Radial velocities of K–M dwarfs and local stellar kinematics[★]

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ABSTRACT

Aims. The goal of this paper is to present complete radial-velocity data for the spectroscopically selected McCormick sample of nearby K–M dwarfs and, based on these and supplementary data, to determine the space-velocity distributions of late-type stars in the solar neighborhood.

Methods. We analyzed nearly 3300 measurements of radial velocities for 1049 K–M dwarfs, that we obtained during the past decade with a CORAVEL-type instrument, with a primary emphasis on detecting and eliminating from kinematic calculations the spectroscopic binaries and binary candidates. Combining radial-velocity data with HIPPARCOS/Tycho-2 astrometry we calculated the space-velocity components and parameters of the galactic orbits in a three-component model potential for the stars in the sample, that we use for kinematical analysis and for the identification of possible candidate members of nearby stellar kinematic groups.

Results. We present the catalog of our observations of radial velocities for 959 stars which are not suspected of velocity variability, along with the catalog of U, V, W velocities and Galactic orbital parameters for a total of 1088 K–M stars which are used in the present kinematic analysis. Of these, 146 stars were identified as possible candidate members of the known nearby kinematic groups and suspected subgroups. The distributions of space-velocity components, orbital eccentricities, and maximum distances from the Galactic plane are consistent with the presence of young, intermediate-age and old populations of the thin disk and a small fraction (~3%) of stars with the thick disk kinematics. The kinematic structure gives evidence that the bulk of K–M type stars in the immediate solar vicinity represents a dynamically relaxed stellar population. The star MCC 869 is found to be on a retrograde Galactic orbit ($V = -262 \text{ km s}^{-1}$) of low inclination (4°) and can be a member of stellar stream of some dissolved structure. The Sun's velocity with respect to the Local Standard of Rest, derived from the distributions of space-velocity components, is $(U_\odot, V_\odot, W_\odot) = (9.0 \pm 1.4, 13.1 \pm 0.6, 7.2 \pm 0.8) \text{ km s}^{-1}$. The radial solar motion derived via the Strömberg's relation, $V_\odot = 14.2 \pm 0.8 \text{ km s}^{-1}$, agrees within the errors with the value obtained directly from the V distribution of stars on nearly circular orbits.

Key words. techniques: radial velocities – stars: late-type – stars: kinematics and dynamics – binaries: spectroscopic – solar neighborhood

1. Introduction

The immediate neighborhood of the Sun is the only region of the Galaxy where we can at present obtain fairly complete and accurate observational data of its stellar content. Nearly all solar-type stars in the solar vicinity are well known and accurately mapped after the successful HIPPARCOS satellite mission (ESA 1997) and follow-up surveys of the pre-*Gaia* era. Among the latter, the most comprehensive is the Geneva-Copenhagen Survey (GCS, Nordström et al. 2004; Holmberg et al. 2007, 2009) of a magnitude-complete, kinematically unbiased sample of ~14 000 dwarf stars of spectral types F and G, which provides a wealth of information on the distribution functions of stellar kinematics, metallicity, and age that have efficiently been used to test models of the evolution of the Galactic disk (e.g., Schönrich & Binney 2009a,b, 2012; Schönrich et al. 2010; Sharma et al. 2011, 2014). However, our knowledge of the observed parameters for dwarf stars of spectral types K and M is fragmentary and incomplete. Differently from their higher-mass

counterparts, late-type dwarfs have not been beneficial targets for comprehensive studies, mainly because of difficulties in getting stellar models and, consequently, determining their metallicities and ages. The number of nearby K–M dwarfs that have the full set of accurate phase-space parameters is, however, small compared to thousands of F–G stars in the GCS catalog and does not permit to reveal the distribution functions for their observable quantities to the same level of significance as that of GCS.

One of the largest collections of basic data on nearby K–M stars is contained in the catalog of nearby stars CNS3 (Gliese & Jahreiß 1991) and its latest, not yet published version CNS4. Another large collection of such stars comes from the lists of stars selected spectroscopically by A. N. Vyssotsky and his colleagues in 1943–1958 at the McCormick Observatory (hereinafter MCC). The CNS catalog and the MCC lists, although different in the ways of sampling – the former being volume-limited (25 pc) and the latter magnitude-limited ($V \sim 11.5$) – are two main sources of nearby K–M dwarfs, which complement each other and provide a joint collection of about 2000 stars. With new observational data being progressively incorporated, the CNS and MCC samples have been used in nearly all kinematical studies of late-type stars during the past few decades.

[★] Full Tables 2, 4, 5, 7, and a table of the individual RV measurements are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/596/A116>

The early kinematical solutions inferred from the then available data on MCC stars were summarized in the review paper by Delhaye (1965). Later on, Wielen (1974) presented the velocity distributions of K–M dwarfs from the catalog of nearby stars compiled by Gliese (1969). The much more accurate results on the local kinematics of late-type dwarfs, based on HIPPARCOS astrometry, have been reported by Uggren et al. (1997) and Jahreiß & Wielen (1997). The Palomar/MSU nearby star spectroscopic survey (Reid et al. 1995, 2002; Hawley et al. 1996; Gizis et al. 2002) has resulted in the analysis of chromospheric activity and kinematics of ~ 1700 M dwarfs from the CNS3 catalog. As kinematic probes to distances exceeding the CNS limit (25 pc), Bochanski et al. (2005) have used a sample of 574 M-type dwarfs within 100 pc, based on spectroscopic parallaxes. Recently, a comprehensive- and growing-data base of stars within 25 pc of the Sun has been compiled by the RECONS (REsearch Consortium On Nearby Stars)¹ team, in an effort to investigate the stellar and planetary companion populations of red dwarfs, the spread of the lower main-sequence in luminosity, the excess emission due to unseen companions and dust, etc. (Henry et al. 2015). Local samples of M-type stars now deserve the utmost attention in search for extra-solar terrestrial planets orbiting nearby stars (e.g., Zechmeister et al. 2009; Bean et al. 2010; Bonfils et al. 2013; Alonso-Floriano et al. 2015). Due to their higher planet/star mass ratios, M dwarfs are the most potential targets for detection of low-mass planets by Doppler spectroscopy.

At present, however, kinematical studies of the nearby late-type stars have become somewhat foreshadowed with the advent of deep, wide-field SDSS (York et al. 2000), SDSS/SEGUE (Yanny et al. 2009) and RAVE (Steinmetz et al. 2006) surveys which have made it possible to study K–M dwarfs to much greater distances from the Sun. Using their spectroscopic catalog with radial velocities measured with an external accuracy of $7\text{--}10\text{ km s}^{-1}$ and applying photometric parallax relations, the SDSS teams have traced K–M dwarfs in the distance range up to ~ 2 kpc, thus providing valuable information on the spatial, velocity, and metallicity distributions with respect to vertical distance from the Galactic plane (Bochanski et al. 2007, 2011; Jurić et al. 2008; Fuchs et al. 2009; Bond et al. 2010; West et al. 2011; Schlesinger et al. 2012; Zhang et al. 2013), as well as on the luminosity and mass functions of low-mass dwarfs in the Galactic disk (Covey et al. 2008; Bochanski et al. 2010). Relatively local ($|z| < 500$ pc) samples of late-type dwarfs from the RAVE survey, based on radial velocities accurate to $\sim 2\text{ km s}^{-1}$ and photometrically determined distances, have been used to deduce the solar space velocity with respect to the Local Standard of Rest (Coşkunoğlu et al. 2011; Pasetto et al. 2012a; Golubov et al. 2013). The RAVE survey has also resulted in a catalog of $\sim 44\,000$ candidate active stars (Žerjal et al. 2013) which makes a major contribution to the data on chromospheric emission of cool dwarfs. In the context of these massive surveys, as well as of present-day models of the Galaxy, the samples of nearby late-type dwarfs with most accurate trigonometric parallax and radial-velocity measurements, as well as other high-quality observational data, still remain important, as they provide a fundamental framework for calibration and tests of relations between low-mass star parameters (such as, e.g., color-luminosity, mass-luminosity, activity-age, chemokinematic relations).

Until recently, the principal limitation in observational data for the CNS and MCC stars was the lack of accurately measured

Fig. 1. Location of the MCC K–M dwarfs (open circles) in equatorial coordinates in an Aitoff projection on the sky. The radial-velocity program stars from the CNS list are shown as crosses.

radial velocities, especially for fainter magnitude stars. Of the ~ 900 MCC stars, about 500 have radial velocities that have an error less than 2 km s^{-1} . The early contribution was made by Wilson (1967) who provided radial velocities of ~ 300 MCC stars with an average accuracy of 1.8 km s^{-1} . Later on, Uggren & Caruso (1988) and Uggren & Harlow (1996) obtained much more accurate velocities of 278 stars from the MCC sample. In addition to these contributions, around 150 of the MCC stars were monitored by other authors in search for low-mass binaries and substellar mass companions (e.g., Marcy & Benitz 1989; Tokovinin 1992), for establishing improved radial-velocity standards (Nidever et al. 2002) or for other purposes. Shortly before 2000, with manufacturing at the Vilnius University Observatory of the radial-velocity scanner, one of the authors (A.R.U.) initiated a completion of the radial-velocity observations of all MCC stars.

In this paper, we present radial-velocity measurements for nearby K–M dwarfs carried out within our CORAVEL program (Uggren et al. 2002) in 2000–2014 and report the results of kinematical analysis obtained with these observational data. The paper is structured as follows. In Sect. 2 we describe the sample. In Sect. 3 we describe the radial-velocity scanner used, summarize our observations and data reductions, and present the catalog of mean radial velocities for 959 stars not suspected in velocity variability, together with error analysis. In Sect. 4 we briefly describe the observational data used to compute the space velocities (U, V, W) and the potential models used for integration of galactic orbits. In this section, the online catalogs of input observational data on a total of 1160 K–M dwarfs and computed kinematic parameters for 1088 of these stars are described. Section 5 is devoted to the identification of nearby kinematic groups among these late-type stars. In Sect. 6 we briefly discuss possible kinematic biases built in due to sample selection effects and present the local kinematics and the determination of the Sun’s motion with respect to the local standard of rest (LSR). Conclusions are summarized in Sect. 7.

2. The sample

A sample of spectroscopically selected MCC stars forms the basis of the kinematical analysis presented in this paper. The original MCC sample comprised 895 stars (plus 22 fainter components) of spectral types K0 V to M5 V, with a few stars on the reddest side of this range. These stars were identified decades ago by Alexander Vyssotsky and his colleagues (for a review, see Uggren & Weis 1989) from McCormick objective prism plates

¹ <http://www.recons.org/>

taken to the magnitude limit of $V \sim 11.5$ at all RA and northward of declination -30° (Fig. 1). As a result of the spectroscopic sampling, the MCC stars should form a kinematically unbiased sample. In the ARI database for nearby stars (ARICNS)² compiled by H. Jahreiß at the Astronomisches Rechen-Institut, Heidelberg, the MCC sample is expanded by adding to many of the original MCC stars their fainter secondary components. This brings the total number of stars in the MCC sample up to 1120. However, the fainter components below the magnitude limit $V \approx 12$ mag, as well as those having no individual parallax or proper-motion data to assess their relationship with primaries, were not included in our regular observing program. As seen from the distribution histogram of trigonometric parallaxes of the program stars (Fig. 2a), the bulk of the MCC stars (91%) are confined to within 50 pc from the Sun, with the rest of the sample stars (9%) lying in the distance range from 50 to 102 pc. The median distance of the entire MCC sample is 28 pc.

At the time we started CORAVEL measurements of the MCC stars H. Jahreiß initiated radial-velocity observations of two hundred K–M dwarfs selected from a new version (CNS4) of the Catalog of nearby stars (Gliese & Jahreiß 1991), which had no or only poor-quality radial velocities. These stars, however, do not enter the MCC sample, and were included in our observational program as a separate list which, for convenience, will hereafter be called “CNS list”. This small set of stars comes from different parent population of stars, meaning that it is biased in favor of larger proper motions (see Fig. 2c) built in due to the volume limit (25 pc) and, partly, the selection by large proper-motions which may also indicate larger tangential velocities. Thus, in the present analysis of local kinematics these CNS stars will not be used along the same lines as the MCC stars, except for their involvement in the identification of candidate members of the stellar kinematic groups.

On the other hand, a comparison of the numbers of stars in the “CNS list” and those in the MCC subsample within 25 pc (shaded and hatched histograms in Fig. 2c) shows limits of incompleteness of the MCC sample in this distance range. Down to the MCC magnitude limit $V \sim 11.5$, we have at least about 100 CNS stars of spectral types K–M in the same range of declinations, which remain missing in the MCC sample. The number of such “missing” stars within the MCC sample can even be larger since the CNS stars which have precise radial velocities were not included in our program list of observations.

Although the MCC sample indicates increasing incompleteness as one approaches both the magnitude limit and the more southerly declinations (see Fig. 1), these non-sharp cuts, according to Weis & Uggren (1995), are not expected to introduce any kind of bias important to kinematical analysis. Just to verify the validity of this expectation, we checked the possible effect of missing data at southern declinations by comparing simulations of the Besançon model (Robin et al. 2003; Czekaj et al. 2014) at declinations $+90^\circ$ to -30° (MCC domains) with those at declinations -30 to -90 where MCC data are unavailable. However, the distributions of velocity components U , V , and W revealed no appreciable difference, except for the component U which appeared to be somewhat susceptible (differences less than 0.7 km s^{-1}) to the absence of data at southern declinations (for details, see Fig. 15 in Sect. 6.1.1).

The basic observational data for the sample stars, available in the literature, can be summarized as follows. The vast majority of the MCC stars (900 stars in total) have HIPPARCOS based

Fig. 2. Distributions of radial-velocity program stars by values of trigonometric parallax **a)**; its relative error **b)**; and proper motion **c)**. In panel **a)**, the top axis shows distances in pc; the two nearest ($d < 3$ pc) MCC stars are outside the plotting area. To enable a direct comparison of the two different samples in panel **c)**, a separate histogram (hatched) is shown for a subset of MCC stars within 25 pc.

parallaxes, whereas many of the rest, fainter MCC stars have relatively precise ground-based trigonometric parallaxes. With the exception of a significant number of the fainter components (42), all of the MCC stars have photoelectric BVR data, obtained mainly by Uggren (1987), including recent homogeneous $UBV(RI)_C$ photometry by Koen et al. (2010) for 185 stars in common. Currently available astrophysical data on MCC stars are limited to a much smaller fraction of the sample. Chromospheric activity data (H_α , Ca II H and K) are available for half of

² <http://wwwadd.zah.uni-heidelberg.de/datenbanken/aricns/>

Fig. 3. $(M_V, V - I_C)$ diagram for the MCC stars (black solid and red circles) and stars from the CNS list (black open and blue circles). The thick line is the mean relation for the color interval $0.9 < V - I_C < 2.8$, defined by Bartašiūtė et al. (2012) using the present sample stars with $\sigma_\pi/\pi \leq 0.05$ (red and blue circles). The error bars represent uncertainties due to trigonometric parallax error. Spectral types shown on the top axis are in accordance with the calibration of $V - I_C$ by Bessell & Brett (1988).

the sample stars, obtained mainly by the Palomar/MSU spectroscopic survey (Reid et al. 1995; Hawley et al. 1996), the “HK Project” at Mount Wilson Observatory (Duncan et al. 1991), the NStars project (Gray et al. 2003, 2006), and the California Planet Search program (Isaacson & Fischer 2010). A total of only 80 MCC stars, mainly of spectral type K, have $[\text{Fe}/\text{H}]$ estimates from high-dispersion spectra. Similar levels of completeness of available astrometric and astrophysical data are for the program list of 198 CNS stars.

Prior to undertaking our observing program of radial velocities, two-thirds of the MCC sample stars had no accurate (with an error of $<1 \text{ km s}^{-1}$) or any radial velocity data. After our program was nearly complete, a catalog of precise radial-velocities of nearby F–M stars by Chubak et al. (2012), based on spectra taken in 2004–2011 with the Keck I telescope, appeared that includes 195 stars common to our program (139 MCC stars and 56 stars from the CNS list). These and other precise radial velocities published previously for stars we have in common (e.g., Marcy & Benitz 1989; Nidever et al. 2002) were used by us to check the zero point accuracy and precision of our radial-velocity velocity measurements, as well as in our kinematic calculations (Sect. 4.1). We also add, in this context, that for 35 stars of our observing program, accurate radial velocities have recently become available from the latest SDSS APOGEE release (Alam et al. 2015).

The $(M_V, V - I_C)$ diagram for the program stars is shown in Fig. 3. The absolute magnitudes are calculated mainly from the HIPPARCOS parallaxes; in the case when these were unavailable, ground-based trigonometric parallaxes are used. As is apparent, there is considerable scatter of points, an appreciable fraction of which is certainly caused by parallax error (black solid and black open points representing stars with $\sigma_\pi/\pi \geq 0.05$) and the presence of double and variable stars. The gray thick line represents the mean relation defined in the paper by Bartašiūtė et al. (2012) using the present program stars with $\sigma_\pi/\pi \leq 0.05$, which belong kinematically to the thin disk population and which were carefully selected to be single and non-variable (i.e., showing no signs of radial-velocity variability and not contained in the “double and multiple star” or “variability” annex of the HIPPARCOS catalog or reported elsewhere

as binaries and variables). These selected stars (a total of 347 with $V I_C$ photometry) are shown in the diagram by red (MCC) and blue (CNS) symbols. In fitting this relation, no statistical Lutz-Kelker corrections (Lutz & Kelker 1973) were applied to absolute magnitudes as such corrections would be too small to affect the fit. Considering the latter stars, we find an rms scatter of $\pm 0.25 \text{ mag}$ in M_V to this fit that can be the result of both the astrophysical dispersion (possible age and abundance variations or some unknown astrophysical causes) and the errors in apparent magnitudes due to as-yet unrecognized binarity, intrinsic brightness variability, or both. We note that over most of the color range our relation matches quite satisfactorily the relation derived for calibration purposes by Reid & Cruz (2002) using CNS stars with accurate (mainly HIPPARCOS) trigonometric parallaxes. The most significant systematic difference is observed only in the interval $V - I_C = 1.30\text{--}1.80$ (spectral types K7 to M0) where our relation is displaced by $0.12\text{--}0.18 \text{ mag}$ to fainter absolute magnitudes from the Reid & Cruz’s relation given as a 6th degree polynomial. Also, our relation compares rather satisfactorily with the linear relation by Stobie et al. (1989) based on CNS stars with pre-HIPPARCOS parallaxes: the largest systematic departure (around spectral type K4) does not exceed 0.15 mag in M_V .

In addition to the $(M_V, V - I_C)$ relation shown in Fig. 3, the relations $(M_V, B - V)$ and $(M_V, V - R_C)$ were also defined in the above-quoted paper by Bartašiūtė et al. (2012). These three relations were used in the present paper to infer the absolute magnitudes and distances to 29 stars of the MCC sample, which had no any, or very poor, trigonometric parallax data (see Sect. 4.1).

3. Observations and velocity measurements

3.1. CORAVEL-type radial-velocity spectrometer

The radial velocities presented in this paper were all measured with the CORAVEL-type spectrometer of Vilnius University Observatory, working on the principles of the photoelectric radial-velocity scanner developed by Griffin (1967). The principal optics of the spectrometer are assembled in accordance with a Littrow configuration. As the main disperser an Echelle grating

Fig. 4. CCFs for stars of spectral types K7 (dots), M0 (open circles), and M3 (crosses), obtained with the CORAVEL-type spectrometer. The solid lines are Gaussian fits to the measured CCF profiles.

with 75 g mm^{-1} is used. The spectrum is spread over 25 orders from 385 to 640 nm, with dispersions of 0.14 nm mm^{-1} in the 62 order and 0.24 nm mm^{-1} in the 38 order. Cross dispersion is provided by a 22-grad flint prism in double pass mode. An achromatic two-component cemented lens of focal ratio $f/11$ is used as a camera-collimator of the spectrograph. The spectrum is focused on the physical mask, an opaque film of dimension $W60 \times H30 \text{ mm}$, containing 1650 transparent slits centered on the positions of absorption lines, mostly of neutral metals, which were selected from the photographically registered spectrum of the Sun. Some additional lines were selected from the spectra of Arcturus (K2 III) and Procyon (F5 IV–V). The size of the slits, $0.11 \times 0.7 \text{ mm}$, is the same as the one of the spectrograph entrance slit. The light from the mask is collected by the Fabri lens and focused on the photocathode of a Hamamatsu type R647 (S11, bialkali) photomultiplier and then registered in a single photon counting mode. The process of scanning is performed by moving the stellar spectrum along the mask by 1.124 km s^{-1} in every 5 ms and reading the signal at the same intervals of time. The spectrum scanning unit is driven by a step-motor. The operation and monitoring of the spectrometer, signal reading, and preliminary data reduction in real time are performed by the software running on a PC.

The effectiveness of the mask in the cross-correlation process depends on the star's spectral type. In our case, the range of spectral types to which the mask of our spectrometer can be applied is from F5 to about M5, with the highest effectiveness achieved for stars of spectral type K. Examples of the cross-correlation functions (CCF) for stars of different spectral types are shown in Fig. 4.

3.2. Observations and data reductions

Radial-velocity measurements of K–M dwarfs were obtained in 2000–2014. The dates of observing runs, sites, the telescopes used and the number of measurements are given in Table 1.

For each observing night the instrumental velocity zero point and its time-dependent drift were determined by repeated observations of several IAU radial-velocity standards. The values of their radial velocities were taken from Udry et al. (1999). After measuring each program or standard star, two spectral lines of a low pressure Hg lamp were also scanned to control spectrum

Table 1. Runs of observations.

Run	Dates	Observatory	Telescope	Number of measurements
1.	18–29 Mar. 2000	Steward Obs., Mt. Bigelow	1.6 m	153
2.	18–26 Feb. 2002	Steward Obs., Mt. Bigelow	1.6 m	100
3.	15 Mar.–04 May 2002	Moletai Obs., Vilnius Univ.	1.65 m	77
4.	01 Oct.–18 Dec. 2003	Steward Obs., Mt. Lemmon	1.5 m	341
5.	10 Mar. 2010–14 May 2014	Moletai Obs., Vilnius Univ.	1.65 m	2616

Fig. 5. Radial-velocity zero point and its drift for the night January 22, 2010. The solid curve is an approximation of the measurements by a second-degree polynomial.

shifts at the detector due to flexure of the spectrograph when moving the telescope to different positions on the sky. A zero point drift for a typical observing night is shown in Fig. 5.

During each observing run the same technique was followed for measuring the radial velocities. The configuration of the instrument was also the same, except for minor changes in the spectrum-scanning mechanism and data reading procedure. To detect systematic tendencies between the runs we compared the radial velocities of each of the first four observing runs with those measured for the stars in common in the 5th run (2010–2014) during which many repeated observations for most of the stars were obtained. We note that during each of the first three runs only up to five stars were observed more than once, and in the 4th run 135 stars were observed repeatedly. The comparison of observations of each of these four runs with those obtained in the 5th run revealed the systematic differences, in the sense $V_r^{(1,2,3,4)} - V_r^{(5)}$, as follows: $+0.3 \text{ km s}^{-1}$ for the 1st run (123 stars) and 2nd run (38 stars), $+0.6 \text{ km s}^{-1}$ for the 3rd run (39 stars), and $+0.1 \text{ km s}^{-1}$ for the 4th run (108 stars). Given in parentheses are the numbers of stars common to the 5th run. Therefore, the values of V_r from the runs (1) through (4) were corrected to match the main set of velocities of 2010–2014 (the 5th run). We found no $V-I$ color dependence of the velocities in each of the five observing runs.

The internal errors of individual measurements (Fig. 6) are spread over an interval of mostly $0.5\text{--}1.6 \text{ km s}^{-1}$, with the majority being close to 0.6 km s^{-1} . They were calculated taking into account the error on the fitted parameters of the Gaussian approximation of the measured CCF due to photon and instrumental noise and the errors of radial-velocity zero point derived for each observing night. The largest errors are mainly for late

Fig. 6. Distribution of the internal errors for a single radial-velocity measurement.

Fig. 7. Differences in radial velocities, in the sense our values (CORAVEL) minus the values from Chubak et al. (2012), as a function of color index $V-I$. The lines represent the linear and polynomial relations.

M-type stars, for which the depth of the CCF drops below 10%, and for stars the CCFs of which are broadened due to fast rotational velocities or unresolved duplicity.

To get an external measure of the accuracy of our measurements, including a zero-point offset and precision, we compared our velocities to published velocities of high precision. Our sample contains about one hundred stars of constant radial velocity from the catalog by Nidever et al. (2002) and a dozen M-type stars from the list by Marcy & Benitz (1989) of their search for substellar companions to low mass stars. Also, the catalogs of precise radial velocities of nearby F–M stars and V_r standards, based on spectra taken with the Keck I telescope, have recently been published by Chubak et al. (2012), doubling the number of stars we have in common (251). The radial velocities in the latter source share the same velocity scale with the one of Nidever et al. (2002). A significant fraction of the stars sampled for comparison are common among these three sources.

Figure 7 shows the difference between our values of V_r and those from Chubak et al. (2012) as a function of stellar color $V-I$ for 188 stars in common. The average difference is

$$\langle V_{\text{CORAVEL}} - V_{\text{Chubak}} \rangle = -0.33 \pm 0.04 \text{ km s}^{-1}, \quad (1)$$

with an rms scatter of $\pm 0.59 \text{ km s}^{-1}$. As can be seen from Fig. 7, there is no statistically significant evidence for a linear or polynomial correlation of the differences in the velocities with the color of the stars. Thus, we have not applied any color (or spectral type) dependent corrections to our radial velocities.

Comparing our velocities for 96 stars common to those given by Nidever et al. (2002) and Marcy & Benitz (1989), we obtain

$$\langle V_{\text{CORAVEL}} - V_{\text{Nidever+Marcy}} \rangle = -0.36 \pm 0.07 \text{ km s}^{-1}, \quad (2)$$

with an rms scatter of $\pm 0.75 \text{ km s}^{-1}$.

From these comparisons we can conclude that our velocities differ in zero point by 0.3 km s^{-1} . This correction was applied to all of our raw velocities to achieve agreement with the best published standard star velocities. With the above comparisons in mind, we can also conclude that our velocities should be accurate, on average, to within $\pm 0.7 \text{ km s}^{-1}$. Other lines of argument on this precision of our measurements can be added from Fig. 10 in Sect. 3.4.

3.3. Catalog of radial velocities

We obtained a total of 3287 individual measurements of 1055 stars, of which 857 stars are from the MCC sample and 188 stars from the CNS list. The remaining 10 stars measured, also of late spectral type, are non-program stars and enter neither MCC nor CNS sample: three of these stars are CCDM (Dommanget & Nys 2002) components to double or multiple program-stars, and other seven stars were measured due to misidentification. However, since these ten non-program stars have no radial velocities published, we listed them in the table of our observations (Table 2) but not used in kinematic analysis. The distributions in V magnitude and $V-I$ color index of the measured program stars are given in Figs. 8a and b. For the stars which had no previously published velocities or had those of only poor quality, we had originally hoped to obtain multiple observations over a time span of several years, typical for revealing possible velocity variability. However, the vagaries of scheduling and weather prevented the full realization of the program. For 38 such stars in the MCC sample and 22 stars from the CNS list, only single measurements were secured. Five MCC stars (MCC Nos. 88, 168, 346, 349, and 683) at the more southerly declinations ($< -14^\circ$) and three stars from the CNS list, which have no or only poor published velocities, have remained unobserved.

For the stars with multiple observations, the weighted mean radial velocities, $\langle V_r \rangle$, and their uncertainties, ε , were calculated following the formula by Jasiewicz & Mayor (1988). For a specific star with N measurements, ε is taken to be the largest of the two uncertainty estimates, an external error estimate provided by the standard deviation from the mean, E , and the mean internal error I . That is, $\varepsilon = \max(E/\sqrt{N}, I/\sqrt{N})$.

In Table 2, only available at the CDS, the mean velocities and their uncertainties are given for 959 stars which were not suspected of velocity variability on account of criteria described in Sect. 3.4 or have solutions of their spectroscopic orbits (MCC 412 and MCC 796A). This table also includes stars with only one observation even though their error ε is not defined. Instead, we give in this case an internal error of a single measurement. We note that, according to negligible values of trigonometric parallax and (or) to the shape of CCF of CORAVEL measurements, MCC 69 (BD +10°4409), MCC 237 (by CCF only), and MCC 315 (HIP 75435) appear to be giant stars rather than dwarfs.

Table 2. Mean radial velocities of K–M dwarfs measured with the CORAVEL-type spectrometer.

No.	MCC number	Other name	RA 2000.0	Dec 2000.0	V_r (km s ⁻¹)	ε (km s ⁻¹)	N	T_0 (JD–2 400 000)	ΔT (days)	Parent name
1	MCC 871	HIP 18	00 00 12.68	–04 03 13.3	26.1	0.3	3	55669	385	
2	MCC 872	HIP 74	00 00 53.36	+35 45 09.4	–4.0	0.3	2	55461	32	
3	MCC 215B	BD+13 5195B	00 01 12.86	+13 58 19.7	–8.1	0.4	2	55683	396	HIP 96
4	MCC 215A	BD+13 5195A	00 01 13.19	+13 58 30.3	–10.6	0.7	4	55676	411	HIP 96
5	MCC 216	HIP 428	00 05 10.89	+45 47 11.6	–1.5	1.0	1	55816	0	
...	...	...	...	...	...	...	...	...	...	...

Notes. This table is only available at the CDS. A portion of the first page of the table is shown here for guidance regarding its form and content. Description of columns: Col. 1: running number; Col. 2: MCC number (if blank, the star is from the CNS list). Stars are ordered by right ascension; Col. 3: other name (HIPPARCOS number is preferentially listed); Cols. 4, 5: coordinates RA(2000.0) and Dec(2000.0); Col. 6: the mean radial velocity; Col. 7: error in radial velocity; Col. 8: number of radial-velocity measurements; Col. 9: mean of the Julian Dates of observations, in JD–2 400 000; Col. 10: time span (in days) between the first and last observations; Col. 11: parent star name for the components of double stars.

Fig. 8. Distributions of observed stars in magnitude V (panel **a**) and color-index $V-I$ (panel **b**). Spectral types shown at the top of panel **b** are in accordance with the calibration of $V-I$ by Bessell & Brett (1988). The unshaded area denotes a sample of observed MCC stars and the hatched zone is for observed CNS stars.

The catalog of 2487 individual measurements of radial velocities for stars listed in Table 2 is only available at the CDS (Table 2a).

3.4. Detection of binary candidates

Stars to be qualified as spectroscopic binary candidates were identified on account of two quantitative criteria based on the

effect of orbital motion which makes the measured velocities appear to scatter over a time span more than measurement errors alone would cause. As the main criterion we applied the increased ratio of external to internal errors, $E/I > 2$. Relying solely upon our multi-epoch radial velocities, we detected 71 stars which exhibit such a ratio, thereby indicating radial-velocity variability.

To expand a search for binary candidates, especially among the stars with a single observation or too short time span covered by our observations, comparisons were attempted with previously published sources that had considerable overlap with our sample:

- a) Tokovinin (1992), 59 stars;
- b) Upgren & Caruso (1988), 130 stars;
- c) Upgren & Harlow (1996), 27 stars;
- d) López-Santiago et al. (2010), 29 stars;
- e) Young et al. (1987), 24 stars;
- f) Gizis et al. (2002), 238 stars;
- g) Wilson (1967), 199 stars.

A significant time difference between our measurements and those in most of the cited sources favors the possibility of detecting binaries with orbital periods even as long as several decades. Figure 9 shows the plot of the velocity differences, in the sense (present-published), against $V-I$ color for the stars common to each of the above cited literature sources. The mean differences between the velocities do not exceed 0.6 km s^{-1} , without evidence for a color dependence. We note parenthetically that the velocities by Wilson (1967) agree, in most cases, within 0.3 km s^{-1} in zero point (panel g) when compared with modern observations, even though they were obtained nearly five decades ago and exhibit the largest scatter due to their lower accuracy (1.8 km s^{-1}). To identify stars suspected of radial-velocity variability we used a 3σ criterion, $\Delta V_r > 3\sigma$, where σ is the standard deviation indicated in each panel of Fig. 9. On account of this criterion, we revealed 53 stars with variable radial velocities. Overall, 74 of the 1055 stars observed satisfy either $E/I > 2$ or $\Delta V_r > 3\sigma$ criterion.

Among the stars in both the entire MCC sample and our list of CNS program stars (a total of 1155 stars), 39 are spectroscopic binaries known from the literature (of these, 30 have solutions of their orbits). Adding to this number an additional 69 stars revealed by the above-mentioned radial-velocity variability criteria, we have so far 108 known and suspected spectroscopic binaries which constitute 10% of the whole sample of K–M dwarfs with multiple radial-velocity observations (1098 stars).

Fig. 9. Differences in the (present – published) radial velocities as a function of $V - I$ color. The line in each panel represents the mean difference.

In this paper we do not tabulate the mean velocities for the stars suspected in radial-velocity variability since their observations are still in progress in order to get complete phase coverage for solutions of their spectroscopic orbits. With the currently available observational data, final orbital solutions were possible only for two stars (MCC 412 and MCC 796A). One such example, for spectroscopic binary MCC 796A (HIP 86346 = HD 160934), is illustrated in Fig. 10, where the observed velocities are plotted as a function of the calendar date, with its orbit fitted through the data points and the residuals of the fit to the spectroscopic orbit, (O–C), displayed in the bottom panel. The orbital parameters of MCC 796A, based on our radial-velocity

Fig. 10. Radial-velocity variations of the spectroscopic binary MCC 796 (HIP 86346) as a function of the date of observations. The orbit is fitted through the data points (error bars = 1 rms error). The residuals (O–C) are shown in the *bottom* panel.

Table 3. Orbital parameters for MCC 796A (HD 160934).

Parameter	Our solution	Astrometric solution ¹
Orbital period, P (days)	3776 ± 8	3764.0 ± 12.4
Center-of-mass velocity, V_0 (km s ⁻¹)	-30.45 ± 0.09	
Semiamplitude, K (km s ⁻¹)	7.6 ± 0.2	
Eccentricity, e	0.63 ± 0.01	0.636 ± 0.020
Longitude of periastron, ω (deg)	213 ± 2	216.0 ± 3.1
Date of conjunction, T_{conj} (MJD)	$52\,387.5 \pm 8$	$52\,389.5 \pm 64$
Projected semimajor axis, $a_1 \sin i$ (AU)	2.05 ± 0.05	
Mass function, $f(m)$ ($M_\odot$)	0.079 ± 0.008	
Standard deviation of residuals, $\sigma(\text{O-C})$ (km s ⁻¹)	0.8	

Notes. ⁽¹⁾ Evans et al. (2012).

observations, are presented in Table 3, together with the results of astrometric orbital solution by Evans et al. (2012) given for comparison. The parameters of the radial-velocity orbit are in good agreement with those determined from astrometry measurements.

Figure 10 illustrates also the amount of scatter in the data of different observing nights and runs. As is apparent from the figure, the deviations of individual observations from the velocity curve are comparable to, or, in many cases, less than, the rms error of one observation. This confirms the precision of our CORAVEL measurements, evaluated in Sect. 3.2.

Table 4. Observational data for the MCC sample of 962 stars and for 198 K–M stars from the CNS list.

Star name	RA 2000.0	Dec 2000.0	π (mas)	σ_π	Rf	μ_α (mas)	σ_{μ_α}	μ_δ (mas)	σ_{μ_δ}	Rf	V_r (km s ⁻¹)	σ_{V_r}	Rem.	Rf	Mlt	Var	V	B–V	V–R	V–I
MCC001	00 51 21.75	+18 44 21.3	46.79	1.59		52.1	1.1	–266.8	1.1		6.79	0.04		1			9.22	1.23	0.74	1.36
MCC002A	01 02 38.87	+62 20 42.2	100.40	1.52		730.3	2.6	88.4	2.5		–5.90	0.11		1			9.56	1.50	0.99	2.12
MCC003	01 02 21.13	–10 25 25.9	49.06	1.88		27.0	1.4	–176.2	1.5		9.54	0.15		1	X	C	10.03	1.40	0.86	1.65
MCC004	01 52 49.17	–22 26 05.5	90.86	1.16		845.3	1.8	0.4	1.8		12.8	0.2		2		f	8.90	1.44	0.91	1.81
MCC005	02 25 12.21	+49 47 38.1	24.64	2.35		170.7	4.4	–55.9	4.0		18.6	0.3				C	11.16	1.29	0.79	1.46
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Notes. This table is only available at the CDS. A portion of the first page of the table is shown here for guidance regarding its form and content. Description of columns: Col. 1: MCC number or HIPPARCOS number (or other name) for stars from the CNS list. MCC stars (first 962 lines) are ordered by their MCC numbers, and stars from the CNS list (lines 963–1160) by right ascension; Cols. 2, 3: coordinates RA(2000.0) and Dec(2000.0); Cols. 4–6: HIPPARCOS trigonometric parallax (in mas) from [van Leeuwen \(2008\)](#), unless in column “Rf” stated otherwise; Cols. 7–11: proper motion (in mas) from Tycho-2 ([Høg et al. 2000](#)), unless in column “Rf” stated otherwise; Cols. 12–15: radial velocity from this paper (Table 2), unless in column “Rf” stated otherwise. Column “Rem.” marks spectral binaries and radial-velocity variables. When two references are given in Column “Rf”, the first refers to the source from which the radial velocity was taken and the second refers to the source of information on radial-velocity variability (“var”) or binarity (“SB”); Cols. 16, 17: multiplicity and variability flags from the HIPPARCOS catalog and elsewhere (explained in Notes to the full online table); Cols. 18–21: photometric data from the literature: magnitude V and color indices $B - V$, $V - R_C$, and $V - I_C$. References indicated in columns “Rf” for parallaxes (Col. 6), proper motions (Col. 11), and radial velocities (Col. 15) are given in notes to the full online table.

4. Space velocities and galactic orbits

4.1. Data

For the calculation of space velocities and galactic orbits of the MCC stars and, in addition, 188 K–M dwarfs from the CNS list measured in our radial-velocity program, we used as the main astrometric data sources the new-reduction HIPPARCOS catalog ([van Leeuwen 2008](#)) and Tycho-2 catalog ([Høg et al. 2000](#)). For 45 stars, having no HIPPARCOS data, the trigonometric parallaxes were taken mainly from the CNS3 database and the GCTP catalog by [van Altena et al. \(2001\)](#). For a few other stars the trigonometric parallax data were found in several other literature sources. However, 29 stars had no any or very poor trigonometric parallax measurements available in the literature, and we adopted, in this case, their photometric parallaxes inferred from the magnitude-color relations in the (M_V , $V - I_C$) (Fig. 3), (M_V , $V - R_C$), and (M_V , $B - V$) planes, given in [Bartašūtė et al. \(2012\)](#). As a final value of photometric parallax, an average over the three magnitude-color relations was taken, with its error including the rms scatter around the relations (± 0.25 mag in M_V) that contributes a major amount to the total uncertainty.

We used proper motions from the Tycho-2 catalog since it provides a better coverage of our sample stars compared to the HIPPARCOS catalog: 63 non-HIPPARCOS stars in our sample (43 MCC stars and 20 from the CNS list) have Tycho proper motions. For 43 stars having neither HIPPARCOS nor Tycho data, their proper motions were taken mainly from the LSPM-North catalog by [Lépine & Shara \(2005\)](#), as well as from other sources.

Before performing the calculations of (U, V, W) velocities, we combined our radial-velocity data with those published in the literature. For the known spectroscopic binaries with orbital solutions (30 such stars), the center of mass velocities (V_0) were taken from the literature, primarily from the Ninth catalog of spectroscopic binary orbits ([Pourbaix et al. 2004](#)). For new spectroscopic binaries, we used our estimates of V_0 whenever orbital solutions were obtained from our observations. A substantial part of stars in our sample were monitored by other authors in search of exoplanets or for establishing radial-velocity standard stars (e.g., [Marcy & Benitz 1989](#); [Nidever et al. 2002](#); [Chubak et al. 2012](#)). Therefore, we opted to use their high-precision radial-velocities instead of ours. In the calculation of

space velocities and galactic orbits (Sects. 4.2 and 4.3), we used the radial velocities from other sources for 351 stars (which superseded our observations of 231 stars), and for the rest 737 stars we used our own measurements presented in Table 2. The literature sources for radial velocities, as well as for astrometric data, are all referred in the input data table described below.

Table 4, only available at the CDS, summarizes the observational data for the entire MCC sample of 962 stars and the list of 198 CNS stars. The tabulated magnitudes V are all from the ARICNS² database and are corrected for duplicity where possible. In the designation column, component labels for double/multiple stars are the same as in the ARICNS database. For the spectroscopic binaries having orbital solutions (in the table they are marked as SBO), the center of mass velocities V_0 are given. In the case of binaries without orbital solutions and stars suspected in radial-velocity variability, V_r values are omitted.

We note that for 41 common-proper-motion (CPM) pairs in Table 4 there are no individual parallaxes in the HIPPARCOS catalog or elsewhere. Also, 11 of these CPM pairs and one additional CPM pair have no individual proper motions in Tycho2 or other astrometric catalogs. Therefore, we used in such cases the primary parallaxes (or proper motions) for both stars, since their radial velocities suggest they must be a physical pair. For the component B of the CPM pair MCC 410 A,B), we also adopted the primary’s radial-velocity.

4.2. Calculation of space velocities

The space motions and their errors were computed using the matrix equations given by [Johnson & Soderblom \(1987\)](#), modified to accept stellar positions for equinox 2000.0 in the ICRS (International Celestial Reference System) as defined in the HIPPARCOS and Tycho catalogs ([ESA 1997](#), Vol. 1, Sect. 1.5.3). Throughout this article we consider a right-handed rectangular coordinate system (x, y, z) in which the velocity components U , V , and W are positive in the direction of the Galactic center, Galactic rotation and the north Galactic pole, respectively.

After exclusion of the radial-velocity variables (65 stars) indicated in Table 4, three stars having no good or lacking any radial-velocity data (MCC 346, MCC 349, and MCC 683), and two non-dwarf stars (MCC 69 and MCC 315), we are left with

Table 5. Heliocentric space velocities and parameters of galactic orbits for 901 MCC stars and 187 K–M stars from the CNS list.

Star name	U (km s ⁻¹)	σ_U	V (km s ⁻¹)	σ_V	W (km s ⁻¹)	σ_W	R_a (kpc)	σ_{R_a} (kpc)	R_p (kpc)	σ_{R_p} (kpc)	$Z_{\max}$ (kpc)	$\sigma_{Z_{\max}}$ (kpc)	e	σ_e	SKG memb.
MCC001	3.2	0.2	-14.6	0.4	-24.1	0.7	8.297	0.005	7.611	0.044	0.170	0.008	0.043	0.003	
MCC002A	-25.0	0.4	-24.1	0.3	5.7	0.1	8.138	0.022	7.146	0.025	0.128	0.005	0.065	0.002	
MCC003	5.0	0.3	-13.0	0.5	-13.9	0.2	8.383	0.009	7.618	0.048	0.067	0.004	0.048	0.003	
MCC004	-35.9	0.4	-28.6	0.4	-2.0	0.3	8.272	0.034	6.777	0.032	0.050	0.004	0.099	0.003	
MCC005	-36.9	2.1	-13.2	1.8	-1.6	0.8	8.677	0.152	7.410	0.035	0.056	0.009	0.079	0.009	HYD
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	

Notes. This table is only available at the CDS. A portion of the first page of the table is shown here for guidance regarding its form and content. Description of columns: Col. 1: MCC number or HIPPARCOS number (or other name) for stars from the CNS list. MCC stars are listed first (lines 1–901) and stars from the CNS list in the remaining part of the table (lines 902–1088); Cols. 2–7: heliocentric space-velocity components (U , V , W) and their errors; U is positive toward the Galactic center, V is positive in the direction of the Galactic rotation, and Z is positive toward the north Galactic pole; Cols. 8, 9: apogalactic distance R_a and its error (in kpc); Cols. 10, 11: perigalactic distance R_p and its error (in kpc); Cols. 12, 13: maximum orbital distance $Z_{\max}$ and its error (in kpc); Cols. 14, 15: orbital eccentricity e and its error. Col. 16: candidate members of stellar kinematic groups (designations are explained in notes to the full online table).

901 MCC stars and 187 CNS stars with the space velocities calculated. The heliocentric space-velocity components U , V , W and their errors are given in the table of kinematical results (Table 5).

4.3. Galactic orbits

To determine orbital parameters we chose primarily a realistic, yet relatively simple model of the Galaxy’s axisymmetric potential by Johnston et al. (1995, hereafter JSH95). In this model, the disk is represented by a Miyamoto & Nagai (1975) potential,

$$\Phi_{\text{disk}} = -\frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}, \quad (3)$$

the bulge by a Hernquist (1990) potential,

$$\Phi_{\text{bulge}} = -\frac{GM_{\text{bulge}}}{r + c}, \quad (4)$$

and the halo by a logarithmic potential

$$\Phi_{\text{halo}} = v_{\text{halo}}^2 \ln(r^2 + d^2). \quad (5)$$

Here, $M_{\text{disk}} = 1.0 \times 10^{11} M_{\odot}$, $a = 6.5$ kpc, $b = 0.26$ kpc, $M_{\text{bulge}} = 3.4 \times 10^{10} M_{\odot}$, $c = 0.7$ kpc, $v_{\text{halo}} = 128$ km s⁻¹, and $d = 12.0$ kpc. This set of model parameters provides a nearly flat rotation curve outside 1 kpc and a disk scale height of 0.2 kpc. At the solar Galactocentric distance $R_0 = 8.0$ kpc, the model reproduces the circular speed 222.5 km s⁻¹, and the orbital period of the LSR is 218 Myr.

In addition, we integrated the orbits also in the axisymmetric potential by Allen & Santillan (1991, hereafter AS91), just to compare for the two models the orbital parameters and, especially, the orbits of a few of the stars which penetrate very small perigalactic distances and appear to be chaotic. In the AS91 model, the central bulge is less massive and more centrally concentrated than that of JSH95 and is modeled as a Plummer potential, $\Phi_{\text{bulge}} = -GM_{\text{bulge}}/(r^2 + c^2)^{1/2}$, with $M_{\text{bulge}} = 1.4 \times 10^{10} M_{\odot}$ and $c = 0.39$ kpc. For the halo, the model takes a special form of the potential (Eq. (5) in AS91) with the parameters $M_{\text{halo}} = 1.07 \times 10^{11} M_{\odot}$ and $d = 12.0$ kpc. The AS91 disk potential is of the same Miyamoto & Nagai form as in JSH95 (Eq. (3)) but with slightly different parameters: $M_{\text{disk}} = 8.6 \times 10^{10} M_{\odot}$, $a = 5.32$ kpc, and $b = 0.25$ kpc. From this model, the circular velocity at the Sun’s galactocentric distance $R_0 = 8.0$ kpc is

220.05 km s⁻¹, and the orbital period of revolution of the local centroid is 228 Myr.

For the integration of galactic orbits (and throughout this paper), the heliocentric space-velocity components were corrected for the Sun’s velocity with respect to the LSR using the values $(U_{\odot}, V_{\odot}, W_{\odot}) = (11.1 \pm 0.7, +12.2 \pm 0.5, +7.3 \pm 0.4)$ taken from Schönrich et al. (2010). The Sun’s position at 8 pc above the plane of symmetry of the Galaxy (Holmberg et al. 1997) was adopted.

We integrated orbits backwards in time using a Bulirsch-Stoer integrator with adaptive time step size of Press et al. (1992) (specifically their subroutines `odeint` and `bsstep`). The orbital parameters were determined as averages over the number of cycles in a 5 Gyr integration time. The apogalactic and perigalactic radii, R_a and R_p , were calculated from the maximum and minimum of distances $(x^2 + y^2 + z^2)^{1/2}$ averaged over the number of cycles. Similarly, the maximum distance above (or below) the plane, $Z_{\max}$, was calculated as an average over the number of plane crossings. The eccentricities were calculated as

$$e = \frac{R_a - R_p}{R_a + R_p}, \quad (6)$$

where R_a and R_p are the average orbital radii.

One type of errors in the orbital parameters R_a , R_p , and $Z_{\max}$ are the dispersions over the number of cycles within the 5 Gyr interval and the error in eccentricity introduced by the dispersions of R_a and R_p . These dispersions, for the case of the JSH95 model, are plotted Fig. 11 as open blue points. They show the intrinsic variations of orbital parameters from one cycle to another.

Apart from the above-mentioned dispersions, we also calculated the errors in the orbital parameters arising from observational uncertainties in the parallaxes, proper motions, and radial velocities. Here, the uncertainty in the adopted value of the solar motion from Schönrich et al. (2010) was also taken into account. In Fig. 11 these errors are shown by black cross symbols. We also plotted the total error (light gray symbols) calculated by adding to the errors of the two aforementioned types a formal uncertainty of ± 10 km s⁻¹ in the adopted ‘default’ value of the rotational speed θ_0 of the LSR. (In the literature, the estimates of θ_0 and their uncertainties vary in a wide range, with an often given error of ~ 10 km s⁻¹, see, e.g., Schönrich 2012; Reid & Honma 2014.)

From the distribution of points in Fig. 11, where the errors of different types are plotted against the values of orbital parameters, we see that the uncertainty in θ_0 has a most significant

Fig. 11. Distribution of errors in the parameters of galactic orbits integrated using the JSH95 model. Blue open squares denote the intrinsic dispersions of orbital parameters over the number of cycles in a 5 Gyr integration time. Black cross symbols represent the errors introduced by the observational uncertainties in the input data (parallaxes, proper motions, radial velocities, and the adopted solar LSR velocity). Light gray symbols illustrate the total error with a formal uncertainty of 10 km s^{-1} in the adopted rotational velocity of the LSR added.

impact on the error budget of the orbital parameters R_p and R_a , and hence of eccentricity. The errors in the adopted solar LSR velocity components from Schönrich et al. (2010) contribute relatively little to the total error (less than 10 pc on average). Even the largest errors in R_p and R_a owing to this only uncertainty do not exceed 100 pc and 270 pc, respectively. The internal dispersions among the cycles are, on average, much smaller than the errors propagated by observational uncertainties in the input data. However, some orbits show significant variations (especially in Z-coordinate), irrespective of the precision with which the astrometric and radial-velocity data are attained. However, due to the large number of cycles (typically, between 25 and 40) used for averaging the orbital parameters, the error of the mean remains relatively small. In Table 5 of the kinematical results we tabulated the errors of the orbital parameters calculated by adding (in quadrature) to the error propagated by observational uncertainties the dispersion over the orbital cycles.

As it can be seen from Fig. 11, the orbits of a few of the stars do attain perigalactic distances around, or even less than, 1 kpc and have chaotic orbits (see Sect. 6.3.4). Therefore, we investigated differences in the orbital parameters of these and all remaining stars due to different potentials, JSH95 and AS91. Our results have shown that model-induced differences in the orbital parameters are of the order of the estimated errors and that the

dispersions in the parameters from the two models are comparable. However, the orbits may significantly differ. As an example, we show in Fig. 12 the orbit for MCC 799 (Barnard’s star) of a relatively high eccentricity, obtained using both models. Regardless of the difference in the orbit’s trace, the average orbital parameters for the two models remain closely similar.

In Table 5, available at the CDS, we present the orbital parameters for one of the models, JSH95, and we use these results in the kinematic analysis in the remainder of this paper.

5. Bulk streaming motions

5.1. Clustering patterns in velocity space

Since the release of the HIPPARCOS astrometric data, a richly structured phase-space distribution has been revealed in the solar neighborhood (e.g., Chereul et al. 1998, 1999; Asiain et al. 1999b; Famaey et al. 2005), in addition to classical moving groups (MGs), associations, and a number of superclusters (SCI) and MGs discovered and surveyed in a series of seminal papers of 1957–1998 by Eggen. Efficient methods have been developed for capturing kinematic substructures with a low contrast level (Klement et al. 2009; Bond et al. 2010) that are tested in the SDSS and will be used in the upcoming surveys. Recent analysis by Chumak & Rastorguev (2015) of fractal

Fig. 12. Galactic orbit of Barnard’s star (MCC 799) integrated back in time for 2 Gyr in the potential models by JSH95 (*top panels*) and AS91 (*bottom panels*). The open square shows the present position of the star. The values of orbital parameters and their dispersions, indicated in the panels, are from the 5 Gyr integration time (24 to 27 cycles).

properties of real velocity space, based on the GCS data for F–G stars, has shown a well-defined coarse-grained structure on various scale lengths. Distinct clustering patterns in the kinematical plane are also clearly seen from the distribution of K–M dwarfs (Figs. 13 and 14).

Streams and similar small-scale structures may not necessarily all be associated with dissolution of star clusters. A wide range of stellar ages observed within superclusters lends strong support to other dynamical mechanisms of multiscale structuring, such as the effect of spiral pattern (De Simone et al. 2004; Famaey et al. 2005; Antoja et al. 2009; Pompéia et al. 2011), the outer Lindblad resonance of the rotating Galactic bar (Dehnen 2000; Fux 2001; Minchev et al. 2010), or both (Quillen 2003; Minchev & Famaey 2010).

Prior to undertaking calculations and analysis of the kinematics of nearby K–M dwarfs in the next Sect. 6, we should consider how significantly the bulk streaming motions can affect the results. Neglect of the presence of clumps in the velocity space can lead to deriving distorted distributions of velocities, especially in the cases which require a well-mixed distribution without kinematic bias (e.g., in determining the LSR velocity).

Out of 1088 K–M dwarfs considered in this paper, 98 stars were found in the literature to be attributed to nearby stellar kinematic groups (SKGs) at various levels of probability (probable, possible, doubtful members), including stars with conflicting membership statements from different studies. However, the removal of all 98 stars from our sample, even irrespective of their membership probabilities, did not smooth significantly the velocity distribution in the kinematical plane which in Figs. 13 and 14 is dominated by clear overdensities. Therefore we made an attempt to identify possible candidate members of SKGs using the kinematical data from the present paper.

5.2. Kinematic identification of SKGs

To detect the kinematic substructures in the velocity distribution we used initially the Bottlinger (V vs. U) and Toomre (V vs. $(U^2 + W^2)^{1/2}$) diagrams, shown in Figs. 13 and 14, respectively. In these diagrams, we can look for groupings of stars sharing similar kinematical properties. To facilitate this, the number-density contours were plotted on each of the diagrams that were obtained using a Gaussian smoothing with a standard deviation of 0.5 km s^{-1} . The contour levels correspond to 0.05, ..., 0.95 of the maximum value at the center of the most concentrated clump (in the left-hand diagrams, the number-density peak is associated with the Hyades Moving Group).

Visual inspection of the left-hand diagrams in Figs. 13 and 14 can easily reveal the well-known kinematic groups of Hyades, Sirius, Pleiades, and Castor. Also, both diagrams reveal more overdensities which can be associated with other nearby substructures or streams. Therefore, we expanded our search for possible candidate members of the most significant MGs by adding to the list of the latter the numerous subgroups and streams identified by Asiain et al. (1999b, hereafter ASI99) and Chereul et al. (1999, hereafter CHE99) from their analyses of HIPPARCOS early-type stars.

In order to identify possible candidate members of SKGs and subgroups, the following steps were taken. First, based on the knowledge of the present-day phase-space coordinates and age of a particular SKG, we integrated back in time both the orbit of the SKG’s center and the orbits of our K–M stars. In this way we obtained the relative separation ΔD_0 between the star and the SKG’s center at the supposed time of the SKG’s birth. Then, we ranked the candidate stars according to the smallness of their spatial separation ΔD_0 . To adopt a reasonable cutoff value for ΔD_0 above which candidate stars should be considered spurious, we applied, in addition, the smallness of Δv criterion, where Δv is the difference between the present-day value of the total (U, V, W) space-velocity vector of the star and that of the SKG. For the candidacy to young ($\leq 100 \text{ Myr}$) SKGs, $\Delta v \leq 6 \text{ km s}^{-1}$ was taken, while in the case of older SKGs the members of which should be more dispersed during their rotation around the Galactic center we adopted $\Delta v < 10 \text{ km s}^{-1}$. Combining the two criteria, ΔD_0 and Δv , helps to avoid the candidacy of stars with small ΔD_0 but rather different velocity vectors.

An approach to tracing back in time the orbits in the gravitational potential of the Galaxy has been successfully used by Asiain et al. (1999a) and Ortega et al. (2002, 2007) in their analysis of trajectories of the young SKGs. The method in principle is the same as the epicyclic approximation used by Makarov (2007) in his study of the kinematic history of young SKG members in the solar neighborhood and, more recently, by Nakajima et al. (2010) and Nakajima & Morino (2012) in search for SKG members among the stars within 30 pc of the Sun. However, the method is most effective for SKG members younger than 200 Myr (age of the Castor group). In the case of relatively old SKGs, such as of Ursa Major and Hyades (500–600 Myr), the integration back in time yields large separations ΔD_0 since these values increase significantly with time. Therefore, in this case, values of ΔD_0 should be considered only as a relative measure of spatial separation.

For more stringent selection of the SKG candidate members identified by the scheme described above, we (1) added the requirement that the orbits of individual members are isoperiodic (Eggen 1992b, 1996) and that the orbital oscillations in the vertical direction are in phase, and (2) examined the location of the identified stars in the $M_V, V-I$ diagram, mainly in the case of the

Fig. 13. Velocity structures of K–M dwarfs in the Bottlinger diagram, delineated using Gaussian smoothing with a standard deviation of 0.5 km s^{-1} . *Left-hand and right-hand panels* show the distributions before and after removal of candidate members of SKGs (Table 7), respectively. The contour levels correspond to color scale numbers which indicate fractional overdensities normalized to a unit maximum associated with the heaviest concentration (the Hyades MG) in the *left-hand diagram*. Small dots denote the actual positions of K–M dwarfs with $\sigma_\pi/\pi < 0.30$.

Fig. 14. Velocity structures in the Toomre diagram. Notations are the same as in Fig. 13.

youngest SKGs, since isochrones of more than 80 Myr converge in the region of late-type dwarfs. Due to these additional constraints a few stars were eliminated from the candidate member list. Spectroscopic criteria, such as based on lithium abundance, H_α spectrum, CaII H and K fluxes, were not involved because of limited amount of such data.

In Table 6 we give the list of SKGs and subgroups to each of which we assigned at least three candidate stars from our sample

of K–M dwarfs. The mean velocity components (U , V , W), their dispersions, and age estimates of the SKGs and subgroups were taken from the literature sources referred in the notes to the table. The second column for SKG age gives the age adopted in the present paper for the estimation of the distance ΔD_0 of candidate members from the center of their SKG at the time of its birth. In the last column of the table, the number of candidate members assigned to each SKG is given. In order to smooth

Table 6. Main properties of the nearby stellar kinematic groups or subgroups and the statistics of the member candidates identified or rediscovered in the sample of K–M dwarfs.

Stellar kinematic group or subgroup	U (km s ⁻¹)	V (km s ⁻¹)	W (km s ⁻¹)	Age (Myr)	Ref.	Age [†] (Myr)	N
β Pictoris Moving Group	-10.1 ± 2.1	-15.9 ± 0.8	-9.2 ± 1.0	~ 10	1	12	4
Subgroup 1–7 (Pleiades Supercluster/Local Association)	-11.1 ± 1.7	-21.9 ± 3.0	-6.0 ± 1.8	≥ 10	2	30	5
IC 2391 Supercluster	-22.0 ± 0.3	-14.4 ± 1.3	-5.0 ± 1.3	40	1	40	4
Subgroup B2 (Pleiades Supercluster/Local Association)	-10.7 ± 5.3	-18.8 ± 3.7	-5.6 ± 2.2	60 ± 20	3	60	3
AB Doradus Moving Group	-6.8 ± 1.3	-27.2 ± 1.2	-13.3 ± 1.6	70	1	140	7
Subgroup B4 (Pleiades Supercluster/Local Association)	-8.7 ± 4.8	-26.4 ± 3.3	-8.5 ± 4.7	150 ± 50	3, 4	150	4
Subgroup 1–6 (Pleiades Supercluster/Local Association)	-13.1 ± 3.1	-21.9 ± 3.3	-7.1 ± 2.5	$\sim 10, \sim 1000$	2	150	10
Suspected subgroup 1 (Local Association?)	-10.8 ± 5.0	-27.3 ± 1.1	-3.1 ± 1.0			150	6
Suspected subgroup 2 (Local Association?)	-25.4 ± 1.8	-24.2 ± 1.4	-6.3 ± 1.6			150	4
Suspected subgroup 3 (Local Association?)	-20.3 ± 3.7	-24.6 ± 1.5	1.2 ± 0.6			150	4
Subgroup C4 (Castor Moving Group?)	-13.6 ± 5.2	-6.1 ± 3.3	-17.0 ± 2.0	190 ± 30	3	190	6
Castor Moving Group	-10.6 ± 3.7	-6.8 ± 2.3	-9.4 ± 2.1	320 ± 80	5	320	7
Subgroup C1 (Castor Moving Group?)	-13.4 ± 6.4	-6.4 ± 3.7	-3.3 ± 2.7	370 ± 190	3	320	6
Ursa Major Moving Group / Sirius Supercluster	14.5 ± 2.2	2.9 ± 1.7	-8.6 ± 2.9	500 ± 100	6	500	9
Subgroup A4 (Sirius Supercluster)	1.7 ± 4.2	6.6 ± 2.0	-15.9 ± 1.3	520 ± 80	3	500	8
Subgroup 2–37 (Sirius Supercluster)	12.4 ± 4.0	0.7 ± 4.6	-7.7 ± 4.7	~ 600	2	500	5
Suspected subgroup 4 (Sirius Supercluster?)	-5.1 ± 1.8	8.1 ± 1.1	-3.8 ± 1.5			500	4
Subgroup 2–25 (Hyades Supercluster)	-32.8 ± 2.8	-11.8 ± 2.8	-8.9 ± 2.9	$\sim 500, \sim 1000$	2	500	6
Subgroup 2–18 (Hyades Supercluster)	-33.0 ± 4.2	-14.1 ± 4.0	-5.1 ± 3.1	$\sim 500, \sim 1000$	2	600	8
Subgroup 2–10 (Hyades Supercluster)	-31.6 ± 2.8	-15.8 ± 2.8	0.8 ± 2.7	$\sim 500, \sim 1000$	2	600	4
Subgroup D3 (Hyades Supercluster)	-43.1 ± 2.4	-18.4 ± 2.7	-9.2 ± 1.3	~ 660	3	600	4
Hyades Supercluster	-39.7	-17.7	-2.4	~ 600	7	600	22
Wolf 630 Moving Group [‡]	18.8	-33.4	10.9	2700 ± 500	8	2700	6

Notes. [†] Age adopted in the present paper for the estimation of the distance ΔD_0 of member candidates from the center of their SKG at the time of SKG's birth. [‡] For the Wolf 630 Moving Group, the velocities (U, V, W) are taken as the average for the multiple star system Wolf 630.

References. (1) [Torres et al. \(2008\)](#); (2) [Chereul et al. \(1999, CHE99\)](#); (3) [Asiain et al. \(1999b, ASI99\)](#); (4) [López-Santiago et al. \(2006\)](#); (5) [Ribas \(2003\)](#); (6) [King et al. \(2003\)](#); (7) [Montes et al. \(2001\)](#); (8) [Bubar & King \(2010\)](#).

out a significant clump of stars around the position (U, V, W) = $(-25, -25, 0)$ km s⁻¹ and a small overdensity near the domains of the Sirius Supercluster (SCI) that still appear after the removal of the candidate stars of the known SKGs and subgroups, we introduced four suspected subgroups: three to belong to the Local Association³ and one supposedly to the Sirius SCI. The center coordinates (X, Y, Z) for the β Pictoris and AB Doradus moving groups (MGs) were taken those of the stars β Pictoris and AB Doradus, respectively, and for the IC 2391 SCI we adopted the center position and velocity (U, V, W) of the Argus Association. For the centers of the remaining SKGs and subgroups the heliocentric coordinates (X, Y, Z) = $(0, 0, 0)$ were adopted.

5.3. List of candidate members

We assigned a total of 146 stars as possible candidate stars to seven most significant known kinematic groups and 16 subgroups. Their list is given in Table 7, only available at the CDS.

Below we give brief comments on each of the kinematic groups and its candidate members.

β Pic Moving Group. According to various literature sources the age of this MG is in the range 8–40 Myr. For orbit integration back in time we adopted the often-cited age of 12 Myr. We identified four candidate members; however all of these are known

from the literature. Adopting a greater age (e.g., 23 Myr as derived by [Mamajek & Bell 2014](#), by combining isochronal and lithium depletion boundary ages) led to the same set of four candidate members, but with slightly larger values of ΔD_0 than using an age of 12 Myr.

Subgroup 1–7 (Pleiades Supercluster/Local Association) is one of the velocity structures detected by CHE99 from a 3D wavelet analysis of HIPPARCOS A–F stars at a scale of velocity dispersion of ~ 2.4 km s⁻¹. The authors assign it to a younger group of Pleiades SCI and give an age of few 10^7 yr. We identified five stars to possibly belong to this subgroup, tracing their location 30 Myr back. If to exclude MCC 424, the latter four candidates can also be assigned to Tuc-Hor ($\Delta D_0 = 36$ –77 pc), Columba ($\Delta D_0 = 40$ –82 pc) or Carina ($\Delta D_0 = 24$ –64 pc) associations of age 30 Myr ([Torres et al. 2008](#)). Furthermore, these four candidate stars have similar ΔD_0 values (17 to 69 pc) with respect to subgroup B2 from ASI99, if to adopt for orbit integration an age of 30 Myr. We note that, [Malo et al. \(2014\)](#) consider MCC 424 as a bona fide member of Columba Association, identified through the BANYAN Bayesian inference method which takes into account the position, proper motion, magnitude, color, radial velocity and parallax.

IC 2391 Supercluster. In search for candidate members with small ΔD_0 distances from the center of the IC 2391 Moving Group we used the group's mean velocities (U, V, W) taken from [Montes et al. \(2001\)](#), CHE99, and those given by [Torres et al. \(2008\)](#) for the Argus Association. The latter is considered to be associated with the open cluster IC 2391 (see [Torres et al. 2008](#); [De Silva et al. 2013](#)) and, hence, with the IC 2391 Supercluster.

³ The Local Association, postulated in the 1960s by Eggen, is often referred to as the Pleiades SCI, or Pleiades MG. It is regarded to include stars in the Pleiades, several star clusters, and the Sco-Cen association, all in a fairly wide range of ages.

Table 7. Candidate stars of the kinematic groups in the sample of K–M dwarfs.

MCC	HIP	d (pc)	U (km s ⁻¹)	V (km s ⁻¹)	W (km s ⁻¹)	e	$Z_{\max}$ (pc)	Δv (km s ⁻¹)	ΔD_0 (pc)	Notes
<i>β Pictoris Moving Group</i>										
MCC 392A	11437	40	-13.6 ± 0.9	-15.0 ± 0.4	-8.2 ± 0.6	0.015 ± 0.003	14 ± 2	3.7	18	M(2)
MCC 392B		40	-11.1 ± 1.6	-14.0 ± 1.6	-7.5 ± 1.7	0.007 ± 0.008	11 ± 1	2.7	43	M(2)
MCC 111	23200	26	-12.4 ± 0.3	-16.9 ± 0.4	-9.6 ± 0.2	0.019 ± 0.003	23 ± 3	2.5	19	M(1)
MCC 824	102409	10	-10.1 ± 0.2	-16.4 ± 0.2	-10.4 ± 0.1	0.017 ± 0.003	30 ± 3	1.3	23	M(2)
...	...	...	...	...	...	...	...	...	...	...

Notes. This table is available at the CDS. A portion of the first page of the table is shown here for guidance regarding its form and content. Description of columns: Cols. 1, 2: MCC number or HIPPARCOS number (for stars from the CNS list); Col. 3: distance from the Sun, in pc; Cols. 4–6: heliocentric velocity components and their errors; Col. 7: orbital eccentricity and its error; Col. 8: orbital distance $Z_{\max}$ and its error; Col. 9: difference Δv between the total velocity of the star and the velocity of the SKG; Col. 10: distance ΔD_0 from the center of SKG at the time of SKG’s birth; Col. 11: notes on SKG membership from the literature (M – probable/possible member, NM – nonmember, with the source indicated in parentheses).

The small group of K–M dwarfs was identified to show the best match with both the Argus Association and Subgroup 1–20 of CHE99. Using the group’s mean velocity from Montes et al. (2001), ΔD_0 values appear to be systematically displaced by about 100 pc from those obtained with respect to the Argus Association or Subgroup 1–20.

Subgroup B2 (Pleiades Supercluster/Local Association) is one of the subgroups of the Pleiades SCl, identified by ASI99. We assigned three stars as candidates to this subgroup. The same stars can be assigned to the above-commented Subgroup 1–7 for an age of 30 Myr. However, the orbital oscillations in Z -coordinate for the candidate stars to each of the two subgroups, B2 and 1–7, are in opposite phase. Therefore, we separated the stars into two groups, based on smaller ΔD_0 values for a reported age. Dual candidacy is to be expected for a number of stars due to the large velocity dispersion observed in the Local Association (Montes et al. 2001) and the overlap of its subgroups in the velocity space.

AB Doradus Moving Group is a well-known nearby SKG discovered independently by Torres et al. (2003) and Zuckerman et al. (2004). For this group, we adopted a formal age of 140 Myr, keeping in mind that (1) a conservative age range of 75–150 Myr is given in the literature (e.g., Luhman et al. 2005) and (2) for the eight candidate stars in our search the smallest differences ΔD_0 were obtained using the group’s age 140 Myr (ΔD_0 in the range 29–214 pc; the star AB Dor itself traced back 140 Myr is at 175 pc from its present position). Among the seven candidate members given in Table 7, four are the known members.

Subgroup B4 (Local Association) is one of the four subgroups found by ASI99 inside the Local Association. In addition to four stars given in Table 7, we identified by the smallest distance ΔD_0 eight stars as possible B4 members, which were assigned by us before to the AB Dor MG. Considering B4 as a separate group we chose to include in this group the stars with their velocities and orbital parameters slightly different from those of AB Dor MG.

Subgroup 1–6 (Pleiades Supercluster/Local Association). We used the mean (U, V, W) velocity of Subgroup 1–6 of CHE99, the oldest of the two sub-streams of the Pleiades SCl, identified in their earlier paper (Chereul et al. 1998). Ten candidate members were assigned to this subgroup. At the age adopted for the calculation of ΔD_0 , 150 Myr, the same group of stars was revealed using the mean (U, V, W) velocity for the Local

Association taken from Montes et al. (2001), with even smaller values of Δv , but larger values of ΔD_0 . For tracing back in time we adopted an age of 150 Myr, the largest within the range 20–150 Myr cited by Montes et al. (2001). We note that a few stars from those assigned to Subgroup 1–6 can also be attributed to the Hercules-Lyra Association, using its mean (U, V, W) velocity and age of 200 Myr taken from López-Santiago et al. (2006). However, we made no attempt to uncouple these few stars from Subgroup 1–6 since the existence of Hercules-Lyra as an entity separate from the Local Association is not well established (see, e.g., López-Santiago et al. 2006).

Suspected subgroups 1, 2, and 3 (Local Association?). After removal of candidate members of all of the known SKGs and subgroups, still an obvious clump remained in both the Bottlinger and Toomre diagrams around the position (U, V, W) $\approx (-25, -25, 0)$ km s⁻¹. Therefore, we introduced three new subgroups to supposedly belong to the Local Association, and adopted rather arbitrarily the same age as that given for other subgroups of this association (e.g., 1–6, B4, or AB Dor MG). Possible candidates within each of the three subgroups share close eccentricities and coherent orbital oscillations. We note that, in velocity space, suspected Subgroup 1 is very similar to Subgroup B4. However the orbits of the stars slightly differ between the two subgroups; thus we assigned these stars to separate subgroups.

Subgroup C4 (Castor Moving Group?) is one of a family of subgroups labeled by ASI99 “c” or “C”. We suspect that C4 (in ASI99, it is labeled “c4”) can be associated with the Castor MG. However, no candidate members of the Castor MG, known from the literature, appear in this subgroup.

Castor Moving Group. In the literature (e.g., Barrado y Navascues 1998; Montes et al. 2001; Ribas 2003; Caballero 2010) there are reported as many as 17 Castor MG candidate stars (including seven doubtful) common to our sample. Of these, only one star was included in our list of candidate members identified using the group’s center velocities from Ribas (2003). Other four stars of 17 show vertical orbital oscillations not in phase with Castor itself and were assigned to Subgroup C1.

Subgroup C1 (Castor Moving Group?). We assigned six stars to the group “c1” of ASI99 (we labeled it C1), four of which, as mentioned above, were considered in the literature as members of the Castor MG.

Ursa Major Moving Group (Sirius Supercluster). The nine candidate members were identified using the mean (U, V, W) velocities derived by King et al. (2003) for the nucleus stars and stars having final membership designations. Five of these nine candidates are the UMa MG members known from the literature. CHE99 and ASI99 have found evidence that the Sirius SCl, which harbors the main UMa MG, is composed of several subgroups. Therefore, we used also the mean (U, V, W) velocities of the Sirius SCl subgroups from CHE99 and ASI99 in search for additional candidates (see below).

Subgroup A4 (Sirius Supercluster) is one of the four subgroups discerned by ASI99, which in velocity space resemble the classical UMa MG. We note that, according to our criteria, the eight candidates for Subgroup A4 can also be assigned to Subgroup 2–43 which in CHE99 is revealed as one of five substreams that form New Supercluster of age ~ 800 Myr, in the velocity space located close to Sirius SCl.

Subgroup 2–37 (Sirius Supercluster) is one of the two streams, identified by CHE99, into which splits the Sirius SCl. We assigned five stars to this subgroup. The stars which, according to our criteria, could be assigned to the second Sirius stream (Subgroup 2–41), were included by us in the UMa MG.

Suspected subgroup 4 (Sirius Supercluster?). We introduced a group of four stars at $(U, V, W) = (-5, 8, -4)$ km s $^{-1}$, which can presumably belong to the Sirius SCl. For this subgroup we adopted arbitrarily an age of 500 Myr, in accordance with that given for UMa MG (King et al. 2003) and taken for the rest of the Sirius SCl subgroups. In the velocity space this subgroup is similar to Stream 2–46 of CHE99. However, combining the Δv and ΔD_0 criteria yields too spurious candidacy for 2–46.

Hyades Supercluster and its subgroups. The main group of candidate stars was identified using the mean (U, V, W) velocities from Montes et al. (2001). We list 22 stars, nine of which are known members, including five stars of the Hyades open cluster (Melotte 25). As it has been pointed out by Eggen (1992a), the supercluster contains at least three groups around 300–400 Myr, 600 Myr, and 800 Myr. Based on the velocity pattern of HIPPARCOS early-type stars, CHE99 have also revealed three groups, 2–10, 2–18 and 2–25, each with characteristic age distribution, but all include a ~ 500 Myr old component. We assigned six stars to Subgroup 2–25 and four stars to Subgroup 2–10. Eight candidate stars of Subgroup 2–18 can also be attributed to Subgroup D by ASI99. A small group of stars with closely similar kinematics was assigned to Subgroup D3 of ASI99, the oldest of a family of groups labeled “d”, which has a velocity vector and age similar to those of the Hyades cluster.

Wolf 630 Moving Group was first identified by Eggen (1965), who noted that several K and M dwarfs and giants in the solar neighborhood appeared to have space velocity similar to that of the multiple star system Wolf 630 (MCC 782) which kinematically belongs to the old disk population. For this MG, we adopted as a mean velocity the average over the components of the Wolf 630 system: MCC 782AB = Wolf 630, MCC 782C = VB8, and MCC 782D = Wolf 629. Wolf 629 is a spectroscopic binary the system’s velocity of which is unknown, nevertheless we used instead the radial velocity given by Gizis et al. (2002) as it does not differ from that of the remaining components of the system (for Wolf 630, center-of-mass velocity is known). In addition to the known quadruple system Wolf 630, three possible candidates members were identified.

The Bottlinger and Toomre diagrams with the 146 stars of Table 7 removed are displayed in the right-hand panels of Figs. 13 and 14. Comparison of the left- and right-hand panels shows that after extraction of candidate members the

Table 8. Comparison with the results from LACEwING identification.

SKG	This work	LACE ⁽¹⁾ ≥50%	N ⁽¹⁾ match	LACE ⁽²⁾ 20–49%	N ⁽²⁾ match
β Pictoris MG	4	6	3	5	0
IC2391/Argus	4	4	2	1	0
AB Doradus MG	7	14	6	11	1
Her-Lyr (Local Ass.)	(21)	5	(4)	12	(5)
Ursa Major MG	9	3	1	3	0
Hyades OC	7	5	4	4	2

velocity distribution is apparently less dominated by overdensities, though not so much as it would be expected if small-scale structures were randomly distributed. Some number of potential SKG members yet remain unrecognized in the present study. On the whole, a rich small-scale structure is still evident in the kinematical plane.

5.4. Comparison with other results

Table 7 lists 146 candidate members, which comprise 13% of the sample of 1083 stars with $\sigma_\pi/\pi < 0.30$, used in SKG member search. In this context, it is interesting to note that CHE99 in their wavelet analysis of clustering and streaming among HIPPARCOS A–F stars have evaluated percentages of stars in streams of 38% and 18% at typical scales of stream velocity dispersions 3.8 and 2.4 km s $^{-1}$, respectively. Thus we can conclude that our list of SKG candidate members is helpful to only partially clean the velocity space of nearby K–M star sample from stellar streams.

Of the 98 stars common to our sample which are mentioned in the literature as bona fide members, probable, doubtful or spurious members, only half (47 stars) appear in our list of candidate members. Seven stars in Table 7 are reported in the literature as nonmembers of a given group.

To check our results, we made a comparison with the results obtained using the moving group membership identification code LACEwING⁴ by Riedel (2016). The code calculates probabilities for membership in ten moving groups and four open clusters by matching the proper motion, distance, radial velocity, and spatial location of the stars to those estimated for a group member at that location. Using this code we found in our total sample (MCC+CNS) 37 stars with SKG membership probabilities $\geq 50\%$ and 38 stars with lower membership probabilities (20–49%). The statistics of comparison are given in Table 8. The second column gives the numbers of candidate members from Table 7, while the columns labeled “N/match” give the number of stars for which the SKG membership from both LACEwING and our paper matches. Best agreement with the LACEwING results is for the β Pictoris, IC 2391/Argus, and AB Dor groups and the Hyades open cluster. The LACEwING candidates for the Hercules-Lyra group are among the stars assigned by us to Subgroups 1–6, B2, and Suspected group 1, all of the Local Association. The numbers in parentheses refer to the stars assigned by us to the entire Local Association, not separately for the Hercules-Lyra group. However, the worst match is in the case of the UMa MG, for which we have only one star in agreement with the LACEwING result.

It should be noted that candidate members listed in Table 7 not necessarily all represent a particular group and subgroup they are ascribed to. A dual candidacy is common among the stars assigned to the subgroups of the Local Association.

⁴ <https://github.com/ariedel/lacewing>

Fig. 15. Comparison of the distributions of space velocities U , V , W of K0–M5 dwarfs in the simulated datasets with different declination cuts. Data are based on the Besançon model. The hatched area shows the declination zone between -30° , an observational limit of the MCC sample, and -15° , where a decline in completeness of the sample starts to take place.

Concluding this section we would like to point out that kinematics and galactic orbital parameters alone are not sufficient to ascertain SKG membership. Stellar properties such as lithium abundance, chromospheric activity or other age indicators, as well as elemental abundances, need to be involved to verify that candidates and bona fide members of the group do indeed share similar properties.

6. Kinematics in the solar neighborhood

6.1. Checks of kinematic bias

6.1.1. Declination cut

In the paper by Weis & Uggren (1995), a proper motion bias arising as a consequence of non-sharp magnitude and color limits to the MCC survey was investigated, and it has been shown that this incompleteness for stars of decreasing proper motion gives no evidence for a kinematic bias. However, Reid et al. (1995) from their analysis of 368 MCC M-type stars common to the PMSU survey have noted that there may be a kinematic bias towards higher velocities in the MCC sample.

Before we begin analyzing the kinematics, we check first for possible effects due to MCC survey limit at declination of -30° that in Galactic coordinates produces a large area uncovered around the longitude $\ell \sim 300^\circ$ and latitude $b \sim -30^\circ$.

For this purpose we compared the U , V , W velocity distributions of K–M dwarf stars simulated in the Besançon model⁵ of the Galaxy (Robin et al. 2003; Czekaj et al. 2014) with sky coverage decreasing in declination. The simulations were done in the absolute magnitude range of K0–M5 dwarfs, $M_V = 5.8$ – 12.3 mag, and apparent magnitude and color intervals $V = 7.0$ – 11.5 mag and $B - V = 0.80$ – 1.65 mag, which represent roughly the observational limits of the MCC survey. The results of comparison are displayed in Fig. 15. The leftmost points at Dec -90° come from the entire sky coverage. The points from left to right represent the mean values of velocity distributions obtained with successive declination cuts of 10° until part of the sky with declination $>30^\circ$ remains covered. The U , V , W values

are taken from a Gaussian approximation of the velocity component's distribution (center values and their errors). As can be evaluated from the plots, the most susceptible to the absence of data at southern declinations is the velocity component U which at the MCC survey limit (Dec -30°) appears to be shifted by 0.3 km s^{-1} to a more positive values relative to the mean value of U distribution obtained across the entire sky. At Dec -15° , where decline in completeness of the MCC sample starts, the difference in U reaches 0.7 km s^{-1} , which is larger than typical errors of $\sim 0.3 \text{ km s}^{-1}$ displayed in the figure. The components V and W both show a difference not exceeding 0.1 km s^{-1} from the entire sky values.

Since model velocities given in the figure are with respect to the Sun, they reflect the negative solar motion with respect to the LSR assumed in the model, except for the component V which is indicative of asymmetric drift.

6.1.2. Malmquist effect

Further kinematic bias for the magnitude-limited MCC sample may be present owing to the Malmquist effect that gives rise to systematic over-representation of intrinsically more luminous objects relative to the fainter ones. To diagnose this effect for the MCC sample, we generated a volume-complete sample in the Besançon model and explored how the behavior of kinematic parameters changes with different magnitude cut-offs. For this, we populated a spherical volume of 140 pc radius that at the MCC magnitude limit ($V = 11.5$) includes completely late-type dwarfs on the bluest side (K0, $M_V = 5.8$ mag) of the spectral range covered by the MCC sample. To include M5 dwarfs, the magnitude limit was set at $V = 18$. We calculated the velocity distributions (mean values and dispersions) for both the volume-limited sample and the subsamples with magnitude cuts at 11.5, 11.0, and 10.5 mag.

The results are displayed in Fig. 16, separately for three spectral-type intervals of simulated dwarfs, K0–K4, K5–K9, and K9–M5. As can be seen, at the magnitude cut-off $V = 11.0$ that can be considered a conservative magnitude limit for the MCC sample, a small shift to more negative U and V values and smaller dispersions in U , V , and W is clearly present.

For a more specific evaluation of the Malmquist effect for the entire MCC sample, we must first compare the distributions of stars by spectral type in the magnitude-limited synthetic sample and in the MCC sample. The histograms of such distributions are plotted in Fig. 17. In sharp contrast with the synthetic sample that manifests visibly the Malmquist bias, the MCC sample, due to its incompleteness and bias against K-type stars within the magnitude limit, seems to be less susceptible to this effect. The fractions of stars in each of the three intervals of spectral types, K0–K4, K5–K9, and M0–M5, are respectively $0.23 : 0.35 : 0.42$ for the MCC sample and $0.77 : 0.19 : 0.04$ for the synthetic sample. Using these proportions and the differences in velocities and their dispersions from those in the volume-limited sample, we found for the entire MCC sample the largest (but within the errors) corrections for U and σ_U , $+0.6 \text{ km s}^{-1}$ and $+1.4 \text{ km s}^{-1}$, respectively. For other velocity components and dispersions, the corrections are negligible ($+0.4 \text{ km s}^{-1}$ for σ_V and 0.1 – 0.2 km s^{-1} for the rest). We note that a correction of 0.7 km s^{-1} in U due to the declination cut of the MCC sample (Sect. 6.1.1) is in the opposite sense and, if applied, cancels out the above correction of $+0.6 \text{ km s}^{-1}$. Thus, we conclude that, in general, the Malmquist effect is unlikely to appreciably influence our kinematical results to be presented in the next section.

⁵ <http://model.obs-besancon.fr/>

Fig. 16. Comparison of space velocities U , V , W and their dispersions in the simulated samples of K0–M5 dwarfs with different limiting magnitudes. The colored lines represent different spectral intervals: K0–K4 (blue), K5–K9 (green), and M0–M5 (red). The filled points within the gray vertical stripe indicate the values for volume-limited sample ($d = 140$ pc). The hatched zone shows an approximate magnitude limit of the MCC sample.

Fig. 17. Distributions of the synthetic K0–M5 dwarfs down to $V_{\text{lim}} = 11.0$ mag (shaded gray, with hatched areas corresponding to different spectral intervals) and the K–M dwarfs in the MCC sample (black-border bars) by $B - V$ color.

As we mentioned in Sect. 2, our small set of 187 stars from the CNS list is not used in the present kinematic analysis along with the MCC sample, except in a search for SKG candidate stars (Sect. 5) and in composing a subsample of chromospherically active stars (Sect. 6.3.3). Therefore, we do not consider possible

Lutz & Kelker (1973) corrections for this set of stars. Moreover, nearly all of these CNS stars have relative parallax error less than 10%.

6.2. Sun's velocity with respect to the LSR

The distributions of the heliocentric space-velocity components U , V , and W of the MCC stars are shown in Fig. 18. Instead of classical histograms where parameters being analyzed are treated as delta functions, we constructed a whole ensemble of probability density functions (PDF) of the velocities (or other parameters considered) and their known Gaussian errors. Here we used the Gaussian mixture model (GMM) program⁶ by Bovy et al. (2009) and the regularization parameter $w = 4$ recommended by these authors. It is known that GMM can fall into a local minimum instead of global. Thus, we performed at least 200 runs using random initial values of GMM parameters. In the analysis, we put no restriction on upper value of the relative parallax error and used all MCC stars from Table 5.

The one-component Gaussian curves that should be an adequate description of the symmetric distributions of U and W velocities give straightforwardly the values (with opposite sign) of the two components of the Sun's motion relative to the LSR, $U_{\odot}$ and $W_{\odot}$. As seen from comparison of the U values indicated in panels a and d of Fig. 18, excluding the candidate members of SKGs yields a somewhat smaller value for the radial solar velocity. This is not surprising since the many SKGs (except of the Sirius Supercluster) have negative U motions (see Table 6). It seems that over the many SKGs and subgroups, each representing minor fraction of the whole sample, the effect of bulk motions may not be completely smoothed away.

A comparison of the distributions of the MCC sample and those for the combined sample with 187 stars from the CNS list added revealed no appreciable differences: $U = -9.5 \pm 1.2$ km s⁻¹ and $W = -7.4 \pm 0.5$ km s⁻¹ (1088 stars). This may be due to a relatively small number of CNS stars that contribute relatively little to the velocity distributions.

In Fig. 18 the distributions of MCC stars are compared with the Besançon model stars generated in the same sky area. The mean values of U derived from the MCC sample agree within the errors with that of the model stars, whereas the mean W component of the MCC stars is shifted by 1 km s⁻¹ relative to the model distribution. All three velocity dispersions are larger than the model values.

To have the values of the Sun's motion less susceptible to possible effects of kinematic bias, we adopted as final the results obtained from the MCC sample of 777 stars, free of candidate members of SKGs:

$$U_{\odot} = 9.0 \pm 1.4 \text{ km s}^{-1},$$

$$W_{\odot} = 7.2 \pm 0.8 \text{ km s}^{-1}.$$

The component $V_{\odot}$ is much harder to determine, because stars in the direction of Galactic rotation systematically lag behind the LSR, and this lag, or the asymmetric drift, increases with the velocity dispersions of the respective stellar population.

The classical solution to determining this component of the Sun's peculiar motion is to reduce to the LSR the mean velocities V for different types of stars using Strömberg's asymmetric drift equation (e.g., Binney & Tremaine 2008, Eqs. (4)–(228)),

$$\bar{V} - V_{\odot} \approx \frac{\sigma_U^2}{2\theta} \left[\frac{\sigma_V^2}{\sigma_U^2} - 1 - \frac{\partial \ln(\nu \sigma_U^2)}{\partial \ln R} - \frac{R}{\sigma_U^2} \frac{\partial(\sigma_U \sigma_W)}{\partial z} \right], \quad (7)$$

⁶ <http://code.google.com/p/extreme-deconvolution/>

Fig. 18. Distributions of heliocentric space-velocity components U , V , and W for K–M dwarfs in the MCC sample. The mean values of U and W and their errors, indicated in the panels, are from the GMM (red line). For V (panels **b** and **e**), the Gaussian curves of the Besançon model simulations are shown for different age groups and for the entire population. The percentages indicated are relative numbers of model stars in different age groups.

that gives a linear relation between the negative mean heliocentric velocity $\bar{V}$ of any relaxed stellar population and its dispersion σ_U squared. Here, R and z are respectively the distance from the Galactic center and the height above the plane, θ is the circular speed, and ν denotes the number density of stars. Hence, a linear fit to the data points, extrapolated to $\sigma_U = 0$ representing strictly circular orbits, or the LSR, yields the value of $V_\odot$.

Figure 19 shows the plots of V against σ_U^2 for K–M dwarfs of the MCC sample representing the thin disk population. The thick-disk stars were eliminated from the sample using criteria described in Sect. 6.3.2. To define subgroups of stars within the sample, we chose the value of maximum orbital height above (or below) the Galactic plane, $Z_{\max}$, as a criterion providing a rough age discrimination. This approach of dividing stars into subgroups is based on the assumption that the motion of a star parallel to the galactic plane (U , V -velocities) is decoupled from its z -motion. We calculated mean V and dispersions σ_U^2 for six bins in $Z_{\max}$ (0–50, 50–100, 100–150, 150–200, 200–300, and 300–600 pc). From Fig. 19 we found for the Sun’s velocity the value $V_\odot = 14.2 \pm 0.8 \text{ km s}^{-1}$. In this case, the candidate members of SKGs were not eliminated from the subgroups of MCC stars. The exclusion of the SKG member candidates changed no result: $V_\odot = 14.1 \pm 1.2 \text{ km s}^{-1}$. However, it gave rise to larger uncertainty of the result due to small-number statistics at a lower end of $Z_{\max}$ (and hence low σ_U).

In Fig. 19 we also show, for comparison, the plots for synthetic stellar subsamples of K0–M5 thin-disk stars from the Besançon model, defined by age with bins of 0–0.15, 0.15–1, 1–2, 2–3, ..., 7–10 Gyr. The model data points lie almost on a straight line, except for the youngest subsample of synthetic stars. The intercept with the vertical axis gives the value of $V_\odot$ close to that adopted in the model (5.9 km s^{-1}).

Fig. 19. Dependence of the velocity component V on σ_U^2 for K–M dwarfs: solid points represent subgroups of MCC stars, defined by the orbital vertical height $Z_{\max}$, and open squares are for synthetic stellar subsamples of the Besançon model, defined by age. The black thick line is a linear fit to the MCC points, with uncertainty limits shown as gray lines. The dotted blue line is a linear fit to the model data.

Other approach to deriving the Sun’s velocity component $V_\odot$ can be to use the distribution of V velocity for stars in nearly circular orbits, that is, by restricting the sample by eccentricity in the U , V -plane. From a subsample of stars with eccentricities $e \leq 0.05$ (92 stars), extracted from a sample of MCC stars free of candidate members of SKGs, we obtained

$$V_\odot = 13.1 \pm 0.6 \text{ km s}^{-1}. \quad (8)$$

This value does not differ from the one derived using a more numerous subsample of 150 stars with the same eccentricity cut but which includes stars from the CNS list and candidate stars of SKGs: $V_{\odot} = 13.1 \pm 0.5 \text{ km s}^{-1}$.

Previous solutions for the solar motion relative to the LSR, based on a maximum-likelihood analysis of MCC stars with the then available radial-velocity data and pre-HIPPARCOS parallaxes, yielded the following values: $(U, V, W)_{\odot} = (8.1 \pm 1.4, 7.4 \pm 2.5, 6.4 \pm 0.7) \text{ km s}^{-1}$ (Ratnatunga & Uppgren 1997). The same data set of MCC stars, but with HIPPARCOS parallaxes employed, gave closely similar values (Uppgren et al. 1997).

In the literature, most of the inconsistencies are found in the value for $V_{\odot}$, with its estimates varying from 3 km s^{-1} to $\sim 20 \text{ km s}^{-1}$. In general, the estimates based on large stellar samples, such as from the entire HIPPARCOS catalog, GCS, or RAVE and SDSS surveys, converge to three values of $V_{\odot}$. One value is close to 5 km s^{-1} , see, for example, estimates by Dehnen & Binney (1998), Hogg et al. (2005), van Leeuwen (2007), Aumer & Binney (2009) or recent estimate by Golubov et al. (2013) from a different approach to the application of Strömberg's equation to the RAVE data. At the other extreme, $V_{\odot}$ value based on nearby M dwarfs is around 20 km s^{-1} (Reid et al. 2009; Fuchs et al. 2009; Bond et al. 2010; Bochanski et al. 2011). The interim values are typically in the range $11\text{--}14 \text{ km s}^{-1}$ (see, e.g., Francis & Anderson 2009; Schönrich et al. 2010; Coşkunoğlu et al. 2011). In agreement with the latter values is also an estimate by Bobylev & Bajkova (2010) based on known masers.

As it has been pointed out by Mignard (2000), the radial component $U_{\odot}$ is much more variable compared to $W_{\odot}$, with its values based on young disk objects being larger ($U_{\odot} \sim 10\text{--}12 \text{ km s}^{-1}$) than those derived using later types of stars ($U_{\odot} \sim 7\text{--}8 \text{ km s}^{-1}$). Recent estimates based on nearby M dwarfs from SDSS give the values of $U_{\odot}$ in the range $8\text{--}10 \text{ km s}^{-1}$ (Fuchs et al. 2009; Bond et al. 2010; Bochanski et al. 2011). In the same very narrow range are the estimates of $U_{\odot}$ from the RAVE survey, $8.5\text{--}10.0 \text{ km s}^{-1}$ (Coşkunoğlu et al. 2011; Pasetto et al. 2012b,a).

The literature values of $W_{\odot}$ all are generally in concordance ($6.5\text{--}8 \text{ km s}^{-1}$). Our estimate of $W_{\odot}$, although based on a relatively small sample of stars, is comparable to the results deduced from large samples.

6.3. Kinematical analysis of the sample

6.3.1. Distributions of eccentricity and Z_{max}

We lack the necessary data to discriminate between the constituent populations of the entire MCC sample by non-kinematic variables (e.g., taking into consideration chromospheric activity or other age indicator). Therefore we made an attempt to reveal the underlying Gaussian components from the distributions of orbital eccentricity and maximum distance from the Galactic plane, Z_{max} . These distributions are shown in Fig. 20.

In panels a, c of Fig. 20, the best fit to the shape of the eccentricity distribution, given by the minimum description length (MDL) criterion (Bovy et al. 2009), is provided by the sum of four Gaussian distributions. Two Gaussian curves with the smallest values of mean eccentricity, around 0.05 and 0.09, can presumably be identified with the young disk and the intermediate-age disk populations. The third Gaussian curve, with the mean eccentricity around $e = 0.17$ and the number of stars comparable to those of the two Gaussian distributions at smaller eccentricity values, is likely to represent the old thin-disk population.

And, finally, the fourth curve with the smallest fraction of stars ($\sim 10\%$), centered at $e = 0.28$, can be associated with the mixture of the old thin disk and thick disk components. Approximate fractions of stars associated with the three components of the thin disk are, in order of increasing mean eccentricity, on the order of 0.20:0.40:0.30. For comparison, the simulated K0–M5 dwarfs in the Besançon model (Robin et al. 2003; Czekaj et al. 2014) comprise similar fractions of stars in different age groups of the thin disk population (see panels b or e of Fig. 18): 26% for 0.15–1 Gyr, 45% for 1–5 Gyr, and 27% for 5–10 Gyr. The model stars that belong to the thick disk constitute 2.5% of the complete simulated sample, while the large-eccentricity component of the MCC stars with its 10% fraction can hardly represent the pure thick disk population.

The same can be said about the distribution of the orbital distance Z_{max} (panels b, d of Fig. 20). In concordance with eccentricity, the three major Gaussian components of the MCC stars can be associated with the three constituents of the thin disk with mean Z_{max} values of approximately 50 pc, 120 pc, and 280 pc. A hardly discernable component with the mean Z_{max} around 0.8 kpc and its fraction of only 5% can represent the old thin disk stars with a more substantial admixture of thick-disk stars than in the case of eccentricity distribution. We consider the thick disk stars in the MCC sample in the next section.

6.3.2. Constituent populations

To isolate the most probable individual members of the thick disk (or any other population) from the bulk of the sample, we used the kinematical approach proposed by Bensby et al. (2003) and taken in a number of studies (e.g., Reddy et al. 2006; Trevisan et al. 2011). The procedure relies on the assumption that the space velocities of each population follow a Gaussian distribution with given mean values and dispersions $\sigma_U, \sigma_V, \sigma_W$. The equation determining the probability that the star belongs to the population i is

$$P_i = f_i \frac{p_i}{p}, \quad (9)$$

where f_i is the population's relative density in the solar neighborhood, p is the probability for the sum of n populations, given by

$$p = \sum_{i=1}^n f_i p_i, \quad (10)$$

and p_i are Gaussian distributions of the velocities for each population:

$$p_i = \frac{1}{(2\pi)^{3/2} \sigma_{U_i} \sigma_{V_i} \sigma_{W_i}} \exp \left[-\frac{U^2}{2\sigma_{U_i}^2} - \frac{(V - V_{ai})^2}{2\sigma_{V_i}^2} - \frac{W^2}{2\sigma_{W_i}^2} \right]. \quad (11)$$

Here, U, V, W , and V_{ai} denote the velocity components and asymmetric drift relative to the LSR.

In the calculation of population membership probabilities by the above equations we adopted the parameter values taken from the literature. Specifically, the kinematic parameters for the components of the thin disk and halo and the relative densities f_i for all of the populations were taken the same as adopted in the Besançon model of the Galaxy (see Table 4 in Robin et al. 2003). The parameters of the young thin-disk and the old thin-disk were combined from the model values adopted for the two youngest

Fig. 20. Distribution of MCC stars by eccentricity (panels **a**, **c**) and maximum distance $Z_{\max}$ from the Galactic plane (panels **b**, **d**). *Top panels* represent MCC stars without candidate members of SKGs and *bottom panels* display the distributions of all MCC stars. The red line represents the sum of underlying Gaussian distributions. Their parameters are given in each panel; indicated in the last column are fractions of stars covered by each curve.

Table 9. Parameters adopted in the calculation of population membership probabilities.

Stellar population	σ_U (km s ⁻¹)	σ_V (km s ⁻¹)	σ_W (km s ⁻¹)	V_a (km s ⁻¹)	f	Ref.
Young disk	18.3	11.8	7.0	-3.3	0.25	1
Interm. disk	31.4	20.3	13.0	-8.0	0.42	1
Old disk	43.1	27.8	17.5	-14.8	0.26	1
Thick disk	56.1	46.1	35.1	-50	0.068	2, 1
Halo	131	106	85	-220	0.005	1

References. (1) Robin et al. (2003); (2) Pasetto et al. (2012b).

(0–0.15 Gyr and 0.15–1 Gyr) and two oldest (5–10 Gyr) stellar components, respectively, each in its age group having closely similar velocity dispersions. The parameters of the intermediate-age disk were adopted as averages over three age bins in the interval 1–5 Gyr. The values of velocity ellipsoid and asymmetric drift for the thick disk were taken from the RAVE data analysis by Pasetto et al. (2012b). The adopted values of the parameters are summarized in Table 9. We note that here and throughout this paper the heliocentric space-velocity components were corrected for the solar motion with respect to the LSR using the

values $(U_{\odot}, V_{\odot}, W_{\odot}) = (11.1, +12.2, +7.2)$ km s⁻¹ taken from Schönrich et al. (2010).

Application of the above approach yielded the following results. In addition to 68 candidate members of young SKGs (typically younger than the Sirius SCl), we have 98 K–M stars with the young thin-disk probabilities >50%. Their mean eccentricity is $\langle e \rangle = 0.046 \pm 0.019$ (s.d.) and the mean maximum distance is $\langle Z_{\max} \rangle = 53 \pm 26$ (s.d.) pc. With these kinematically young stars can be associated the underlying Gaussian component with $e \approx 0.05$ and $Z_{\max} = 50$ pc deconvolved in Fig. 20. The mean orbital parameters of the K–M stars with the intermediate-age disk and old thin disk probabilities >50% are respectively $\langle e \rangle = 0.12 \pm 0.04$ (s.d.), $\langle Z_{\max} \rangle = 136 \pm 71$ (s.d.) pc ($N = 344$) and $\langle e \rangle = 0.22 \pm 0.08$ (s.d.), $\langle Z_{\max} \rangle = 271 \pm 161$ (s.d.) pc ($N = 142$). In line with these values, within the errors, also are the parameters of the second and third Gaussian components in Fig. 20.

The main purpose of the calculation of population membership probabilities was to separate the thick-disk stars from the thin-disk stars that dominate the sample. As a result, there are 40 stars within the entire sample which have the thick-disk probabilities >55%; of these, 22 stars are with $P \geq 80\%$. These stars comprise 2 to 4 percent of the entire sample of K–M dwarfs (MCC plus CNS list), depending on the cut-off limit set on

Fig. 21. Distributions of the sample stars with the thick-disk probabilities (Eq. (9)) $>55\%$, $\geq 60\%$ and $\geq 80\%$ by eccentricity **a**) and maximum orbital distance Z_{max} **b**).

the probability. Their histogram distributions by eccentricity and Z_{max} are shown in Fig. 21. Apparently, these stars make a major contribution to the fourth Gaussian component with $e = 0.28$ and $Z_{\text{max}} = 0.8$ kpc deconvolved in Fig. 20.

6.3.3. Velocity ellipsoids

After excluding from the MCC sample the stars with the thick-disk membership probabilities $>60\%$ and an additional two stars with the kinematics resembling halo stars, the velocity ellipsoid of the MCC stars, representing the entire thin disk population ($N = 866$), is

$$(\sigma_U, \sigma_V, \sigma_W) = (36.4 \pm 1.1, 21.2 \pm 0.6, 16.4 \pm 0.4) \text{ km s}^{-1},$$

and the rotational lag relative to the LSR is $V_a = -5.9 \pm 0.7 \text{ km s}^{-1}$. The exclusion of the candidate members of SKG, which are supposed to be of young age, makes the dispersions and asymmetric drift for a sample of 742 stars only slightly higher (see Table 10).

The vertex deviation of the thin-disk velocity ellipsoid, given by the relation (see, e.g., Binney & Merrifield 1998, Eq. (10.16))

$$\ell_v = -\frac{1}{2} \arctan \frac{2\sigma_{UV}}{\sigma_U^2 - \sigma_V^2}, \quad (12)$$

Fig. 22. Chromospheric emission indices S_{HK} collected from the literature vs. $B - V$ color for 408 stars in our sample. The blue data points denote the stars reported as active. The solid line is the lower envelope for main-sequence dwarfs, defined by Isaacson & Fischer (2010) as a basal activity level S_{BL} . Four data points with the largest values of S_{HK} lie outside of the y -axis range.

is in both of the cases small, $\ell_v = 7^\circ \pm 2^\circ$. No tilt of the velocity ellipsoid is discerned in the meridional plane spanned by U and W velocities. The velocity dispersion ratios are $\sigma_U/\sigma_W = 2.2$ and $\sigma_U/\sigma_V = 1.7$. A relatively small vertex deviation, the dispersion ratios and the anisotropy parameter $\beta = 0.73$, defined as

$$\beta = 1 - \frac{\sigma_V^2 + \sigma_W^2}{2\sigma_U^2}, \quad (13)$$

suggest that the bulk of K–M stars in the immediate solar neighborhood are dynamically relaxed.

In the previous kinematic analysis of the MCC stars, carried out by Ratnatunga & Uppgren (1997) and Uppgren et al. (1997), the velocity ellipsoids were derived separately for the young disk stars and old disk stars (see Table 11) using a maximum likelihood method. In the present paper, we attempted to distinguish between the two thin-disk populations by using the chromospheric activity information that is available in the literature. We found such information for 394 stars from the MCC sample and 101 stars from the CNS list. For the most part, the activity data came from the Palomar/MSU spectroscopic survey (Reid et al. 1995; Hawley et al. 1996), “HK Project” at Mount Wilson Observatory (Duncan et al. 1991), NStars project (Gray et al. 2003, 2006), and the California Planar Search program (Isaacson & Fischer 2010). From this collection of data, we have 146 MCC and 42 CNS stars showing chromospheric activity based on Ca II H and K, H_α or other activity indicators. Most of our sample stars (408 in total) have chromospheric emission index S_{HK} given, and nearly half of these have $\log R'_{\text{HK}}$ values calculated. In Fig. 22 we plotted the S_{HK} , $B - V$ diagram, with active stars indicated by separate symbols. Here, the S_{HK} values are on, or very close to, the Mount Wilson scale. The line shown in the figure is the polynomial relation defined by Isaacson & Fischer (2010), which represents the basal (rotation independent) activity level, S_{BL} .

For all known active stars in our sample, including stars from the CNS list, we found for this group of presumably “young”

Table 10. Velocity dispersions, asymmetric drift, and vertex deviation for different subsamples of K–M dwarfs.

Stellar sample	Sample size	σ_U (km s ⁻¹)	σ_V (km s ⁻¹)	σ_W (km s ⁻¹)	V_a (km s ⁻¹)	σ_{UV} (km s ⁻¹) ²	σ_{UW} (km s ⁻¹) ²	ℓ_v (°)	Comments on sample selection
Thin disk	866	36.4 ± 1.1	21.2 ± 0.6	16.4 ± 0.4	-5.9 ± 0.7	-103.4	7.2	6.6 ± 1.8	MCC stars, SKGs included
	742	38.7 ± 1.2	22.4 ± 0.6	17.5 ± 0.5	-6.4 ± 0.8	-115.8	5.1	6.6 ± 1.9	MCC stars, SKGs excluded
Inactive	238	43.9 ± 2.4	22.7 ± 1.1	17.8 ± 0.8	-7.2 ± 1.5	-4.4	67.1	0.2 ± 2.7	MCC stars, chrom. inactive
Active	188	25.6 ± 1.3	16.5 ± 1.1	13.6 ± 1.0	-3.7 ± 1.2	-120.1	-1.1	16.0 ± 3.8	MCC+CNS, chrom. active
SKG stars	139	16.8 ± 0.9	10.6 ± 0.5	5.7 ± 0.2	-1.3 ± 0.9	-95.5	44.3	24.3 ± 2.5	SKG candidate members (Table 7)

Table 11. Previous kinematical results based on studies of nearby late-type dwarfs.

Study	Stellar sample	Sample size	σ_U (km s ⁻¹)	σ_V (km s ⁻¹)	σ_W (km s ⁻¹)	V_a (km s ⁻¹)	ℓ_v (°)	Comments on sample selection
Wielen (1977)	All stars	516	39	23	20			MCC stars with HK data
	~0.3 Gyr		18	10	8			MCC stars with HK +8/+3
	~5 Gyr		38	23	20			MCC stars with HK 0
	~9 Gyr		66	27	23			MCC stars with HK -2/-5
Reid et al. (1995)	M-type	368	39	26	23			MCC M dwarfs in PMSU I survey
Reid et al. (1995)	H α	86	27	23	21			CNS3 M dwarfs with H α emission
Reid et al. (1995)	M-type	514	43	31	25			CNS3 M dwarfs within 25 pc
Ratnatunga & Upgren (1997)	Young disk		30.6	18.5	12.4	-7.4	11.7	MCC stars (max. likelihood), with pre-HIPPARCOS astrometry
	Old disk		54.0	35.9	31.3	-23.0		
Upgren et al. (1997)	Young disk		30.2	17.3	11.9	-8.2	9.7	MCC stars (max. likelihood), with post-HIPPARCOS astrometry
	Old disk		56.1	34.2	31.2	-28.3		
Reid et al. (2002)	dMe	83	25.0	21.1	17.8			CNS3 dMe in PMSU IV survey
	dM+dMe	436	37.9	26.1	20.5			CNS3 dM+dMe in PMSU IV
Bochanski et al. (2005)	Active	155	19	15	16			M dwarfs within 100 pc
Bochanski et al. (2005)	Inactive	419	35	21	22			M dwarfs within 100 pc
Bochanski et al. (2007)	M-type	70	28.4	21.3	19.2			SDSS M dwarfs, $ z < 100$ pc
Fuchs et al. (2009)	M-type	48 075	32.4	23.0	18.1			SDSS M dwarfs, $ z < 100$ pc

disk stars ($N = 188$) the velocity ellipsoid

$$(\sigma_U, \sigma_V, \sigma_W) = (25.6 \pm 1.3, 16.5 \pm 1.1, 13.6 \pm 1.0) \text{ km s}^{-1},$$

the asymmetric drift $V_a = -3.7 \pm 1.2 \text{ km s}^{-1}$, and a vertex deviation ℓ_v of approximately 16° . Their mean orbital eccentricity is $\langle e \rangle = 0.09 \pm 0.05$ (s.d.). These velocity dispersions are very close to those of active M6–M7 dwarfs from the SDSS, obtained by Bochanski et al. (2011). Also, the values of the ellipsoid and vertex deviation are close to the earlier results of Ratnatunga & Upgren (1997) and Upgren et al. (1997) based on different approach (i.e., maximum likelihood procedure) to distinguish between “young” and “old” populations.

In Table 10, we give for comparison the velocity dispersions for the subsample of the SKG member candidates from Table 7, with the old-disk Wolf 639 group excluded. This small sample of supposedly young stars shows a significant vertex deviation, $\ell_v = 24 \pm 3^\circ$, and an apparent tilt in the meridional plane (-10°). Curiously, the values of this ellipsoid agree well with the result obtained by Wielen (1977) for the MCC stars in the youngest age bin at 0.3 Gyr dated from the Ca II H and K emission intensity (see Table 11).

The thin disk stars indicated in literature as inactive have the velocity dispersions similar to those of CNS3 M-type stars in the PMSU survey (Reid et al. 2002) or of the 5 Gyr year group of

inactive MCC stars analyzed by Wielen (1977). More results of the velocity ellipsoid determinations for late-type stars are given in Table 11.

Concluding this subsection we would like to mention that two stars in the MCC sample, MCC 731 and MCC 869, have large rotational lag (exceeding -200 km s^{-1}) and high orbital eccentricities ($e > 0.8$) which would be typical of the halo population. The radial velocity of the high-proper-motion star MCC 731 was measured by us only once, but our value is close to that of recent SDSS MARVELS observations (Alam et al. 2015) or earlier observations quoted in the ARICNS database² and in the Pulkovo compilation of radial velocities (Gontcharov 2006). However, the space-velocity components for MCC 731 have very large uncertainties and we have excluded this star from further consideration. The second halo candidate, the K-type dwarf MCC 869, with relatively small velocity errors is discussed in Sect. 6.3.4.

6.3.4. MCC 869

The K-type dwarf MCC 869 (HIP 117795) deserves special attention. Its very large radial velocity (-286 km s^{-1}) and very small transverse velocity (11 km s^{-1}) show that the star is heading almost straight towards us. But the most distinguishing

Fig. 23. Galactic orbit of MCC 869 integrated back in time in the potential models by JSH95 (*upper panels*) and AS91 (*bottom panels*) in projections onto the (X, Y) plane (*left-hand panels*, for -9 Gyr) and the (R, Z) plane (the remaining six panels, for -9 , -2 , and -1 Gyr). The open square shows the present position of the star. The *inset* to panel **d**) shows a projection of the orbit in more detail with the R, Z -axes scaled independently.

feature is its very large rotational lag, -250 km s^{-1} , which places the star into a retrograde Galactic orbit ($V_{\text{rot}} = -30 \text{ km s}^{-1}$). No signs of variability in its radial velocity have yet been detected from our repeated CORAVEL observations during a period of four years. However, in the HIPPARCOS catalog, this star is marked by multiplicity flag “G” which is used to denote accelerating proper motions (for acceleration data on this star, see the catalogs of Makarov & Kaplan 2005; Frankowski et al. 2007). According to the statistical criterion by Frankowski et al. (2007), MCC 869 does not fall in the expected region of proper-motion binaries.

With currently available radial velocity data (Table 2), the kinematics of MCC 869, as well as its orbital eccentricity ($e = 0.84$), are typical of a halo object. However, a presumably mild metal deficiency ($[\text{Fe}/\text{H}]$ around -0.6 dex), evaluated from the CORAVEL correlation curve, is not typical of the halo. Its Galactic orbit integrated back in time in the potential models by JSH95 and AS91 is displayed in Fig. 23, in projections onto the planes (X, Y) and (R, Z) . As seen in the figure, the star’s Galactic orbit is unusual. Being retrograde, its current orbit is nearly confined to the Galactic disk. The inclination angle with respect to the Galactic plane, averaged over the number of recent plane-crossings, is $3.9^\circ \pm 0.7^\circ$ (s.d.) in the JSH95 potential (the past 1 Gyr) and $4.3^\circ \pm 1.4^\circ$ (s.d.) using the AS91 model (the past 0.6 Gyr).

Such a star with a retrograde motion and a chaotic orbit, which gradually becomes coplanar with the Galactic plane, can be a member of stellar stream associated with some dissolved structure (e.g. accreted dwarf galaxy or dissolved globular cluster) or an exile from a strongly perturbed binary star system. The closest match can be found with the kinematics of the Kapteyn group (Eggen 1996; Silva et al. 2012) or debris from ω Cen progenitor dwarf galaxy (Dinescu et al. 1999; Dinescu 2002). The current Galactic orbit of ω Cen is both planar and retrograde, with the velocity components $(U, V_{\text{rot}}, W) = (61, -36, 6) \text{ km s}^{-1}$ (see, e.g., Wylie-de Boer et al. 2010), of

which only the component U is not quite compatible with that of MCC 869. However, as it is demonstrated in Meza et al. (2005, their Fig. 10), the ω Cen group candidates span a large symmetric range in U , from -300 to 300 km s^{-1} . Therefore, along with additional observations of radial velocity of MCC 869, the study of its chemical composition is probably the first to address the question of the status of this star.

7. Conclusions

During the progress of our CORAVEL program a total of 3287 individual measurements of radial velocities for 1049 nearby K–M dwarf stars were obtained. The overwhelming majority (857 stars) of the program targets are from the McCormick (MCC) sample of spectroscopically selected stars. With these observations we redressed the scarcity of radial-velocity data that have existed for nearly half of the MCC stars. In this paper, we presented a catalog of radial-velocity observations of 959 stars not suspected in velocity variability. The spectroscopic binaries, both confirmed and suspected, comprise 10% of the overall sample of K–M dwarfs.

Based on solely kinematic criteria, 146 stars were identified as possible candidate members of the known nearby kinematic groups and subgroups. These stars comprise 13% of the total sample of 1088 stars considered in this analysis.

Using the velocity distributions of stars from the MCC sample, we derived the velocity of the Sun with respect to the LSR $(U_\odot, V_\odot, W_\odot) = (9.0 \pm 1.4, 13.1 \pm 0.6, 7.2 \pm 0.8) \text{ km s}^{-1}$. The radial solar motion derived via the Strömberg’s relation, $V_\odot = 14.2 \pm 0.8 \text{ km s}^{-1}$, agrees within the errors with the above value obtained directly from the V distribution of stars on nearly circular orbits ($e \leq 0.05$). This component of the Sun’s motion is in concordance with recent estimates based on the velocity distributions of stars from the GCS and RAVE surveys.

The velocity ellipsoid of the thin disk stars in the MCC sample is $(\sigma_U, \sigma_V, \sigma_W) = (36.4 \pm 1.1, 21.2 \pm 0.6, 16.4 \pm 0.4) \text{ km s}^{-1}$, and the rotational lag of the thin disk stars relative to the LSR is $V_a = -5.9 \pm 1.7 \text{ km s}^{-1}$. The velocity ellipsoid of the thin disk stars shows a vertex deviation of $7^\circ \pm 2^\circ$. The velocity dispersion ratios are typical of the solar neighborhood and, together with an absence of appreciable vertex deviation, suggest that the bulk of the local K–M dwarfs represents a relaxed population. The velocity ellipsoid of the subsample of the candidate stars of young stellar kinematical groups shows a significant vertex deviation, $\ell_v = 24^\circ \pm 3^\circ$.

The distributions of MCC stars by orbital eccentricity and maximum distance from the Galactic plane are consistent with the presence of stellar populations of K–M dwarfs of different kinematical age. The thick disk stars comprise 2–4% of the MCC sample. One of the two high-velocity stars, the K dwarf MCC 869 (HIP 117795), was found to be on a retrograde Galactic orbit ($V_{\text{rot}} = -30 \pm 0.3 \text{ km s}^{-1}$) of low inclination (4°). If it does not appear to be a spectroscopic binary, this star can be a member of stellar stream of some dissolved structure or disrupted binary system. To deduce the origin of such high-velocity star, long-term radial-velocity observations are needed in addition to our four year coverage, and its chemical composition also needs to be established.

In this paper we relied solely on kinematical data for the McCormick sample that has been the main target of our CORAVEL program during the past decade. With upcoming data from the *Gaia* satellite mission, the questions considered here will naturally be put on much more rigorous basis. However, we hope that our radial-velocity observations will be of use in the future, especially for the identification of new spectroscopic binaries which undoubtedly yet remain in the MCC sample.

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