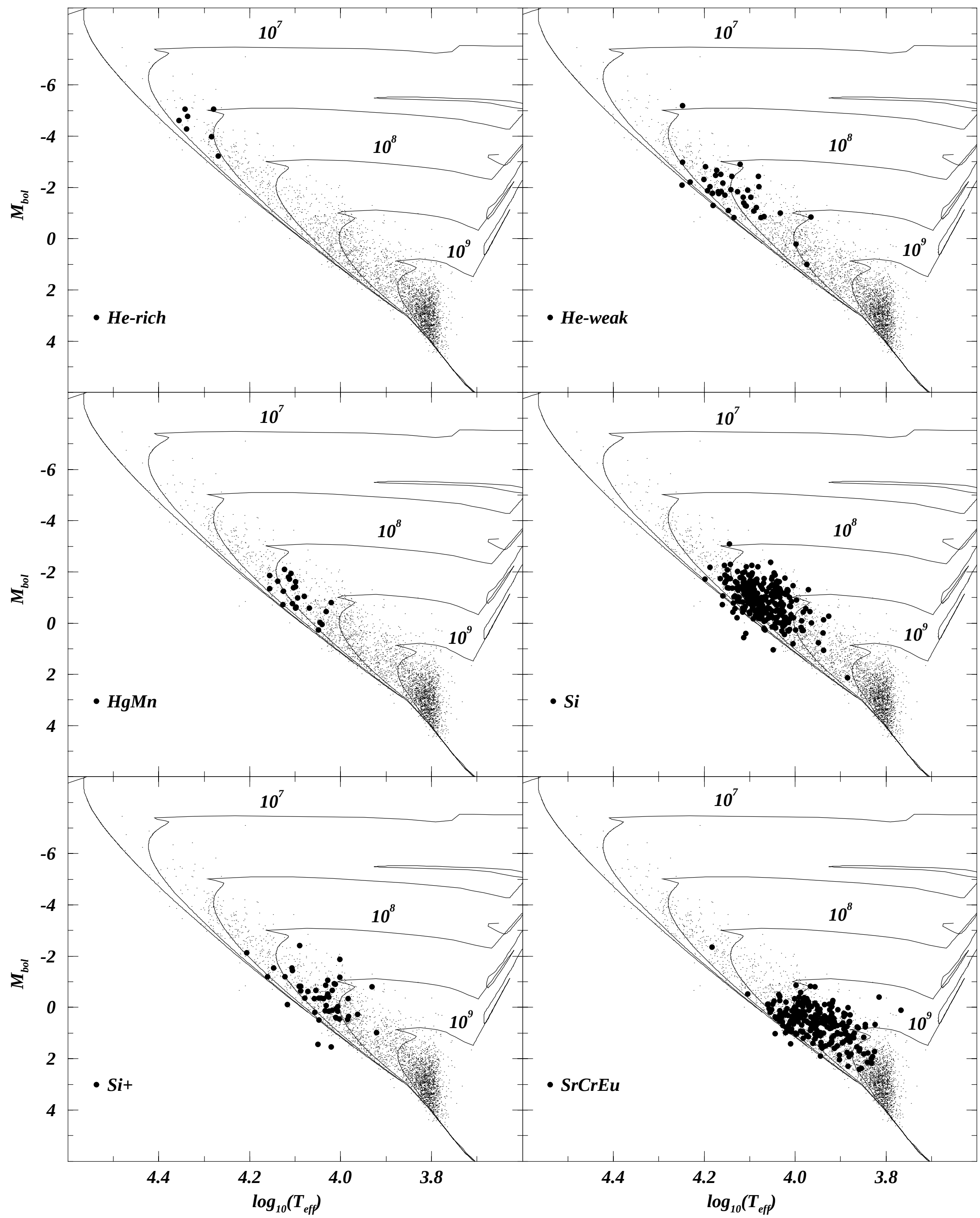

Fig. 2. Distribution in the $[\log_{10}\,T_{eff}, M_{bol}]$ plane of the stars in the main groups (circles). The results for non-peculiar stars from Gómez et al. (1997a) are indicated (dots)

It is well known from the study of Bp - Ap stars in open clusters and associations (North, 1993) that they belong to the young disk population. Consequently, it is expected that their spatial and velocity distributions agree with those observed for non-peculiar main sequence stars of the same spectral range. Fig. 3 displays the distribution in the $[x, z]$ plane for the stars in the main groups, x and z being the heliocentric distances in the direction of the galactic center and perpendicular to the galactic plane, respectively. When going from the hottest groups to the cooler ones, the stars are less concentrated to the galactic plane.

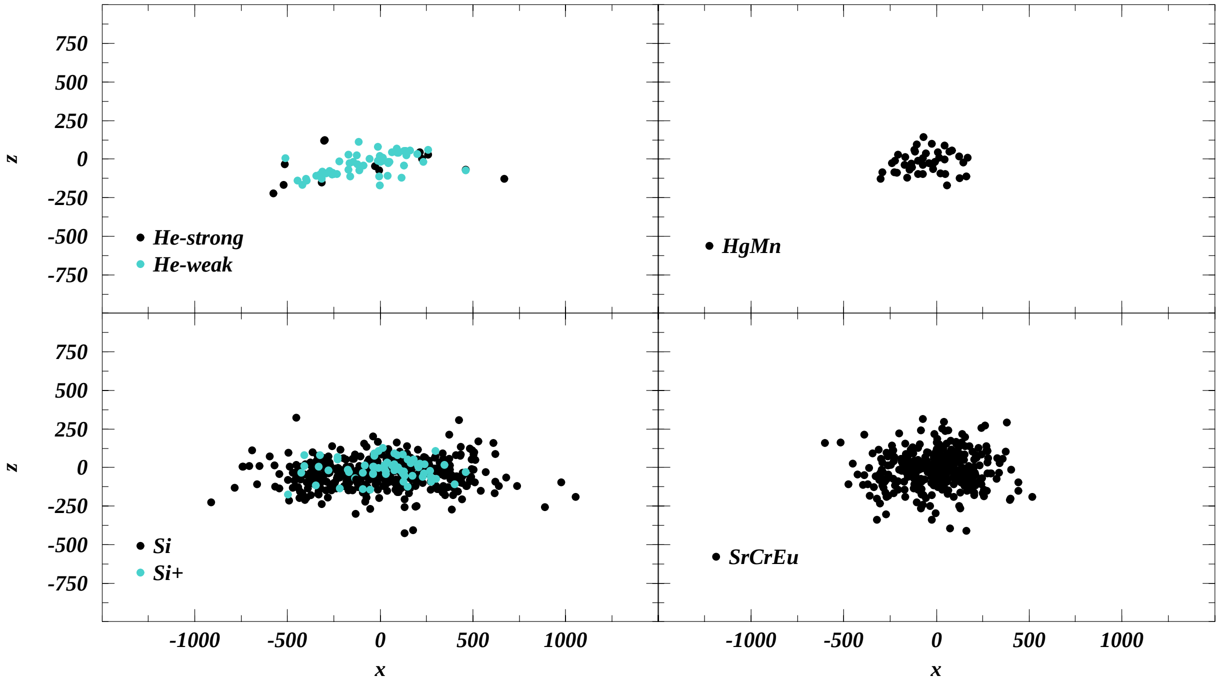

Fig. 3. Spatial distribution in the $[x, z]$ plane of stars in main groups, x and z are expressed in pc

Table 2. Mean visual absolute magnitudes, kinematics and scale heights of Bp-Ap stars (main groups)

	He-rich	He-weak	HgMn	Si	Si+	SrCrEu
M_0	-1.6 $\pm$ 1.0	-0.2 $\pm$ 0.3	-0.1 $\pm$ 0.5	0.13 $\pm$ 0.10	0.44 $\pm$ 0.21	1.27 $\pm$ 0.07
σ_M	1.2 $\pm$ 0.4	0.6 $\pm$ 0.2	0.6 $\pm$ 0.4	0.76 $\pm$ 0.09	0.75 $\pm$ 0.15	0.76 $\pm$ 0.06
U	-15.0 $\pm$ 3.2	-12.0 $\pm$ 1.5	-11.5 $\pm$ 2.0	-11.9 $\pm$ 0.5	-11.6 $\pm$ 2.5	-11.0 $\pm$ 1.2
σ_U	8.7 $\pm$ 4.3	8.6 $\pm$ 1.2	8.9 $\pm$ 1.9	9.8 $\pm$ 0.3	14.6 $\pm$ 1.8	19.1 $\pm$ 1.2
V	-8.5 $\pm$ 2.7	-13.9 $\pm$ 1.3	-14.1 $\pm$ 2.0	-12.9 $\pm$ 0.5	-12.4 $\pm$ 1.7	-11.3 $\pm$ 0.7
σ_V	7.6 $\pm$ 3.1	8.2 $\pm$ 1.8	11.0 $\pm$ 1.7	10.2 $\pm$ 0.5	9.0 $\pm$ 1.4	9.5 $\pm$ 0.8
W	-5.2 $\pm$ 2.7	-6.5 $\pm$ 0.8	-6.8 $\pm$ 1.0	-6.9 $\pm$ 0.4	-6.7 $\pm$ 0.9	-6.4 $\pm$ 0.5
σ_W	5.0 $\pm$ 4.3	3.7 $\pm$ 0.8	5.4 $\pm$ 0.8	5.8 $\pm$ 0.3	6.0 $\pm$ 0.7	7.0 $\pm$ 0.4
Z_0	81 $\pm$ 19	58 $\pm$ 9	57 $\pm$ 10	69 $\pm$ 3	49 $\pm$ 8	96 $\pm$ 8
%	100	100	95 $\pm$ 2	97 $\pm$ 3	95 $\pm$ 4	95 $\pm$ 1
N	14	58	44	415	66	353

Z_0 varies from about 60 pc to 100 pc, in good agreement with the values obtained for non-peculiar stars of the same spectral type (Luri et al., 1998). For He stars, the presence of the Gould Belt, a structure inclined about 17 - 20^o to the galactic plane (Torra et al., 1997), is clearly visible.

Concerning the kinematic behaviour of normal stars, Gómez et al. (1997b) obtained (using Hipparcos data) that up to 1 Gyr σ_V and σ_W remain practically unchanged (10 ± 0.5 km s^{-1} and 5 - 7 ± 0.5 km s^{-1}, respectively), while σ_U increases from 11 ± 0.5 km s^{-1} at 10^8 years to 20 ± 1 km s^{-1} at 10^9 years. These results may be compared with those given in Table 2 for the different samples of Bp - Ap stars. As for non-peculiar stars, σ_V and σ_W do not show significant variations and σ_U varies from about 9 ± 1 km s^{-1} for He-rich, He-weak, HgMn and Si stars to 15 ± 2 km s^{-1} for Si+ stars and 19 ± 1 km s^{-1} for SrCrEu stars. It is difficult to estimate a mean kinematic age for each group because the kinematic behaviour of stars younger than about 1 Gyr shows the signature of moving groups (Sabas, 1997; Figueras et al., 1997; Gómez et al., 1998; Sabas et al., 1998). The kinematic results are compatible with the upper age limits obtained by North(1993) from the study of CP stars in clusters and associations and from the position of stars in the HR-diagram (see Fig. 2). He-rich stars constitute the youngest group with ages less than a few 10^7 years. For He-weak, HgMn and Si groups the maximum age is about log(age) = 8.5, and for Si+ and SrCrEu stars it is log(age) = 8.75 and 9, respectively. As expected, Bp - Ap stars have the same kinematic behaviour of non-peculiar thin disk stars younger than about 10^9 years.

5.2. Bp - Ap secondary groups

As explained above, the LM method identified secondary groups which may differ from the main groups in luminosity, in kinematics or in both. These groups seem to be inhomogeneous,

Table 5. List of high-velocity or high-$|z|$ Bp - Ap stars

HIP	Group	Velocity	$\|z\|$	Remark
291	Si		866 (37%)	
4995	SrCrEu	77±12	568 (16%)	JJGG83, St91
6907	SrCrEu	* 87±25	371 (29%)	JJGG83, St91
20837	Si	65±8	375 (31%)	JJGG83
23691	SrCrEu	221±15		St91
42819	Si	* 136±14		JJGG83
54985	Si	* 94±21	432 (22%)	S74
89594	HgMn	101± 2		AS72, St91
110616	Si		855 (40%)	
112709	SrCrEu	* 116±30	447 (26%)	

AS72: Adelman & Sargent (1972)
JJGG83: Jaschek et al. (1983)
S74: Stalio (1974)
St91: Stetson (1991)

containing a mixture of misclassified stars and stars with spatial and kinematic behaviour differing from the corresponding main groups. In particular, high-velocity stars and stars out of the galactic plane ($|z| > 300$ pc) or both are found. This result is not surprising given that high-velocity stars have been observed in samples of normal A-type stars at high galactic latitudes (Rodgers et al., 1981; Lance, 1988) and in the solar neighbourhood (Stetson, 1991 and references therein; Royer, 1997). Jaschek et al. (1983) obtained a list of candidates for high-velocity Ap stars using reduced proper motions. It was argued that these stars could be the tail of the velocity distribution of the total samples and not bona fide high-velocity stars. Our results confirm the existence of high-velocity stars among Bp - Ap stars. Such objects are clearly very interesting, because an explanation of how apparently young stars have acquired high velocity and/or large distances from the galactic plane is needed. We have searched in each secondary group for high-velocity stars as well as for stars out of the galactic plane. The main difficulty is that since these stars are far from the Sun, accurate parallax data are missing. The Hipparcos parallaxes have relative errors $> 50\%$ and sometimes $> 100\%$, thus preventing the estimation of reliable tangential velocities. Using our estimated distances with their corresponding errors, stars out of the galactic plane and/or with high velocity have been identified. Let us remark that not all the stars have a known radial velocity, which is necessary to compute the total space velocity. A star was considered to have a high velocity whenever the modulus of its total space velocity was larger than 65 kms^{-1} or that of its tangential velocity larger than 60 kms^{-1}.

Table 5 gives the stars identified. The column Velocity gives the velocity and the corresponding error expressed in kms^{-1} (an asterisk refers to the tangential velocity). The column $|z|$ gives the z-distance (in pc) and the relative error.

Several hypotheses have been proposed to explain the existence of such objects (for details see Lance, 1991). One of the mechanisms invoked is the ejection from the galactic plane of normal young stars. They could be ejected from clusters or accelerated by a supernova in binary systems. This last mechanism produces runaway stars more massive than 10 $M_\odot$, so it cannot explain the case of A-type stars. Other possibilities include the formation from the compression of gas and dust at the outer edges of supernova bubbles. Among the stars given in Table 5, the star HIP 291 points in the direction of the cluster Blanco 1. Its high-velocity characteristics might be the result of an ejection from this cluster. However, its distance is not compatible with the cluster distance, a result already obtained by Westerlund et al.(1988). Another explanation often advanced is that these stars are misclassified objects: HB or blue stragglers (BS). The hypothesis that some of these stars may be population I BSs is very attractive because over 60 % of the BSs found in young and intermediate age open clusters (log(age) ≤ 9) are found to be peculiar or metallic B - A stars (for details see Stryker, 1993). Finally, accretion of gas from a merged satellite galaxy has also been invoked. This mechanism may explain the existence of young stars out of the galactic plane. The analysis of these different mechanisms for normal early-type stars as well as for Bp - Ap stars is underway.

Finally, we remark that a few stars in the main groups have $|z| > 300$ pc. With the exception of stars HIP 12051 and 111396 in the Si group and HIP 7473 in the SrCrEu group, the other stars are only marginally high - $|z|$ stars.

6. Conclusions

The LM algorithm has been applied to a sample of about 1000 Bp - Ap stars observed by Hipparcos. Six types of stars (He-rich, He-weak, HgMn, Si, Si+ and SrCrEu) have been considered. In most of the samples, with the exception of the He-rich and He-weak stars, two groups have been separated, the main groups containing the largest number of stars. Our results can be summarized as follows:

- Bp - Ap stars are main sequence objects. They occupy the whole width of the main sequence band, which reaches up to 2 mag. The intrinsic dispersion in absolute magnitude varies from 0.6 to 0.8 mag for all the groups except He-rich stars. These latter stars spread over a large range in luminosities, the intrinsic dispersion being about 1.2 mag.
- Mean absolute magnitudes are given for each category of stars (main groups). For these stars individual absolute magnitudes and individual distances are also given (Table 3). The secondary groups are rather inhomogeneous, containing high-velocity stars and misclassified objects.
- From a kinematical point of view, Bp - Ap stars are young thin disk stars: their kinematic behaviour is similar to that of non-peculiar stars younger than about 10^9 years. The kinematic ages are compatible with the upper age limits observed for peculiar stars in open clusters and associations.
- A few objects show high-velocity or are found out of the galactic plane ($|z| > 300$ pc). The origin of these stars is not well established.

Acknowledgements. This work was supported by the CICYT under contract ESP95-0180 and by the PICS program (CNRS PICS 348, CIRIT). The technical assistance of Mrs D. Morin and A. Sellier is gratefully acknowledged.

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