IDENTIFICATION OF MOVING GROUPS IN A SAMPLE OF EARLY-TYPE MAIN-SEQUENCE STARS

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ABSTRACT

The kinematic structure of young B5–F5 main-sequence stars in the solar neighbourhood is analysed using both accurate observational data – new astrometric Hipparcos data and complementary data from the ground – and several robust statistical methods. The coherence of the results obtained from the different methods (SEMMUL, kernel estimator, wavelets, dynamical clusters) allows us to definitively confirm the existence of the Eggen's moving groups and to determine, without any *a priori* knowledge, their mean characteristics in the 4-dimensional space (U,V,W, age). We find that mean velocity dispersion in the velocity component in the direction of the galactic rotation for Sirius, Pleiades, Hyades and Praesepe moving groups are in the range 3–8 km s^{-1}, a value larger than classically expected.

Key words: young stars; galactic kinematics; moving groups.

1. INTRODUCTION

The study of the irregularities in the velocity field of young stars in the solar neighbourhood yields important clues to understand the history of star formation and the dynamical processes involved in the evolution of our Galaxy. The detection and analysis of features such as moving groups, the vertex deviation, and gradients of the velocity field demands the use of robust statistical methods and highly accurate astrometric and physical data. Our project attempts both to definitively confirm the presence of moving groups and, through the kinematic and physical properties of its members, to constrain models accounting for their origin.

A selection of 2588 young B5–F5 main sequence Hipparcos stars within about 250 pc from the Sun, with known individual ages, computed from Strömgren photometry and Hipparcos parallaxes, and a careful compilation of radial velocities have been used for this study.

Different methods have been used to characterize moving groups in the 4-dimensional space of (U,V,W, age): a parametric approach (SEMMUL algorithm, Celeux & Diebolt 1986); a non-parametric technic using a Kernel estimator (Chen et al. 1997), a method based on the wavelet transform and a method based on the aggregation of groups through moving centers. In Section 2, we describe the sample's compilation and its mean characteristics. Section 3 contains a brief description of the statistical methods used and the results obtained, and Section 4 is devoted to the analysis of the moving groups mean parameters.

2. THE SAMPLE

The working sample (compiled by V. Sabas (1997)) has been selected from the global set of Hipparcos B5–F5 main-sequence stars with apparent magnitude 7.5 or brighter. In order not to bias the results when looking for moving group members among the field stars, the stars known as open cluster's members have been rejected. To compute reliable physical parameters and ages, double or suspected double stars and stars with peculiarities in the spectra (spectral types from the Inca Catalogue) have also been rejected. The radial velocities have been taken from the recent compilations of Barbier-Brossat (1997)) and Duflot et al. (1995), and from the Key-Programmes undertaken to complement the Hipparcos data (OHP – Marly Spectrograph, ESO – Echelee Spectrograph: Grenier 1997. Individual ages have been obtained (Asiain et al. 1997) interpolation algorithm) from Lebreton 1995 stellar evolutionary models, taking into account the metallicity, the effective temperature being computed from Strömgren photometry (Hauck & Mermilliod 1996, Jordi et al. 1996), the stellar luminosity from Hipparcos M_v and the bolometric correction of Malagnini (1966). Only stars with log(age) larger than 7.5 have been retained. Distances have been computed directly from Hipparcos parallaxes for the stars with $\Delta\pi/\pi \leq 0.15$, and with a weighted mean between Hipparcos and photometric distance for the rest (few stars). Meillon (1996) algorithm has been used to compute the (U,V,W) components of the heliocentric space velocity (U directed towards the galactic center, V towards the galactic rotation direction and W towards the north galactic pole) and the corresponding errors considering the Hipparcos correlation coefficients among variables. Finally, the stars with residual velocity larger than 65 km s^{-1} have been rejected because they probably do not belong to the galactic disk population. The sample contains 2588 stars with a mean velocity components $(U, V, W) = (-11.72 \pm 0.06, -11.38 \pm 0.06, -7.03 \pm 0.05)$ km s^{-1} and a vertex deviation of $\phi = 22.5^o \pm 1.2^o$. The mean observational errors in the velocity components are $(\epsilon_U, \epsilon_V, \epsilon_W) = (2.4,2.3,1.9)$ km s^{-1} and the distribution of the relative error in age is presented in Figure 1.

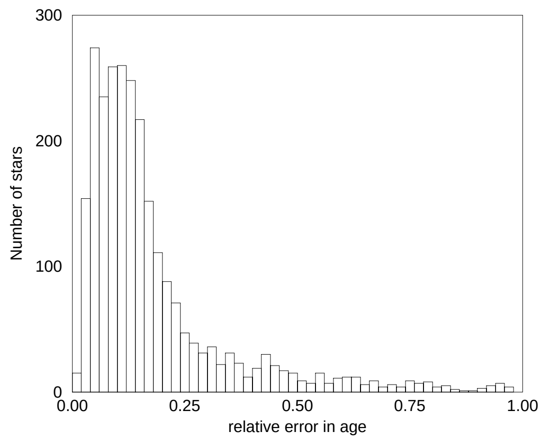

Figure 1. Relative errors in age for the total sample (computed using Monte Carlo simulations, Asiain et al. (1997)).

3. STATISTICAL METHODS

Figure 2 shows the distribution of the total sample in the (U,V) plane. Definitively, and as already noticed by Palouš and Hauck (1986), the observed velocity distribution in these spectral ranges cannot be described by a unique velocity ellipsoid, indicating that a mixture of several kinematic structures is present.

Four different statistical methods have been applied to the total sample to determine which are the mean characteristics of these kinematic structures. They are based on different hypothesis (Gaussian distribution of the sub-structures, Gaussian distribution for the remaining field without imposing any predefined knowledge of the substructures, clustering methods without previous hypothesis, etc), so the coherence among the obtained results will give us a wide understanding of the real phenomena.

The position of the stars around the Sun does not provide any discriminant information for the detection of moving groups, so the working parameters are

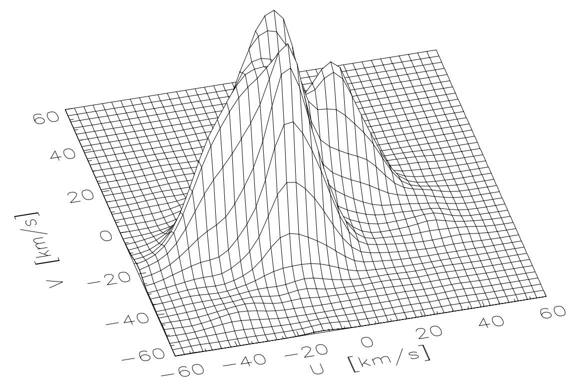

Figure 2. The distribution of the total sample in the (U, V) plane.

the (U,V,W) components of the heliocentric space velocity and the individual ages (τ). As will be seen, this last parameter give important clues to the definition of the moving groups physical properties

3.1. SEMMUL Algorithm

SEMMUL algorithm (Stochatique, Estimation, Maximisation, MULtidimensionnel), developed by Celeux & Diebolt (1986), is a parametric method allowing the separation of Gaussian components inside a sample. It does not need to adopt a set of initial conditions and can work without a predetermined knowledge of the number of components (only needs a maximum number). Adapted by Arenou (1993), it takes into account a Gaussian distribution of the observational errors.

It has been applied to the whole sample in the four-dimensional space of (U,V,W, log(τ)) and about 50 runs have been performed assuming a maximum of 6,7, and 8 groups (Sabas 1997). The results are presented in Table 1.

3.2. Wavelet Transform

The wavelet transform provides an easily interpretable visual representation of a signal s(x,y,z). Moreover, it allows to detect structures working at different scales (detection of hierarchic classes), including voids in the distribution. The wavelet coefficients are computed from:

$$WC(x, y, z, \sigma) = g(x, y, z, \sigma) \bigotimes s(x, y, z) \qquad (1)$$

The adopted wavelet function $g(x, y, x, \sigma)$ is the radial Mexican Hat (Murenzi 1990) which in the 3-Dimensional space takes the form:

Table 1. The means and dispersions of the groups found using the **SEMMUL** *algorithm in the 4-dimensional space: U, V, W components (Units: km s^{-1}) and* $\log(\tau)$.

U	V	W	σ_U	σ_V	σ_W	$\log(\tau)$	$\sigma_{\log(\tau)}$	%	
$-16.8_{\pm 0.6}$	$-10.3_{\pm 0.6}$	$-6.5_{\pm 0.3}$	$7.2_{\pm 0.4}$	$7.6_{\pm 0.4}$	$4.2_{\pm 0.2}$	8.0	0.2	$6.4_{\pm 3.4}$	
$-9.7_{\pm 0.3}$	$-23.9_{\pm 0.3}$	$-5.5_{\pm 0.3}$	$6.4_{\pm 0.3}$	$4.6_{\pm 0.2}$	$4.4_{\pm 0.2}$	8.2	0.2	$13.8_{\pm 5.2}$	Pleiades
$-9.7_{\pm 0.3}$	$-6.0_{\pm 0.2}$	$-8.4_{\pm 0.5}$	$4.4_{\pm 0.2}$	$3.1_{\pm 0.2}$	$6.3_{\pm 0.3}$	8.5	0.2	$8.2_{\pm 5.2}$	
$-26.5_{\pm 0.4}$	$-14.5_{\pm 0.3}$	$-5.3_{\pm 0.4}$	$6.4_{\pm 0.3}$	$4.8_{\pm 0.2}$	$6.7_{\pm 0.3}$	8.6	0.3	$10.3_{\pm 3.5}$	
$10.0_{\pm 0.4}$	$2.8_{\pm 0.3}$	$-7.0_{\pm 0.3}$	$7.5_{\pm 0.3}$	$5.2_{\pm 0.2}$	$6.5_{\pm 0.2}$	8.7	0.2	$15.1_{\pm 2.3}$	Sirius
$-37.4_{\pm 0.4}$	$-15.2_{\pm 0.4}$	$-7.9_{\pm 0.5}$	$6.0_{\pm 0.3}$	$5.2_{\pm 0.3}$	$7.6_{\pm 0.4}$	8.9	0.2	$7.7_{\pm 3.7}$	Hyades
$-10.9_{\pm 0.6}$	$-12.4_{\pm 0.4}$	$-8.0_{\pm 0.3}$	$16.9_{\pm 0.4}$	$13.4_{\pm 0.3}$	$10.2_{\pm 0.2}$	8.8	0.4	$38.5_{\pm 12.9}$	field

$$g(x,y,z,\sigma) = (3 - \frac{x^2+y^2+z^2}{\sigma^2})e^{-\frac{x^2+y^2+z^2}{2\sigma^2}} \qquad (2)$$

where σ is the scale variable: its biggest value is constrained by the extent of the sample and the lowest by the observational errors (~ 2 km s^{-1}). With this method a given structure is detected when its characteristic size is of the same order than the wavelet scale σ, even if it is superimposed on constant background or flat gradient.

In this work, the method has been applied in the 2-dimensional space of (U,V) and in the 3-dimensional case using (U,V,log(τ)). We have checked that the W component of the space velocity does not give additional information.

Figure 3 shows the contour map of the wavelet coefficients obtained in the (U,V) space for $\sigma = 5$ km s^{-1}, together with the results given by the SEMMUL algorithm for comparison. Different scales have also been computed – according to Daubechies (1990) a correct sampling is obtained by increasing σ with a factor $\sqrt{2}$ – being $\sigma = 5$ km s^{-1} a good compromise between the obtained substructures and the observational errors involved.

Due to the difficulty of plotting the wavelet coefficients in the 3-dimensional case, Figure 4 shows the maximum wavelet coefficient obtained for each log(τ) value. The (U,V,log(τ)) values for each maxima are indicated in the top of the figure.

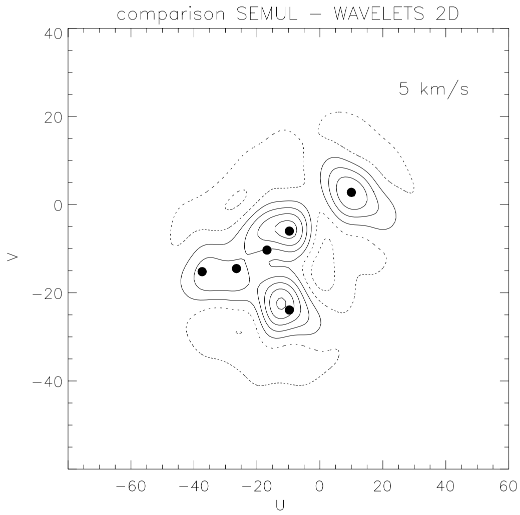

Figure 3. Comparison of the contour map of the wavelet coefficients at $\sigma = 5$ km s^{-1} and the results obtained using SEMMUL (Units: km s^{-1}).

3.3. Non-parametric Approach using KERNEL Estimators

The non-parametric kernel approach used in this work (Chen et al. 1997) is based on the hypothesis that the presence of the moving groups is indicated by a concentration over the ellipsoidal velocity distribution of the field stars. It has the advantage that there is no a predefined hypothesis about the kinematics of the substructures associated to the moving groups. The real probability density function (pdf) of the total sample is computed from:

$$\hat{p}_{\mathrm{real}}(\mathbf{x}) = \frac{1}{nh^d}\sum_{i=1}^{n} K(\frac{\mathbf{x}-\mathbf{x_i}}{h}) \qquad (3)$$

where as Kernel function (K) we use the multivariate normal density function (Fukunaga 1972). This pdf can be expressed as a sum of field stars and moving groups members:

$$p_{\mathrm{real}}(\mathbf{x}) = p_{\mathrm{field}}(\mathbf{x}) + p_{\mathrm{mov}}(\mathbf{x}) \qquad (4)$$

where the pdf of the field stars has been expressed by a multivariate Gaussian function with unknown mean and covariance matrix. Moving groups members are then separated by means of a two hypothesis tests using two thresholds parameters C1 and C2 (Chen et al. 1997). An automatic procedure is used to determine the best C1 and C2 applying a Kolmogorov-Smirnov test to the first main axis of the Principal Component Analysis. After the separation of moving groups members from field stars, cluster analysis is used to assign each star to a moving group. Their means and dispersions are presented in Table 2.

Table 2. Means and dispersions of the groups found using KERNEL algorithm in the 4-dimensional space (U, V, W,$\log(\tau)$) (Units = km s^{-1}).

U	V	W	σ_U	σ_V	σ_W	$\log(\tau)$	$\sigma_{\log(\tau)}$	%	
-10.4	-22.9	-6.3	6.7	5.3	3.9	8.01	0.20	10	Pleiades
11.1	3.5	-6.4	7.5	4.9	6.9	8.81	0.19	11	Sirius
-16.1	-11.9	-6.4	6.4	7.1	3.9	8.34	0.26	17	IC 2391 ?
-44.7	-18.1	-6.1	2.5	2.4	8.5	9.18	0.08	0.5	Hyades
-34.3	-15.5	-4.7	3.2	2.6	5.4	8.77	0.17	3	Praesepe

Table 3. Means and dispersions of the groups found using the BMDP K-means algorithm in the 3-dimensional space (U, V, $\log(\tau)$) (Units: km s^{-1}).

U	V	σ_U	σ_V	$\log(\tau)$	$\sigma_{\log(\tau)}$	%	
-7.1	-26.3	8.7	6.2	8.37	0.31	14	Pleiades
+11.7	+0.5	9.4	7.5	8.81	0.28	20	Sirius
-30.5	-20.1	12.3	8.8	9.01	0.22	18	Hyades ?
-22.7	-16.4	8.3	5.3	8.31	0.24	16	IC 2391 ?
-13.2	-3.9	8.6	6.8	8.81	0.28	19	
-11.3	-7.2	8.5	7.3	7.95	0.30	13	

3.4. BMDP K-means Clustering

The program K-means clustering of cases developed by BMDP Statistical Software Inc. is a particular case of the dynamical clusters algorithm. Based on the aggregation of groups through moving centers, it does not need the knowledge of the location of the groups although the number of groups must be fixed. The results obtained when applying the method to the total sample in the (U,V,$\log(\tau)$) space are presented in Table 3.

4. MEAN PARAMETERS OF THE MOVING GROUPS

The centers of the substructures obtained using the four statistical methods are presented in Table 4 for comparison. The mean velocity components and age of some of the obtained groups can be clearly associated with open clusters present in the solar neighbourhood. Let us remind that known open clusters members have been rejected. In particular, the coherence obtained among SEMMUL, WAVELET and KERNEL methods for the moving groups of Pleiades, Sirius, and Hyades is excellent, definitively confirming the presence of such stellar streams and their association with the corresponding open clusters. Our results show good agreement with those obtained by Eggen (1991, 1992a, 1992b) using the FK5 catalogue: (-11.6, -20.7, -10.4), (14.9, 1.3, -11.2), (-40.0, -17.0, -2.0) km s^{-1} for the moving groups of Pleiades, Sirius and Hyades respectively. Furthermore, thanks to the good quality of the data provided by Hipparcos, Kernel and wavelet-3D methods allow, for the first time, to subdivide the Hyades moving group in two different structures with mean kinematic and age parameters in excellent agreement with Hyades and Praesepe open clusters. Here we must emphasize that the methods have not considered any knowledge of the center of the structure obtained. Another new substructure seems to be present in the Sirius moving group when using the wavelet-3D method, although it has not been possible to associate with any known kinematic structure. The existence of this substructure cannot be confirmed when simulated samples are analysed to derive the threshold of significance of the irregularities obtained with the wavelet-3D method. The existence of substructures in Sirius has also been found by Sabas (1997) and interpreted according to Weidemann (1992) model.

More doubtful is the association of the moving groups we have obtained with the IC 2391 open cluster. Eggen (1992c) obtained (-20.8, -15.9, -8.3) km s^{-1} for the IC 2391 moving group, whereas Palouš (1997) derived (-18.3, -13.5, -5.9) km s^{-1} for the mean velocity of the open cluster. As can be seen in Table 4, SEMMUL and kernel methods can detect this structure but, wavelet method and BMDP can not. The difficulty comes from the fact that this structure is placed near the center of the remaining field stars distribution, its identification becoming in this case more conflictive. Finally, no open cluster counterpart has been found for the young structure obtained around (U,V,W) = $(-10, -6, -8)$ km s^{-1} and the structure placed around (U,V) = $(-26, -15)$ km s^{-1}, although three of our methods indicate their existence.

KERNEL method allows, in addition to the determination of the mean kinematic properties, the identification of the moving group members in the fourth dimensional space of (U,V,W,$\log(\tau)$). In Figure 5 the spatial distribution of the obtained members is plotted, confirming the fact that the stars belonging to moving groups are disseminate around the Sun with-

Table 4. Comparison between different methods: obtained moving groups and their association with open clusters.

SEMUL 4D (U,V,W),log(τ)	WAVELETS 2D - (U,V) $\sigma = 5$	WAVELETS 3D (U,V,log(τ)) $\sigma = 3$	KERNEL 4D + CA (U,V,W,log(τ))	BMDP (U,V,log(τ))	Associated open cluster Gómez et al. (1990)
(-10,-24,-5) 8.2	(-10,-23)	(-15,-24) 8.13 (-14,-21) 7.78	(-10,-22,-6) 8.01	(-7,-26) 8.38	Pleiades: (-5.8,-24.0, -12.4)
(+10, +3,-7) 8.7	(+10, +2)	(+13, +2) 8.63 (+7, +6) 9.04	(+11, +4,-6) 8.81	(+11,+0) 8.81	Sirius: (+14.5,+2.5,-8.5)
(-37,-15,-8) 8.9	(-40,-17)	(-44,-19) 9.20 (-33,-16) 8.82	(-44,-18,-6) 9.18 (-34,-15,-5) 8.77	(-30, -20) 9.01	Hyades: (-44.4, -17.0, -5.0) Praesepe: (-37.1,-23.5,-7.0)
(-16,-10,-6) 8.0			(-16,-12,-6) 8.34		IC 2391: (-18.3,-13.5, -5.9)
(-26,-14,-5) 8.6	(-26,-17)	(-26,-17) 8.50		(-22,-16) 8.31	
(-10, -6,-8) 8.5	(-11, -6)	(-9, -6) 8.00		(-11,-7) 7.9	
				(-13,-4) 8.8	
		(-17, -5) 8.22			

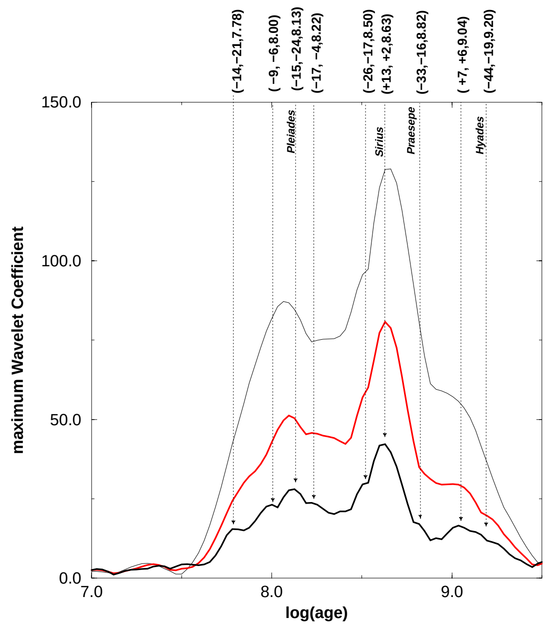

*Figure 4. Maximum wavelet coefficient obtained in the (U,V,*log(τ)*) space at each* log(τ) *for σ = 5 (top), 4, 3 (bottom).*

out showing any concentration near the open clusters counterparts.

One of the most important characteristics of the moving groups in order to understand their origin and evolution is its velocity dispersion. The coherence among the results provided by the methods is excellent except for the BMDP K-means method where the large values obtained are explained by the fact that field stars are mixed with moving group members. When the wavelet transform is computed at different scales the structure of Sirius appears around $\sigma = 8$ km s^{-1}, being maintained until $\sigma = 3$ km s^{-1}, whereas Pleiades is well recognized at $\sigma = 5$ km s^{-1} and Hyades at $\sigma = 4$ km s^{-1}. The dispersions obtained from SEMMUL and Kernel methods are plotted in Figure 4. versus the age. The mean values are: σ_U= 5.84 km s^{-1}, σ_V = 4.80 km s^{-1} and σ_W= 5.85 km s^{-1}. A slight trend on ages seems to be present although we have not physical explanation for it and will deserve further studies. Taking into account that the distribution of the observational errors in our total sample $((\epsilon_U, \epsilon_V, \epsilon_W) = (2.4, 2.4, 1.9)$ km s^{-1}) is contributing to the velocity dispersion of the moving groups in no more than 0.5–0.6 km s^{-1}, the classical point of view that a moving group should have a small dispersion in the V component must be definitively rejected. Other interpretations in terms of a local concentration of dark matter (Casertano et al. 1993) or a model assuming the origin of these groups to lie in large scale spiral shocks associated to the spiral density waves (Comerón et al. 1997) must be considered.

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REFERENCES

Arenou, F., 1993, PhD Thesis. Observatoire de Paris-Meudon

Asiain, R., Torra, J., Figueras, F., 1997, A&A, (in press)

Barbier-Brossat, M., 1997, private communication

Casertano, S., Iben, I., Shiels, A., 1993, ApJ, 410, 90

Celeux, G., Diebolt, J., 1986, R.S.A., 34, n2, 35

Chen, B., Asiain, R., Figueras, F., Torra, J., 1997, A&A, 318, 29

Comerón, F., Torra, J., Figueras, F., 1997, A&A, (in press)

Daubechies, I., 1990, in Wavelets, eds. Combes J.M., Grossman, A., Thamitchian, Ph., Springer, Berlin, p. 38

Duflot, M., Figon, P., Meyssonnier, N., 1995, A&AS, 114, 269

Eggen, O.J., 1991, AJ, 102, 2028

Eggen, O.J., 1992a, AJ, 103,1302

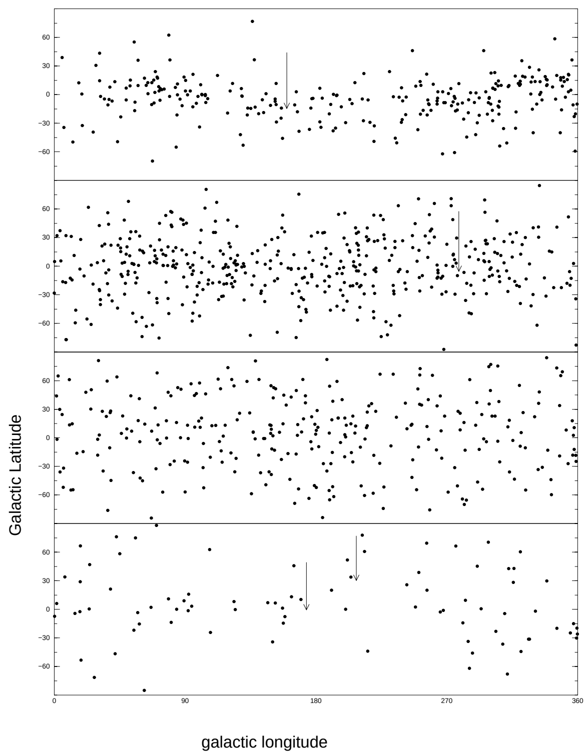

Figure 5. Spatial distribution of the moving group members obtained using KERNEL method. From the top to the bottom: Pleiades, IC 2391, Sirius, and Praesepe + Hyades. Arrows indicate the position of the open cluster.

Eggen, O.J., 1992b, AJ, 104, 1482

Eggen, O.J., 1992c, AJ, 104, 1493

Fukunaga, K., 1972, in Introduction to Statistica Pattern Recognition, New York Academic Press, p. 175

Gómez, A.E., Delhaye, J., Grenier, S., et al., 1990, A&A, 236, 95

Grenier, S., 1997, private communication

Hauck, B., Mermilliod, J.C., 1996, private communication

Jordi, C., Figueras, F., Torra, J., Asiain, R. 1996, A&AS, 115, 401

Lebreton, Y., 1995, private communication

Meillon, L., Crifo, F., Gómez, A.E., 1997, private communication

Murenzi, R. 1990, in Wavelets, eds. Combes J.M., Grossman, A., Thamitchian, Ph., Springer, Berlin, p. 239

Palouš, J., Hauck, B., 1986, A&A, 162, 54

Sabas, V. 1997, PhD Thesis. Observatoire de Paris

Weidemann, V., Jordan, S., Iben, I., Casertano, S., 1992, AJ, 104, 1876

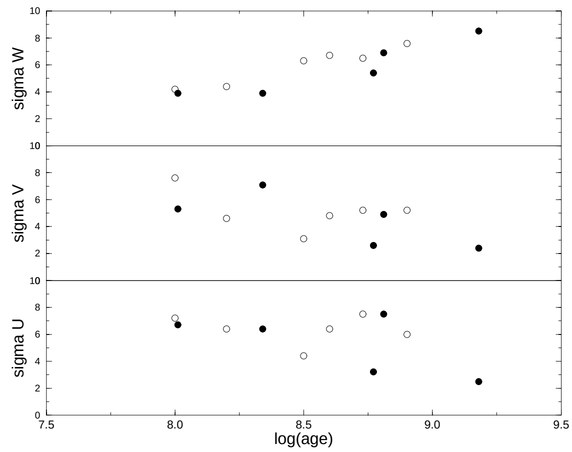

Figure 6. Moving group velocity dispersion versus age, using SEMMUL (open circles) and KERNEL (dots) methods.