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Radial velocities⋆,⋆⋆

IX. Measurements of 2800 B2-F5 stars for Hipparcos

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Abstract. Radial velocities have been determined for a sample of 2930 B2-F5 stars, 95% observed by the Hipparcos satellite in the north hemisphere and 80% without reliable radial velocity up to now. Observations were obtained at the Observatoire de Haute Provence with a dispersion of 80 Å mm^{-1} with the aim of studying stellar and galactic dynamics. Radial velocities have been measured by correlation with templates of the same spectral class. The mean obtained precision is 3.0 km s^{-1} with three observations. A new MK spectral classification is estimated for all stars.

Key words: techniques: radial velocities — stars: early-type — stars: fundamental parameters

1. Introduction

The Hipparcos mission, the first space experiment dedicated to astrometry, was active from November 1989 to March 1993 and gave very precise astrometric data for about 118 000 stars. 44% belong to the Hipparcos Survey (Turon et al. 1992) which is complete from $V = 7.3$ to 9.0 as a function of the galactic latitude and the spectral type. The results are published in The Hipparcos Calalogue (ESA, 1997). For the Hipparcos magnitude below $Hp = 9$, the median precision of positions, parallaxes and proper motions are better than 1 mas and 1 mas yr^{-1} respectively while the nominal precision was 2 mas. In addition the satellite measured solved or suspected double systems as well as photometric variables.

One of the aims of the Hipparcos mission was the study of stellar and galactic dynamics. To compute the components of the spatial velocities, the radial velocities are necessary. Their precision should be consistent with the precision of the tangential velocities $V_{\rm t}$ computed from Hipparcos data: the error $\epsilon_{V_{\rm t}}$ is 2.1, 2.2 and 3.0 km s^{-1} for the distances of 100, 200 and 500 pc respectively, with the mean value $V_{\rm t} = 15$ km s^{-1} and an error on the absolute magnitude $M_V = 0.3$.

As early as 1982 Ch. Fehrenbach decided to begin a radial velocities survey for early-type stars observed by Hipparcos. Three instruments were then available and used: the Objective Prism mounted on the Schmidt telescope (SPO), the Petit Prisme Objectif (PPO), and the Marly spectrograph. At that time the Input Catalogue had still not been defined and it was necessary to use a very preliminary version. The aim was to complete the Coravel observations which give radial velocities for spectral types later than F5. So we selected stars from B5 to F5. With the SPO (field 4×4 deg^2) the regions rich in early-type stars up to the magnitude $B = 12$ were observed, with PPO (same field) regions rich with bright stars up to the magnitude $B = 8.5$ were observed while with the Marly isolated stars were measured up to $B = 9$. The priority was given to Bp-Ap and A-type stars belonging to the Hipparcos Survey, taking into account the radial velocities already published. The results of the SPO are published by Fehrenbach et al. (1990, 1992), those of the PPO by Duflot

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⋆ Based on observations made at the Haute Provence Observatory, France and on data from The Hipparcos Catalogue, ESA.

⋆⋆ Tables 4, 5 and 6 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr or via http://cdsweb.u-strasbg.fr/Abstract.htm et al. (1990, 1992, 1995a) and Fehrenbach et al. (1987b, 1997). The Marly observations run from 1983 to 1995 for about 3 000 stars. First results are in Fehrenbach et al. (1987a) named Paper I. Since that paper, many measurements were added, the calibration method was improved and the visual spectral classification was revised. So the first published radial velocities were recomputed and are given here for the sake of homogeneity.

The Hipparcos North Survey contains 12286 B5-F5 stars, 33% of which have a published radial velocity in Barbier-Brossat & Figon (1997) or in WEB (Duflot et al. 1995b), the number of measurements being ≥ 2 without taking into account the above quoted papers based on SPO and PPO observations. For the stars included in the Hipparcos North Survey 2.6% radial velocities have been added by the SPO, 8.4% by the PPO and 18% by the Marly (this paper). Finally 62% of the B5-F5 stars of the North Survey have a measured radial velocity. In addition, some B2-B4 stars, some stars not in the Hipparcos Survey as well as some stars not in the Hipparcos Catalogue (in 1982 the Hipparcos Input Catalogue had not been determined) were observed with the Marly. Some stars with Coravel radial velocities were added to calibrate our measurements. Moreover a certain number of selected F5 stars were seen in fact F6. Finally about 3040 stars were observed with the Marly, 80% not having up to now reliable radial velocity (published value with an error lower than 6.0 km s^{-1} and a number of measurements ≥ 2).

2. Observations and data reduction

2.1. Instrumentation

The Marly spectrograph was installed at the Newtonian focus of the 1.2 m telescope. A detailed study of Marly optical characteristics is in Lemaître et al. (1990). Let us recall that the radius of curvature of the camera mirror was 420 mm and the aperture ratio in the direction perpendicular to the dispersion was f/2.8. The spectra covered 24 mm in the direction of dispersion. The dispersion was 80 Å mm^{-1} with the 600 L mm^{-1} grating, allowing to observe a magnitude $B = 9$ in about 30 min. The central wavelength was 4260 Å with an usable range of 1200 Å. The slit width was 50 μm ($1''.4$ on the sky and 30 μm on the plate). The slit height was 250 μm ($7''.0$ on the sky and 500 μm on the plate). The emulsion of plates was IIaO. Six spectra were taken on each plate. An iron spectrum was made before and after each exposure for wavelength calibration. The focus of the camera was tested before each run. The use of an exposuremeter allowed very even plate density levels and therefore homogeneous expositions whatever the spectral type. Spectra were digitalized on the Fentomix device, specially built in OHP for this programme. Until the end, the use of plates was dictated to keep a precision consistent with Hipparcos data. During the observation range (1983-1995), an adapted CCD (more than 2 000 pixels of maximum size 15 μ) was not available, allowing adequate resolution and wavelength range. A minimum of 3 spectra per star was obtained. The rule was to separate the two first by at least 8 days and the third by at least 10 months, allowing to detect possible variability. To avoid the influence of the instrumental flexions, stars were observed near the meridian (±1 hour). This instrumentation allowed a range of magnitude $B = 6.5$ to 9 with observation times from about 3 to 30 mn. Some brighter reference stars were observed using a neutral filter. A possible influence of this neutral filter on the radial velocity was tested as other parameters (see Sect. 2.3). A cross correlation method was adopted for the obtention of the radial velocities.

Table 1. List of the used templates

template	HD	ST	$\log T_{\rm eff}$
B2	1334	B2.5V	4.32
B5	19968	B5III	4.18
B8	11927	B7IV	4.11
A0	23946	A0IV	3.99
A2	9071	A2IV	3.95
A5	26212	A5V	3.91
A7	13857	A7III	3.88
F0	15733	A8/A7V	3.85
F2	94456	F3V	3.84
F5	15631	F5V-IV	3.81
F6	89449	F6IV	3.80
G0	154417	F8.5IV-V	3.79
G5	18749	G8IV	3.72
K0	8779	K0IV	3.70
K2	26162	K2III	3.65
K4	9138	K4III	3.60

2.2. Correlation method

The adopted method to obtain the radial velocities was the cross-correlation of each spectrum with templates, stellar spectra obtained with the same instrumentation. This correlation method is described in Paper I. The templates used in Paper I were kept throughout and completed by two B stars. They are given in Table 1. To restrict computing times the program selected a limited number of templates. An automatic spectral classification was used for this purpose (see Paper I), but this method was considered not to be sure enough and was checked by a visual classification. In fact the height of spectra was fixed to optimize the exposure time and not for a precise classification. The MK classification criteria were used. For Ap stars the strongest peculiarities only were given. The luminosity class was used for an easier final choice of the template but has to be taken with cautiousness. The test of this classification is described in the Sect. 2.6.

The reduction program took into account both spectral classifications, visual and automatic, selecting an optimum grid of templates. For Am stars, the Hydrogen type has been adopted, corresponding to the effective temperature $T_{\rm eff}$ of the star. The three radial velocities corresponding to the three best correlation index were kept for further discussion. At each step the consistency of the data was checked and as a result 4% spectra have been discarded.

2.3. Zero-point of radial velocities and data analysis

The correlation process gave a relative radial velocity but several parameters had to be determined: generally an IAU standard was observed every night to obtain the zero-point of each run. The radial velocity was a linear function of the radial velocity itself and depended of a colour effect as a linear function of the $\log T_{\rm eff}$ of the template. To determine all these parameters a model has been built inside Gaussfit task (Jefferys et al. 1988), a system for least squares and robust estimation by an iterative process.

$$V_{\rm r} = V_{\rm r} + AV_{\rm ref}$$
$$V_{\rm r} = V_{\rm r} + B(\log T_{\rm eff})$$
$$V_{\rm r} = V_{\rm r} + C_n$$

with $n = 1$ to 22, function of the template.

Gaussfit was running into three steps:

- In the first step the parameters A, B and C_n were computed with the IAU standard and some early-type stars with good radial velocity. These stars are given in Table 2 with their adopted published radial velocity. For IAU stars, the Coravel homogeneous velocities given by Mayor (1997) were adopted, taking into account the duplicity information from Mazeh et al. (1996).
- In the second step the radial velocity of all templates was determined with a larger list made up of stars with published radial velocity (see below).

Then the zero-point of each run is determined. As all these parameters were interfering between themselves an iterative process, converging very quickly, was used for the computation.

- Finally all these corrections were applied to the whole sample of the 11 700 spectra, building an homogeneous sample of data.

The mean radial velocities have been derived for each star as well as its standard error $\epsilon_{\rm e} = \sqrt{\frac{1}{n(n-1)} \sum (v_i - \overline{v})^2}$.

The radial velocities of the reference stars were taken from the WEB (Duflot et al. 1995b), Barbier-Brossat & Figon (1997), Nordström et al. (1997), Liu et al. (1991), Morse et al. (1991), Mayor (1989), Prévot (1990) and also from measurements made on 1.5 m OHP telescope with the Coude spectrograph and later the Aurelie spectrometer not published yet. Very wide binaries (Halbwachs 1986) were used when the second component was observed with Coravel. If this late-type component did not show a variable velocity, its value of radial velocity was adopted for the primary. All these selected radial velocities have a standard deviation $\sigma_{\rm e} < 8\,{\rm km\,s^{-1}}$. For Coravel velocities (Mayor 1989 and Prévot 1990) the ratio external vs. internal errors was considered. Moreover, when the difference of the velocities (Marly minus published value) was greater than $8\,{\rm km\,s^{-1}}$, the star was rejected. The duplicity flags of Hipparcos were taken into account and Hipparcos binaries have been rejected except those undetectable for us in any way.

This method allowed to test the influence of parameters such as the meteorological conditions (turbulence and

Table 2. Reference stars used for the first step. 1, Mayor (1997); 2, Morse et al. (1991); 3, Liu et al. (1991); 4, Pedoussaut (1992); 5, Barbier-Brossat et al. (1994); 6, Duflot et al. (1995b)

HD	V	ST	$V_{\rm ref}$	reference
3765	8.30	K2V	−63.89	1
8779	7.65	K0IV	−4.71	1
9138	6.20	K4III	33.72	1
14252	5.34	A2V	−0.2	2, 5
22484	4.86	F9IV-V	27.79	1
23441	6.41	A0Vn	7.8	2, 3
23568	6.8	B9V	9.9	2, 3
23607	8.5	A7V	4.5	2, 3
23791	8.7	A8V	5.7	3, 5
26162	6.57	K2III	24.34	1
26912	4.23	B3IV	14.9	2
29587	7.93	G2V	112.31	1
33542	7.4	B5III	−7.3	5
38899	4.8	B9IV	21.6	2, 3
42824	6.7	A2V	−4.5	5
66141	5.64	K2III	71.16	1
89449	5.24	F6IV	6.20	1
92588	7.14	K1IV	42.22	1
97333	8.54	A2V	17.0	5
103325	9.4	F3IV	−19.5	5
105303	7.92	F2V	8.0	5
107328	6.12	K0IIIb	35.97	1
114762	7.85	F9V	49.25	1
136202	5.60	F8III-IV	54.22	1
144579	7.39	G8V	−59.94	1
172044	5.3	B8II-III	−27.8	4, 5
179761	5.1	B8II-III	−5.0	2,
182572	5.93	G8IV	−100.73	1
186568	6.1	B8III	−8.6	2, 5
187691	5.66	F8V	−0.21	1
201912	6.73	B5IV	−3.8	6
212883	6.4	B2V	−8.2	5
212943	5.84	K0III	53.80	1
213014	8.49	G9III	−40.44	1
217811	6.3	B2V	−3.8	5
223311	7.52	K4III	−20.76	1

transparency), the exposure time or the observing people, entailing some rejected spectra.

2.4. Precision

The errors had two main origins: the precisions on the zero-point of each run and on the velocity of each template. The internal standard deviation σ_i was given by:

$$\sigma_i^2 = \sigma_{\rm run}^2 + \sigma_{\rm t}^2$$

$\sigma_{\rm run}$ is the standard deviation on the zero-point of each run. Gaussfit computed a standard deviation $\sigma_{\rm t}$ for each template taking into account the error on the published radial velocity of the reference stars and the errors on the coefficient of the linear functions of the Gaussfit model. This estimation was tested by the unit-weight-error given by the histogram of the individual values of $(v_i - \overline{v})/\sigma_i$ for the whole sample of IAU spectra. This histogram is Gaussian allowing to adjust the estimation of the internal standard deviation σ_i. The mean internal error $\sigma_i/\sqrt{n}$ equals $3.6\,{\rm km\,s^{-1}}$ when $n = 3$ for early-type stars.

The external error was computed on the mean radial velocity for each star:
the standard deviation $\sigma_{\rm e}$ equals $\sqrt{\frac{1}{n-1}\sum(v_i - \overline{v})^2}$, the maximum of its distribution being at $5.3\,{\rm km\,s^{-1}}$ corresponding to an external error $\epsilon_{\rm e} = \sigma_{\rm e}/\sqrt{n}$ equal to $3.1\,{\rm km\,s^{-1}}$ for 3 observations and 2.7 for 4. In the beginning some stars with negative declination were included. For them $\sigma_{\rm e}$ could be greater.

2.5. Binary and multiple systems

Using the χ^2 test, the variability of the radial velocities was estimated with a confidence level of probability of 95%. The histogram of the probability $P(\chi^2)$ shows its distribution. The peak at $P(\chi^2) < 0.5$ is relative to the detected variable radial velocities. This test depends on the dispersion of radial velocities around the mean value and on the internal error. Variable velocity stars are indicated by "VAR" in Tables 4 and 5. Assuming this variability as duplicity, the obtained frequencies of binaries are given in Table 3, for "normal" stars of classes V or IV, for Ap (Si and/or Sr generally) and Am stars. The result about Am stars was compared with the sample of Abt & Levy (1985), though the bias of selection is different. They found a percentage of binaries of 60%. Taking into account their probable external error, this percentage decreases to 27% function of our limit of $\sigma_{\rm e}$ in the variability detection. With our sample it is found 32% with a confidence level of 95% and 21% when it is 99%, results in agreement with the fact we have 3 or 4 measuremants per star and Abt and Levy more than 10. The percentages given in the Table 3 are lower than those of Jashek & Gómez (1970).

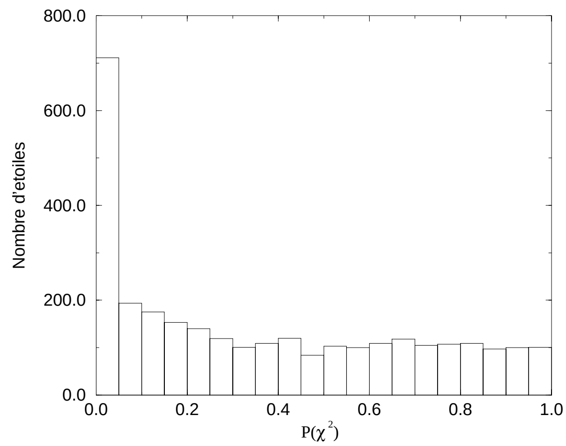

Fig. 1. Distribution of the probability of χ^2 of B2-F5 stars

Table 3. Number of stars and percentages p of binaries of classes V or IV, Am and Ap

type	n	p
B2-B9	386	30%
A0-A4	766	23%
A5-A9	257	21%
F0-F5	576	17%
Ap	278	29%
Am	300	32%

On account of our lower precision, binaries of low amplitude are excluded. The advantage of our measurements is their homogeneity from B2 to F5 types and the size of the sample.

In Table 4 the duplicity flags of Hipparcos were added. This Catalogue (ESA, 1997) gives several flags about suspected or confirmed double or multiple systems from photometry and/or astrometric solution. Lindegren (1997) gives the conditions of detection which are different from the spectroscopic binaries in terms of the separation of components, their magnitude difference and the orbital period. Table 4 gives some indications about the number of components found by Hipparcos, the adopted solution, the quality of the solution, the separation and the difference of Hipparcos magnitude ΔHp when computed or Δm given in CCDM (Dommanget & Nys 1994). Moreover an astrometric orbit in CCDM is indicated by O. Details about these parameters are given in the Hipparcos Catalogue Vol. 1, Sect. 1.4. These double stars can be physical or optical: certain physical when orbital solution (noted "O" in Table 4), probable physical when acceleration solution "G" and physical or optical when resolved system "C" or stochastic solution "X". These flags have two interests: they complete our results for their utilisation and they will be useful to observe these stars again with an another resolution.

Some stars belong to MSC, the catalogue of physical multiple stars of Tokovinin (1997): HD 1658, 4161, 24909, 37438, 58946, 67159, 67501, 102509, 130188, 170073, 172044 and 222326.

As a result from the Table 4, 23% radial velocities are found variables, 13% stars are doubles or suspected by Hipparcos and 3% are commons.

2.6. Tests on the visual spectral classification

The spectral classes were tested with those given by the CDS according to the Jaschek's selection (1978). There was no systematic difference, the dispersion around zero is one spectral class only in 88% of the 449 stars in common and was not date dependent.

To test the luminosity class, the absolute magnitude M_{V*} was computed (Crifo 1997) taking into account the Hipparcos trigonometric parallax (if it is > 0.1 mas), the V magnitude and the interstellar absorption. This absorption was estimated by $4.3\,E_{b-y}$ when this excess was known, or by $0.7\,\mathrm{mag\,kpc^{-1}}$. The error $\epsilon_{M_{V*}}$ on M_{V*} was estimated taking into account the relative error on the parallax σ_π/π. The used reference HR-diagram was picked in Luri (1998) whose first results are given in Gómez et al. (1997). For each spectral class and each luminosity class, Luri (1998) gave the mean $(B-V)_0$, the mean absolute magnitude $M_{V_{\mathrm{HR}}}$ and the standard deviation $\sigma_{M_{V_{\mathrm{HR}}}}$ around the mean value. For each star, M_{V*} was compared with the absolute magnitude given by its spectral type in the HR-diagram. For 88% stars, they were consistent at one σ level. When they were significantly different taking into account $\epsilon_{M_{V*}}$ and $\sigma_{M_{V_{\mathrm{HR}}}}$, the HIP and HD numbers are given in Table 6 with the visual spectral type, the luminosity class found from M_{V*} in the HR-diagram and a possible code explained below.

Some remarks have to be made.

- The luminosity class was determined from M_{V*} taking into account the assumption of a reliable spectral subclass. This was justified by the verified consistency between the visual spectral type and the best correlation index obtained in Sect. 2.2. Nevertheless the distinction between a normal A giant and an Am was sometimes difficult. An other error origin could be a bad estimation of the interstellar absorption A_V. When the value of $(B-V)_0$, computed using A_V was not consistent with the spectral type, a code is given in the Table 6 (available in electronic form only; see footnote to title page): "1" if A_V seemed overestimated and "2" if underestimated. This possible correction on M_{V*} was taken into account. A third error origin could be due to a binary star. When the Hipparcos Catalogue gives a binary with a separation lower than $2''$ and magnitude difference lower than 2 mag, the code "3" is given in Table 6. The code "4" agrees with a variable velocity or a suspected binary by Hipparcos.
- For some stars, the value of the parallax was of the order of its error and brought an error on $M_{V*} = 2$ mag. When $\epsilon_{M_{V*}} > 2$ mag, the code is "5" the absolute magnitude giving the indication of supergiant generally.
- The place of Ap and Am stars in the HR-diagram showing a mean standard deviation 0.75 (Gómez et al. 1998) and the luminosity classes V, IV and III being close in this part of HR-diagram, these classes were considered as normal. It was found 40 Ap not belonging to the general catalog of Ap and Am stars (Renson et al. 1991) and 139 Am not belonging to the fourth catalogue of Am stars with KNO (Hauck 1992). These new classifications have to be confirmed.
- Generally the classes V and IV were not separated because they are very close in the range B5-F5 and the probable precision on the luminosity classes did not justify this distinction.
- On the other hand the height of the spectra did not allow to distinguish the class VI as Hipparcos data displayed some of them. In the Table 6 the adopted classes were:

V-VI if $M_{V*} - M_{V_{\mathrm{HR}}} > \epsilon_{M_{V*}} + \sigma_{M_{V_{\mathrm{HR}}}} + 0.5$
and VI if $M_{V*} - M_{V_{\mathrm{HR}}} > \epsilon_{M_{V*}} + \sigma_{M_{V_{\mathrm{HR}}}} + 1$
$M_{V_{\mathrm{HR}}}$ being the absolute magnitude of the class V.

3. Tables of results

Table 4 (available in electronic form only; see footnote to title page) gives in order, the Hipparcos (HIP) and HD/BD numbers, ICRS coordinates (consistent with J2000) from the Hipparcos Catalogue, V (Johnson) magnitude and its source from the Hipparcos Catalogue ("G": ground-based photometry, "H": from Hp and a colour index, "T": from Tycho photometry), the determined visual spectral type, the adopted template, the mean radial velocity $\overline{v}$, its standard error ϵ_{e}, the number of observations n, the ratio E/I of external to internal error, the indication of variability (χ^2 test), Hipparcos flags of possible duplicity.

Table 5 (available in electronic form only; see footnote to title page) gives the same data for 130 stars out of the Hipparcos Catalogue. Coordinates and V magnitude come from the CDS (Centre de Données Astronomiques de Strasbourg).

4. Conclusion

Radial velocities have been determined for about 2800 early-type stars (B2 to F5), as complementary data to the Hipparcos Catalogue and 130 out of this Catalogue with a standard error equal to about $3\,\mathrm{km\,s^{-1}}$. An estimated MK spectral classification is given.

These radial velocities, obtained at $80\,\mathrm{\AA\,mm^{-1}}$, will be useful for statistical studies mainly. These data are adding a radial velocity measurement for 18% of the B5 to F5 type stars of the Hipparcos north Survey, allowing to 62% of these stars to have a radial velocity.

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