1. INTRODUCTION

The study of metal-poor stars ([Fe/H] < −1) makes it possible to shed light on numerous problems of modern astrophysics, such as heavy element production in supernova explosions, the metallicity distribution function of the stellar halo, the initial mass function (IMF), and the nature of the big bang and the first generation, or Population III, stars. An important place among these fundamental problems is occupied by the questions of the origin and the chemical and dynamical evolution of our Galaxy. The oldest stars with masses of $M < 0.8 M_\odot$ are unevolved. Therefore, the abundance of chemical elements in their atmospheres reproduces the composition of prestellar matter. Additional information on spatial motions of these stars preserves the possibility of reconstructing the way the Milky Way formed.

The orbital elements of binary and multiple stellar systems are an important tool for studying prestellar matter. In single low-mass stars, the mass is the only parameter conserved since the time of star formation. Binary and multiple systems bear three more conserved values: the angular momentum, the eccentricity, and the mass ratio of their components (Larson 2001) in the case of detached systems. Therefore, binary and multiple stars carry more information on the process of star formation than do single stars. The study of binary and multiple metal-poor systems enables us to impose certain restrictions on the physical conditions in prestellar matter at the time of the genesis of our Galaxy. Metal-poor stars are common in the globular clusters, Galactic halo, and in the Galactic field, where an existence of the so-called stellar streams was revealed (e.g., Eggen 1996a, 1996b). The multiplicity and the orbital parameters of binary and multiple stars in these streams may also provide additional information on the nature of the stream’s progenitor and its dynamical evolution.

The problem of stellar multiplicity was widely discussed in the literature; however, it mostly concerned thin disk stars with solar-like metallicities (Duquennoy & Mayor 1991; Fischer & Marcy 1992; Halbwachs et al. 2003). Metal-poor stars were studied much less, as their occurrence in the solar neighborhood is less than 1%, according to the Nordström et al. (2004) catalog. Early works, addressing the rate of binary systems among Population II stars, showed that this value is small compared to the analogous value for Population I stars (Abt & Levi 1969; Crampton & Hartwick 1972; Abt & Willmarth 1987). In subsequent works (Preston & Sneden 2000; Goldberg et al. 2002; Latham et al. 2002), it was concluded that these values are indistinguishable (Abt 2008; Goldberg et al. 2002; Latham et al. 2002; Preston & Sneden 2000). A long-term spectroscopic monitoring of about 1500 nearby stars with high proper motions (Carney et al. 1994 (hereinafter CLLA), 2001; Goldberg et al. 2002; Latham et al. 2002) has played an important role in the study of the multiplicity of metal-poor stars. Spectroscopic studies cover the systems with relatively short orbital periods ($P \lesssim 10$ years).

The study of long-period couples with common proper motion components (Zapatero Osorio & Martin 2004) confirms the hypothesis of an equal frequency of binary systems among the old and young stellar populations (Allen et al. 2000; Zapatero Osorio & Martin 2004). Meanwhile, an “intermediate” period range of $P \approx 10–1000$ years, which corresponds to the semi-major orbital axes of $a \approx 10–100$ AU in the solar neighborhood, remains poorly understood to date. This range can be studied with the use of adaptive optics, speckle interferometry, and long baseline interferometry. The scarce Population II star observations, made by means of interferometric techniques, were run either for the brightest stars (Lu et al. 1987) or with relatively low angular resolution (Zinnecker et al. 2004). Notwithstanding the empirical data available to date, the number of known binary and multiple systems with metal-poor components remains small.

In order to enlarge the database of binary and multiple Population II stars, to define their orbital parameters and the properties of their components, we conducted speckle interferometric observations of 223 metal-poor subdwarfs with high proper motions located in the solar neighborhood (Rastegaev et al. 2007, 2008). The observations were made with the diffraction-limited
resolution of the 6 m Bolshoi Azimuthal Telescope (BTA) of the Special Astrophysical Observatory of the Russian Academy of Sciences (0′023 at the wavelength of 550 nm). In the present work, we analyze the multiplicity and orbital period distribution for binary and multiple stars. We made our analysis based on our own observations and the data adopted from other authors. Additionally, an attempt was made to examine the ratio of binary and multiple stars in the streams of old metal-poor stars located in the solar neighborhood.

2. SAMPLE

For the observations with high angular resolution, we compiled a sample of 223 field subdwarfs of the F, G, and early K spectral classes (Rastegaev et al. 2007) from the CLLA catalog. The CLLA presents a spectroscopically studied sample of the A–K spectral type dwarfs from the Lowell Proper Motion Survey (Giclas et al. 1971, 1978), which mainly includes the stars from the Northern Hemisphere with proper motions exceeding 0′.26 per annum and brighter than 16 mag in the B band.

We selected 223 stars from the CLLA using the following criteria:

1. metallicity $[m/H] < −1$,
2. declination $δ > −10^{°}$,
3. apparent magnitude $m_v < 12$ mag.

The last criterion was determined by the limiting stellar magnitude of our speckle interferometer (Maximov et al. 2003), which was about 13 mag. No restrictions were applied on the heliocentric distances of these stars evenly distributed on the celestial sphere. The maximum distance to the sample objects is 250 pc. The median heliocentric distance of the selected stars is approximately 100 pc. This allows us to take advantage of high angular resolution in order to detect new systems, since at such distances the pairs with semimajor orbital axes from 10 to 100 AU are hard to detect both spectroscopically and visually.

Using the two following criteria, $μ > 0′.26$ yr$^{−1}$ and $[m/H] < −1$, we tried to rule out the thick and thin disk stars. In the case of the thick disk though, these limits are not stringent and some objects may belong to the metal-weak tail of the thick disk (Arifyanto et al. 2005).

To separate the halo stars from the disk stars in our sample, we used a formal method described in the appendix of Grether & Lineweaver (2007). The equations establishing the probability that a star belongs to the thin disk ($P_{\text{thin}}$), the thick disk ($P_{\text{thick}}$), or the halo ($P_{\text{halo}}$) are

$$P_{\text{thin}} = f_1 \frac{P_1}{P}, \quad P_{\text{thick}} = f_2 \frac{P_2}{P}, \quad P_{\text{halo}} = f_3 \frac{P_3}{P}, \quad (1)$$

where

$$P = \sum f_i P_i,$$

$$P_i = C_i \exp \left[ -\frac{U^2}{2\sigma_{Ui}^2} - \frac{(V - \langle V \rangle)^2}{2\sigma_{Vi}^2} - \frac{W^2}{2\sigma_{Wi}^2} - \frac{([Fe/H] - ([Fe/H])^2)}{2\sigma_{[Fe/H]}^2} \right],$$

$$C_i = \frac{1}{\sigma_{Ui} \sigma_{Vi} \sigma_{Wi} \sigma_{[Fe/H]}},$$

$i = 1$ (thin disk), $2$ (thick disk), $3$ (halo).

The input parameters for these equations are adopted from Robin et al. (2003), and presented in Table 1. We rejected 3 out of 221 systems: 2 double stars, G99-48 and G166-45, and 1 single, BD −1′1792, because for these systems there are no heliocentric distances or $UVW$ components in the CLLA. We referred the objects with $P_{\text{halo}} > 0.5$ to the halo stars. There is a total of 148 of such stars in our sample. The remaining 70 objects belong to the thick disk. None of the stars from the sample have $P_{\text{thin}}$ exceeding 0.01. Average metallicity and space velocity vector components for halo stars in our sample are: $⟨([Fe/H]_{\text{halo}}), (U_{\text{halo}}), (V_{\text{halo}}), (W_{\text{halo}})⟩ = (−1.9 \pm 0.5, −16 \pm 152 \text{ km s}^{−1}, −180 \pm 81 \text{ km s}^{−1}, −1 \pm 78 \text{ km s}^{−1})$, where the errors are standard deviations. In a similar way, these values for the thick disk stars are: $⟨([Fe/H]_{\text{thick}}), (U_{\text{thick}}), (V_{\text{thick}}), (W_{\text{thick}})⟩ = (−1.2 \pm 0.2, −12 \pm 83 \text{ km s}^{−1}, −92 \pm 59 \text{ km s}^{−1}, 3 \pm 50 \text{ km s}^{−1})$. However, the system of Equations (1) might be unable to accurately describe the situation in the areas where the star parameters of different populations overlap.

Figure 1 shows the distribution of the sample stars on the graph metallicity versus $V$-component of spatial velocity for the stars in our sample. The circles represent the halo stars and the squares mark the thick disk stars. The dashed line separates the stars on prograde (upper half) and retrograde (lower half) orbits.

### Table 1

| Value | Thin Disk | Thick Disk | Halo |
|-------|-----------|------------|------|
| $σ_U$ | 43        | 67         | 131  |
| $⟨V⟩$ | −15       | −53        | −226 |
| $σ_V$ | 28        | 51         | 106  |
| $σ_W$ | 17        | 42         | 85   |
| $⟨[Fe/H]⟩$ | −0.1 | −0.8       | −1.8  |
| $σ_{[Fe/H]}$ | 0.2 | 0.3        | 0.5   |
| Fraction | $f_1$ | 0.925 | 0.070 | 0.005 |

Note. According to the data from Robin et al. (2003).
The speckle interferometric observations of 223 sample stars were carried out in 2006–2007 on the 6 m BTA telescope (Rastegaev et al. 2007, 2008) whose diffraction-limited resolution is 0′′023 for \( \lambda = 550 \) nm and 0′′033 for \( \lambda = 800 \) nm. Most of the observations were carried out using the system (Maksimov et al. 2009) based on a \( 512 \times 512 \) EMCCD (a CCD featuring on-chip multiplication gain) with high quantum efficiency and linearity. This system allowed us to detect objects with magnitude differences between the components of up to \( \Delta m = 5 \) mag. Taking into account the limiting stellar magnitude of our sample (\( m_V < 12 \) mag), a detected secondary component can be as faint as 17 mag. The 4′4 field of view of our system allows detection of secondary components at a separation of 3′′ from the primary star. The speckle interferograms were recorded using five filters: 545/30, 550/20, 600/40, 800/100, and 800/110 nm (the first number indicates the central wavelength of the filter; the second indicates—the half-width of the filter’s bandwidth) with the exposures of 5–20 ms. For each object, we accumulated from 500 to 2000 short exposure images depending on weather conditions. The observations were made with an average seeing of 1′′5. The accuracy of our speckle interferogram processing method (Balega et al. 2002) may be as good as 0.02 mag, 0′′001, and 0′′1 for the component magnitude difference, angular separation, and position angle, respectively. 

For 19 stars in our sample, we observed the speckle interferometric companions. Sixteen companions were resolved astrometrically for the first time. We discovered five new binary systems (G191-55, G114-25, G142-44, G28-43, and G130-7), three triple systems (G87-47, G111-38, and G190-10), and one quadruple system, G89-14. The position parameters and magnitude differences between the speckle interferometric components are listed in Tables 1 and 2 of Rastegaev et al. (2008). 

4. SAMPLE COMPLETENESS 

To be able to determine the completeness of our sample, we used the star count method. From all known subdwarfs within 25 pc from the Sun, we selected five objects with absolute magnitudes \( M_V < 8 \) mag and metallicities \( [\text{Fe/H}] < -1 \) (see Table 1 in Fuchs & Jahreiß 1998). The star GJ 1064 A, with a metallicity of −1 dex, was also included in our sample. An extrapolation to the volume of our sample (with the radius of \( \approx 250 \) pc) increases the number of such objects to \( \approx 5000 \). Obviously, when we consider the frequency of stars in different volumes, we cannot depart from the uniform distribution of stars in space. We have to bear in mind the structure of the Galaxy and the data available on the star distribution in its various subsystems. However, as we show in the Appendix, for the stars in our sample located within 250 pc from the Sun, the structure of our Galaxy can be neglected. Therefore, the number of objects in our sample constitutes about 5% of the total number of stars in question located in the examined region of space. We have to mention that while examining the stars in different volumes, we were taking account of the primary components only in the case of spectroscopic and speckle interferometric pairs, and of both components in the case of visual and common proper motion pairs. 

5. UNDETECTED COMPANIONS 

Capability to detect a binary system is determined by both the observation method used and the physical characteristics of the system itself. As the sample objects were examined using three different methods—spectroscopic, speckle interferometric, and...
visual—we have to analyze the number of systems unaccounted for by each of these methods. To do that, we conditionally divided the spectroscopic and astrometric pairs by the values of their semimajor axis at $a < 10$ AU and $a > 10$ AU, and their orbital periods at $P < 10,000$ days and $P > 10,000$ days, respectively.

For spectroscopic pairs, we hypothesized that the component mass ratio is uniformly distributed from 0 to 1, then took the deduced period distribution for the studied stars in the range of 0–10,000 days (see below), and made our calculations using the formulae from Mazeh et al. (1996). Our conclusion is that the probability of not detecting a binary system approximately equals 20%.

As for the visual and interferometric binaries, the secondaries can be detected if the following two conditions are satisfied. First, the magnitude difference between the components should not exceed a certain critical value determined by the detector’s dynamical range and the spectral range used. Second, in the case of speckle interferometry, the angular separation between the components should be larger than the telescope’s diffraction limit and smaller than the detector’s field of view, or, in the case of visual studies, the angular separation should be smaller than the certain restrictions imposed.

In order to estimate the number of unresolved systems due to the effect of ellipse projection of the true orbit on the picture plane, and due to the secondary component’s orbital phase at the moment of observation, we used the Monte Carlo simulation. We modeled a sample of stellar orbits, evenly distributed in space, with heliocentric distances from 25 to 250 pc, uniformly distributed eccentricities (from 0 to 0.9) and arguments of periapsis (from 0° to 360°). Inclinations of the true orbits to the plane of the picture plane obey the sin i law.

The resulting orbits were projected onto the picture plane using the following formulae (Couteau 1981):

$$\rho = \frac{a (1 - e^2)}{1 + e \cos \upsilon} \cos (\upsilon + \omega),$$

$$\operatorname{tg} (\theta - \Omega) = \operatorname{tg} (\upsilon + \omega) \cos \upsilon,$$

$$\operatorname{tg} \frac{\upsilon}{2} = \sqrt{\frac{1 + e}{1 - e}} \operatorname{tg} \frac{\upsilon}{2},$$

$$M = u - e \sin u,$$

where $\rho$ is the angular separation between the components in the picture plane, $a$ is the orbital semimajor axis (in arcseconds), $e$ is the eccentricity, $\upsilon$ is the true anomaly, $u$ is the eccentric anomaly, $M$ is the mean anomaly, $\omega$ is the argument of periapsis, $\theta$ is the position angle of a secondary component, $\Omega$ is the longitude of an ascending node, and $i$ is the inclination angle between orbital and picture planes.

Furthermore, a random orbital position of the satellite was predetermined for each simulated system. At this point, we accounted for the fact that a companion spends more time at apastron than at periapsis. Then the projection distances $\rho$ from the satellite to the primary star were counted. A relative number of projection distances greater than 0°033 (the diffraction limit of the 6 m telescope in a 800/100 filter) is, in fact, the probability value of a system detection using the speckle interferometric and visual methods. The results of modeling show that for the systems with an orbital semimajor axis exceeding $a = 10$ AU, such a probability is close to 1 and an influence of the components’ geometry can be neglected. This probability weakly depends on the choice of a plausible distribution of the semimajor axis for $a > 10$ AU.

Let us now consider the incompleteness of detection caused by the magnitude difference between the components. An average mass of a primary star in our sample is $0.65 M_\odot$, and a standard deviation is $\sigma_M \approx 0.05 M_\odot$. The maximum magnitude difference between the components, detected by speckle interferometric and visual methods, is about 5 mag (Maksimov et al. 2009; Zapatero Osorio & Martin 2004). For speckle interferometry, we used a more conservative estimate of 4. mag. According to the model of Baraffe et al. (1997) for $[Fe/H] = -1$, the minimal mass of a secondary, which is 4 mag fainter than a primary of an average mass, equals $M_{\text{min}} = 0.20 M_\odot$ in the $I$ band. This band roughly corresponds to our 800/100 and 800/110 filters. To compute the number of undetected companions, we have to know the function of mass ratio distribution. We used a uniform distribution. If the mass ratio for wide (speckle interferometric, visual, and CPM) pairs obeys a uniform $q$ distribution, then from the following ratio

$$f_{M_2=0.8} dM_2 \approx f_{M_2=0.08} dM_2$$

we find the quantity of undetected secondary components per one detected secondary component. Masses of undetected components vary from $0.08 M_\odot$ (mass of a brown dwarf) to $M_{\text{min}}$. Masses of detected components lie in the range from $M_{\text{min}}$ to $0.8 M_\odot$ (the maximal mass of the stars in our sample). The derived quantity from Equation (3) equals 0.2. Therefore, a fifth of discovered speckle interferometric companions remains undetected at the given distribution of $f(q)$ with the use of the 800/100 (or 800/110) filter. For the 550/20 and 545/30 filters, $M_{\text{min}} = 0.28 M_\odot$ and Expression (3) is approximately 0.38, which makes these filters less suitable for our task in the sense of magnitude difference (yet more suitable from the viewpoint of angular resolution). The search for common proper motion pairs for the sample stars was conducted in the $I$ band (Zapatero Osorio & Martin 2004). Forty-seven objects from our sample were observed speckle interferometrically, solely using the 550/20 or 545/30 filters, nine objects were observed only in the 600/40 filter, and one object (G183-9) was observed in the 550/20 and 600/40 filters. The 166 remaining stars were observed at least once in the 800/100 or 800/110 filters. With this in mind, we found that Expression (3) is approximately equal to 0.25 for all filters. Therefore, according to these rough estimates, for 33 astrometric components in our sample (see Figure 4), we have about eight unaccounted companions or 24%, that is, comparable to 20% of unaccounted speccral companions. Thus, we can assume that the number of unaccounted components in our sample does not depend on the orbital period and is 20%–25%.

Analogously, the IMF-like distribution $f(q) \sim q^{-1.3}$ for $0.08 \leq M/M_\odot < 0.5$ (Kroupa 2001) gives us 37 unaccounted companions. If $f(q)$ grows toward bigger $q$ values (Soderhjelm 2007), then the number of undetected astrometric components in our sample does not exceed five. For our further estimates, we choose the values corresponding to the uniform $q$ distribution.

6. MULTIPlicity of the Sample

6.1. Raw Estimates

In order to calculate the ratio of the systems of different multiplicity among the studied stars, we complemented the results of our speckle interferometric measurements by the data from spectroscopic and visual studies found in the literature.
The information on the spectroscopic companions was adopted from the publications dedicated to long-term spectroscopic monitoring of Population II stars by CLLA (Carney et al. 2001; Goldberg et al. 2002; Latham et al. 2002; D. W. Latham 2008, private communication). The data on wide visual pairs were taken from Allen et al. (2000) and Zapatero Osorio & Martin (2004) via the WDS catalog (Mason et al. 2001). As a result, the ratio of single:binary:triple:quadruple ($S:B:T:Q$) systems for the stars in our sample is $147:64:9:1$ (Rastegaev et al. 2007, 2008). Therefore, at least 159 stars from 306 stars in our sample (221 main components and 85 satellites) belong to binary and multiple systems. The multiplicity of our sample is $\frac{33\%}{-7\%}$, where multiplicity is understood as the ratio of binary and multiple systems to the total number of systems:

$$f_{\text{systems}} = \frac{B + T + Q}{S + B + T + Q}.$$  

A similar value, unadjusted for unresolved companions, for the thin disk stars of spectral classes F7 to G9, equals $51:40:7:2$ (Duquennoy & Mayor 1991), with a multiplicity of about 50%. It is necessary to pay attention to the differences between the two compared samples. While our sample was formed from the stars with a certain apparent magnitude limit and high proper motions, the sample from Duquennoy & Mayor was only limited by the heliocentric distances (all of their stars are located within 22 pc from the Sun).

In terms of multiplicity, the Population II stars differ from the Population I stars. At least a third of metal-poor systems and at least half of the systems with solarlike abundances are binary and multiple. This discrepancy can be explained by the complexity of the detection of low-mass metal-poor spectroscopic satellites, by selection effects, and by the dynamical evolution of binary and multiple stars.

6.2. Corrected Estimates

To estimate the true multiplicity of the sample stars, we have to account for various selection effects that are unavoidable in astronomical observations. The five underlying criteria for the choice of stars in our sample are: proper motion ($\mu > 0.26$ year$^{-1}$), metallicity ($m/[H] < -1$), magnitude ($m_V < 12$ mag), spectral classes (F, G, and early K), and position in the sky (all of our stars are located in the Northern Hemisphere). We also have to take into account the undetected companions (Section 5).

To account for the bias incurred by magnitude, we have to consider the Opik effect (Opik 1923; Goldberg et al. 2003), which applies to binaries detected within a magnitude-limited sample of stars. This effect is an expansion of the Malmquist effect for binary stars. Binaries are on the average brighter than singles. Thus, in a magnitude-limited sample the binaries are observed from a bigger volume in space than the single stars. To avoid this effect, we rejected the binaries which are brighter than 12 mag due to the contribution of the secondary component to the total luminosity. For SB1 binaries, we adopted the notion that the luminosity of the secondary component is not less than two magnitudes fainter than the primary (Goldberg et al. 2002). We discarded the SB1 pairs whose primary component was fainter than 12 mag in the assumption that the secondary component is two magnitudes fainter than the primary. For SB2 pairs, the luminosity of the primary component was determined from the total luminosity of the system and the mass ratio of the components (Goldberg et al. 2002) using evolutionary tracks from Baraffe et al. (1997). We thus rejected four binaries, one SB1 (G242-14), and three SB2 (G86-40, G99-48, and G183-9) as the measured luminosities of the primaries are fainter than 12 mag in the V band. In the worst case scenario for SB2 systems, we have to discard four pairs on the assumption that for a given integrated magnitude the luminosities of primary and secondary components are equal. None of the speckle interferometric pairs have been excluded from consideration due to the Opik effect. The magnitude differences between the components measured by us for a given integrated magnitude suggest that the primary components of the speckle pairs are brighter than 12 mag. Not a single system of higher multiplicity was dropped from the analysis as their primaries are not compliant with the condition $m_V > 12$ mag.

Taking into account an adjustment for unresolved components and the Opik effect, the multiplicity of F, G, and early K subdwarfs in the solar neighborhood is, according to our calculations, at least 40% and at least 60% for the thin disk G dwarfs (Duquennoy & Mayor 1991). In both cases, the correction does not exceed 10%.

### 6.3. Multiplicity as a Function of Metallicity

To investigate the effect of metallicity on the multiplicity of stars in our sample, we divided it into four metallicity bins: $(-3, -2.5), (-2.5, -2.0), (-2.0, -1.5)$, and $(-1.5, -1.0)$. One single star G64-12 with $m/[H] = -3.52$ was rejected from the analysis. In every bin we evaluated the ratio of single:binary:triple:quadruple systems and multiplicity $f_{\text{systems}}$. The
acquired results are presented in Table 2, where it is clear that in the range [m/H] from −2.5 to −1.0 the multiplicity does not depend on metallicity and constitutes one third. In the range (−3, −2.5], the multiplicity is somewhat lower, but the number of systems in this range is smaller than in the rest of the ranges, which affects the accuracy of determination of \( f_{\text{systems}} \) (see Figure 5). It can be seen from Figure 5 that in the first approximation the rate of binary and multiple systems in our sample feebly depends on metallicity. Carney et al. (2005a) obtained analogous results based on a bigger sample of stars studied spectroscopically. Note that the bulk of our triple stars belong analogously based on a bigger sample of stars studied spectroscopically.

An independence of the ratio of binary and multiple systems from the conditional division “thick disk–halo,” as well as the consistency of \( f_{\text{systems}} \approx 33\% \) under metallicity changes (Table 2) might testify that most of the stars in our sample belong to one and the same Galactic subsystem, the halo. Note again that the set of Equations (1) might not be operable in cases where the stellar parameter ranges of different Galactic subsystems overlap. It is not impossible though that the Population II stars, both the halo and thick disk stars, have similar ratios of systems of different multiplicity.

### 6.5. Multiplicity as a Function of Kinematics

Table 3 represents the basic facts on the dependence of multiplicity of the sample stars on kinematics. We excluded three objects from consideration: two double stars (G99-48 and G166-45) and one single (BD −1°1792), because for them there are no distances or \( UVW \) components in the CLLA. For single, binary, and multiple stars, the average values and standard deviations of the space velocity vector components are: \( (U) = −13 ± 137 \text{ km s}^{-1}, (U_{\text{bins}}) = −18 ± 127 \text{ km s}^{-1}, (V) = −160 ± 86 \text{ km s}^{-1}, (V_{\text{bins}}) = −135 ± 81 \text{ km s}^{-1}, (W) = 2 ± 74 \text{ km s}^{-1}, (W_{\text{bins}}) = −3 ± 61 \text{ km s}^{-1}. \) For the norm of velocity vector \( V = \sqrt{U^2 + V^2 + W^2} \) for stars in our sample is shown in Figure 6. The average value of this norm is 214 km s\(^{-1}\) with a standard deviation of 86 km s\(^{-1}\). Figure 7 shows the \( V \) versus [m/H] dependence for single (left upper panel) and double and multiple (right upper panel) stars in our sample. The middle and lower panels of this figure show the dependence of the multiplicity of our stars on the four kinematic parameters \( UVW \) and \( V \). The figure shows that the frequency of double and multiple stars in our sample weakly depends on the change of \( UVW \) components. We can draw lines corresponding to a constant multiplicity of approximately 35\% within a 70\% confidence level (see the middle and lower panels). For the
we can say that with the increase of the norm of the spatial velocity vector, the frequency of double and multiple systems in our sample falls. Most likely, the bigger the spatial velocity of a star is, the less likely is the probability that it has a companion.

Forty-five of 223 stars in our sample are moving on retrograde Galactic orbits ($V < -220$ km s$^{-1}$), i.e., in the opposite direction to the rotation of our Galaxy. For these stars, the ratio of single:binary:triple:quadruple systems is 32:12:1:0 and their multiplicity is 29$\%$+15$\%$−13$\%$. Carney et al. (2005a), analyzing a sample of 374 stars on highly retrograde orbits ($V < -300$ km s$^{-1}$), showed that the frequency of spectroscopic binaries among them is two times smaller than that for the stars moving along with the Galaxy’s rotation. Our data, bearing an analysis of a wide range of periods, do not contradict their findings, yet an insignificant number of highly retrograde objects in our sample does not allow us to make any definitive conclusions.

7. PERIOD DISTRIBUTION

The distribution of orbital periods for binary stars in our sample is shown in Figure 8. The periods of spectroscopic pairs are taken from Goldberg et al. (2002) and Latham et al. (2002). The periods of astrometric pairs were derived with the help of the generalized Kepler’s third law on the basis of an

Figure 6. Norm of velocity vector distribution for stars in our sample.

Figure 7. Upper panel shows $V$ vs. $[m/H]$ dependence for single (left part) and double, and multiple (right part) stars. The middle and lower panels show the frequency of double and multiple stars depending on the components of the velocity vector and its norm. Dashed lines mark the 95% confidence interval. Dotted lines mark the 70% confidence interval.
empirical relation of the projected angular separation between the components and the semimajor axis. Knowing the system’s parallax $\pi$ and the projected angular separation between the components $\rho$, the expected value of the semimajor axis is calculated using the formula from Allen et al. (2000)

$$\langle a \rangle = \text{antilog} \left[ \log \frac{\rho^2}{\pi} + 0.146 \right],$$

where $\langle a \rangle$ is expressed in astronomical units and $\rho$ and $\pi$ in arcseconds. Taking each system individually, we derived the sum mass of the components from the temperatures of the primary (CLLA) and secondary components, and from the magnitude difference, if the temperature of the secondary was unknown. To do this, we used models from Baraffe et al. (1997). Angular distances $\rho$ between the components of astrometric pairs were obtained from speckle interferometric observations or adopted from Allen et al. (2000) and Zapatero Osorio & Martin (2004). If the system’s parallaxes were known from the Hipparcos catalog with an accuracy of better than 30%, we used them instead of the distances cited in the CLLA catalog. As a result, we were able to determine the periods for 60 binary systems out of 64 in our sample. The periods for the four remaining suspected binary systems,—G186-26 and G210-33 and two blue stragglers, BD+25°1981 and G43-3 (Carney et al. 2001)—are too long to be determined (D. W. Latham 2008, private communication). The period distribution for 60 binaries and 10 multiple systems (18 subsystems of 9 triple stars and 3 subsystems of a quadruple star G89-14) is shown in Figure 9. The distributions corrected for the Opik effect and unresolved components in Figures 8 and 9 are marked by a solid line.

Let us compare the resulted distribution with an analogous one for the thin disk stars (Figure 10). The maximum of an unsymmetrical period distribution for the stars in our sample is in the range of $\log P = 2-3$ dex (i.e., hundreds of days). For Population I stars, the $\log P$ distribution, which Duquennoy & Mayor approximated by a Gaussian, has a maximum in the range of 4–5 dex (tens of thousands of days). An important feature of our distribution is a small number of short period ($\log P < 1$) pairs. This range is represented by the only SB2 star, G183-9, with a period of about six days (Goldberg et al. 2002), which is excluded when accounting for the Opik effect.

To make a homogeneity check of the two samples, we conducted a nonparametric $\chi^2$ test (Kremer 2007, p. 368).

Coincidentally, the number of compared periods equals 81 for each population. The test shows that the hypothesis of uniformity (i.e., common general population of two samples) can be rejected with a more than 95% probability.

Both distributions (Figure 10) may be distorted by the selection effects. However, the differences in both the shape of the distributions and the location of the maxima could be induced by the dynamical evolution, undergone by the Population II stars. For example, a small quantity of old systems with periods of more than 10,000 days may be the result of a dynamical evolution at the stage of Galaxy formation. According to a recent concept, a bigger part of the stellar halo in our Galaxy was formed from small Galactic systems (Bell et al. 2008). It is quite likely that at the stage of the accretion of small satellite galaxies of the Milky Way and their destruction, the physical conditions were favorable for dissociations of wide pairs with low binding energy. Attempting to explain the period distribution of Population II stars by a destructive impact of giant molecular clouds and other local perturbations of the gravitational potential of our Galaxy on the old stars orbiting around the Galactic center (Weinberg et al. 1987) is quite problematic. Such objects spend most of their lifespans away from the Galactic plane.
from speckle interferograms using bispectral technique). The magnitude difference between AB and C is 4.2 mag in the 800−

According to the data from CLLA.

Figure 11. On the right: CPM subsystem of G89-14 (Palomar Observatory Sky Survey archive). On the left: the speckle interferometric subsystem (image reconstructed from speckle interferograms using bispectral technique). The magnitude difference between AB and C is 4.2 mag in the 800/100 filter.

Table 4
Population II Multiple Systems in our Survey

| Name   | mv  | [m/H]a | Distancea (pc) | Multiplicity |
|--------|-----|--------|----------------|--------------|
| G95-57 | 8.78| −1.05  | 25             | 3            |
| BD+19°1185 | 9.3 | −1.47  | 42             | 3            |
| G89-14 | 10.4| −1.9   | 94             | 4            |
| G87-45 | 11.44| −1.49  | 123            | 3            |
| G87-47 | 10.34| −1.34  | 62             | 3            |
| G111-38| 9.11 | −1.04  | 50             | 3            |
| G40-14 | 11.2 | −2.71  | 164            | 3            |
| G59-1  | 9.52 | −1.14  | 50             | 3            |
| G17-25 | 9.63 | −1.54  | 35             | 3            |
| G190-10| 11.22| −1.92  | 91             | 3            |

Note. a According to the data from CLLA.

8. INTERESTING TRIPLE AND QUADRUPLE SYSTEMS IN OUR SAMPLE

In this section, we will examine two old multiple systems that we find remarkable: a triple system, G40-14, and a quadruple, G89-14. Such objects are of great interest for studies of the dynamical evolution and for checks of various criteria of dynamical stability. In Table 4, we listed all the detected systems from our sample having more than two components. From 10 multiple systems, 9 are triples and only 1 is a quadruple.

The uniqueness of the triple system G40-14 is in its retrograde Galactic orbit with $V \approx −230$ km s$^{-1}$ (CLLA). The inner subsystem of G40-14 is an SB1 pair with a period of 60.615 days (Latham et al. 2002). The outer subsystem is formed by a visual component, which is located 98′′ away from the spectroscopic pair. Assuming that the system’s heliocentric distance is 235 pc, the expected semimajor axis is $(a) \approx 30,000$ AU (Allen et al. 2000). We made a check for retrograde objects in the latest version (dated 2007 August 13) of the Multiple Star Catalog (Tokovinin 1997), which is a compilation of 1158 known stellar systems with three or more components. In order to do that, we calculated the $UVW$ components of spatial velocities for the catalog stars from the cited parallaxes, radial velocities, and proper motions, using the formulae from Johnson & Soderblom (1987). It appeared that only one object, a triple system ADS 16644, is moving on a retrograde Galactic orbit ($V \approx −330$ km s$^{-1}$). Hence, G40-14 is the second of all known systems with more than two components moving against the rotation of the Galaxy.

G89-14 (for details, see Rastegaev 2009) is the system with the highest multiplicity in our sample. It consists of four components (Figure 11): an SB1 pair AB with a period of 190 days (Latham et al. 2002), a speckle interferometric component C located at $\approx 1''$ from this SB1 pair (Rastegaev et al. 2007), and a common proper motion companion D at $34''$ (Allen et al. 2000). Based on the data from Allen et al. (2000), the evolutionary tracks from Baraffe et al. (1997), and on our speckle interferometric measurements, we evaluated the period ratio of the three G89-14 subsystems: 0.52:3000:650,000 yr. Another well-known metal-poor quadruple system is NQ Ser (Tokovinin 1997) with $[Fe/H] = −1.05$ (Nordström et al. 2004). This multiple star was repeatedly observed on the BTA by means of speckle interferometry (e.g., Balega et al. 2006). According to our information, G89-14 with $[m/H] = −1.9$ (CLLA) is the most metal-poor quadruple system known to date, which makes it an interesting object for a more detailed study.

9. MULTIPLICITY OF METAL-POOR STELLAR STREAMS

Stellar streams (e.g., Eggen 1996a, 1996b) are associations of stars possessing similar kinematics and metallicity. The study of such streams allows us to restore the picture of the formation of various dynamical structures in our Galaxy to a certain degree. Traditionally, the stellar streams are being selected in a certain phase space and then their origin is interpreted using the data of spectroscopic analysis. In a phase space, a fine structure like stellar multiplicity can give additional information on the dynamical evolution of the stream and its primogenitor. However, until now it was not taken into due consideration.

The following six stars of our sample, G10-4, G13-9, G60-48, G24-3, G18-54, and G28-43, are part of Kapteyn’s star moving group (Eggen 1996a), 10 other objects, G130-65, G75-56, G5-35, G40-14, G114-25, G11-44, G13-35, G183-11, G182-32, and G126-52, belong to the Ross 451 moving group (Eggen 1996b). In Table 5, we are listing some characteristics of these two halo streams. In the penultimate column of the table, you can see the ratio of single, binary, and triple systems for the group members in our sample. In the last column, an analogous estimate is given for all known members of the groups with the data taken from...
literature. Unfortunately, the multiplicity of these stars is poorly studied and the ratio in the last column can only serve as a lower limit for the frequency of binary and multiple systems in the streams. The two moving groups listed above have comparable multiplicities, both exceeding 10%. The fact that we find similar multiplicities in moving groups does not contradict the dynamical hypothesis of their origin. In this case, the stellar streams are formed by a random selection from the general population of field stars. Recent work on the problem of origin of stellar streams shows that the Hercules stream (Bensby et al. 2007), as well as the Pleiades, Hyades, and Sirius moving groups (Famaey et al. 2007, 2008), formed as a result of the dynamical (resonant) influence of our Galaxy on the field stars. However, the scenario of accreted stellar streams cannot be ruled out. This requires similar multiplicities of the progenitors of the flows. Further detailed studies are required to help answer the question of whether any distinctions exist between various stellar streams.

10. CONCLUSION

In this paper, we examine a sample of 223 subdwarfs belonging to the F, G, and early K spectral classes, located within 250 pc from the Sun, with metallicities \( [\text{Fe}/\text{H}] < -1 \) and proper motions \( \mu \geq 0' .2 \) yr\(^{-1} \). Stars make up about 5% of the total number of objects of this type in the studied space volume. The subdwarfs were observed using the spectroscopic (Goldberg et al. 2002; Latham et al. 2002), interferometric (Rastegaev et al. 2007, 2008), and visual methods (Zapatero Osorio & Martin 2004). The presented sample is most thoroughly studied in terms of stellar multiplicity in a wide range of orbital periods (orbital axes) among the Population II field stars.

As a result of observations of the sample stars using the method of high angular resolution on the BTA, we detected 20 speckle interferometric components for 19 primaries. Seven of them were known as spectroscopic pairs and four as astrometric binaries (Figure 4). Nine systems were resolved for the first time: five binaries (G191-55, G114-25, G142-44, G28-43, and G130-7), three triples (G87-47, G111-38, and G190-10), and one quadruple (G89-14).

Combining different research methods allowed us to estimate the frequency of the systems of different multiplicity with the orbital semimajor axes ranging from a few to tens of thousands of astronomical units. The ratio of single, binary, triple, and quadruple systems among 221 primary components in our sample amounts to 147:64:9:1. More than half of the stars in the sample are members of binary and multiple systems:

\[
\begin{align*}
\ f_\text{stars} &= \frac{2B + 3T + 4Q}{S + 2B + 3T + 4Q} \approx 52\% \pm 6\% . \\
\ f_\text{systems} &= \frac{B + T + Q}{S + B + T + Q} \approx 33\% \pm 6\% .
\end{align*}
\]

As before, a 95% confidence interval was used as the error of obtained multiplicity. For spectroscopic systems, we made an analysis of the number of undetected components using analytical calculations, while the similar estimates for astrometric pairs were obtained using the Monte Carlo numerical method. For our sample, the multiplicity corrected for undetected components and selection effects (eventually only the Öpik effect was accounted for) is \( f_\text{systems} \approx 40\% \). Duquennoy & Mayor (1991) give \( f_\text{systems} \approx 60\% \) for the thin disk G dwarfs.

For colder subdwarfs of K–M spectral classes, Jao et al. (2009) deduced \( S:B:T:Q = 46:12:2:2 \), and \( f_\text{systems} = 26\% \pm 6\% \) accounting for spectroscopic, speckle interferometric, and visual data. Within errors, our result coincides with the result obtained by Jao et al. (2009).

Seven stars in our sample are blue stragglers. We found that, with the exception of G245-32, all of them are binaries. This supports the hypothesis of the connection of the blue straggler phenomenon with their binary nature.

The ratio of binary:triple:quadruple systems \( (B:T:Q) \) among the Population II stars in our sample is 64:9:1. This can be compared with the ratio 40:7:2 for Population I stars (Duquennoy & Mayor 1991). The difference between the ratios is statistically indistinguishable. Therefore, we came to a conclusion that a stable hierarchical multiple system is the universal evolutionary outcome of the star formation process both at the time of the creation of our Galaxy and nowadays.

Three of the binary systems that we resolved, G76-21 (HIP 12529), G114-25 (HIP 44111), and G217-8 (HIP 115704), have very low metallicities \( [\text{m}/\text{H}] < -2 \). A triple system, G40-14, also belongs to this metallicity range (see Table 4). Altogether, 63 primaries from our sample have \( [\text{m}/\text{H}] < -2 \). From these, 18 primaries have one companion and one, G40-14, has two of them. To date, only a few high multiplicity (\( N > 2 \)) systems in a very low metallicity regime are known. Further accumulation of empirical data for these objects will help answer the question of a possible dependence of the orbital element distribution of binary and multiple systems on their metallicity.

We did not find any significant differences in the multiplicity ratios of subdwarfs moving on prograde and retrograde \( (V < -220 \text{ km s}^{-1}) \) Galactic orbits. Carney et al. (2005a) found a decreased ratio of strongly retrograde \( (V < -300 \text{ km s}^{-1}) \) binaries: 10% ± 2% versus 28% ± 3% for a prograde sample. Their conclusion is supported by our study of 11 stars with \( V < -300 \text{ km s}^{-1} \): only one of them is a binary. With the increase of the norm of spatial velocity vector \( v = \sqrt{U^2 + V^2 + W^2} \), the frequency of double and multiple systems in our sample falls with a probability of at least 70%.

We have shown that the distribution of the orbital periods of the old stars differs both in shape and in the maximum’s location from that of Population I stars (Figure 10). Most of the detected Population II binaries have periods between 1 and 10 yr. The period distribution for G, K, and M thin disk dwarfs does not depend on a spectral class. In the semilog scale, it can
be approximated by a Gaussian with a maximum at log $P_{\text{max}} \approx 5$ dex (see Figure 1 in Kroupa 1995). Orbital periods of the thin disk stars are distributed more symmetrically. Compared to Population II stars, the maximum of the distribution is shifted toward larger $P$ by two orders.

An important feature in the period distribution of binary and multiple substellar objects is the lack of short-period systems with periods of less than one day. The range of $P < 10$ days is represented in our sample just by one SB2 system—G183-9. The reason for that lack of old short-period pairs could be in the dynamical evolution of the systems with short orbital periods, which could lead to a merge of the components and to the formation of blue stragglers (e.g., Bailyn 1995). Another important peculiarity in the period distribution of old metal-poor stars is the presence of couples with $P > 10^8$ days (Figures 8 and 9). It is quite possible that such enormous periods could be an error occurring from Formula (4). Such low-binding energy objects survived over many billions of years and bear important information about the mass density distribution in our Galaxy. The orbital periods of the subdwarfs and thin disk dwarfs lie nearly in the same range and constitute 10 orders. It is impossible to explain such a wide range of periods by dynamical evolution only, as it is formed at the earliest stages of the stellar system formation in the nuclei of molecular clouds (e.g., Kroupa & Burkert 2001). Our data show that the range of possible orbital periods of binary and multiple systems is not decreasing over billions of years of dynamical evolution. Only the shape of the period distribution is changing. An interpretation of the distinctions between the period distributions of the stars of different populations requires further study.

The substellar mass companions (brown dwarfs and planets) were beyond the scope of our consideration. Current studies (e.g., Fischer & Valenti 2005) testify to the existence of a correlation between the metallicity of stars and the presence of orbiting planets. At the time of this writing, catalogs of stars with planets (http://exoplanet.eu; http://exoplanets.org) do not contain stars with $[\text{Fe}/\text{H}] < -1$. Some researchers claim that brown dwarfs and some very low mass stars (and possibly planets?) form a separate population with its own multiplicity and kinematical properties (see, e.g., Kroupa et al. 2003). As likely as not, the low metallicity regime may influence the formation of this population. It is quite possible that Population II field stars do not contain any brown dwarfs or planets as companions at all. Another important question is whether any substellar companions exist in the halo and thick disk systems of high multiplicity ($N > 2$).

The ratio of binary and multiple systems among the Population II stars, found in this study, does not contradict the hypothesis that the chemical composition of protostellar molecular clouds has an insignificant impact on the star formation process. This indicates that the halo stars were formed as a result of fragmentation of molecular clouds’ nuclei, similar to the way the stars form today. However, this issue remains unclear when we consider the substellar mass regime.

The frequency of binary and multiple metal-poor stars imposes some restrictions on the formation of the stellar halo in our Galaxy as well. There are two general scenarios of the formation of the Milky Way’s stellar halo (see Majewski 1993 for more details).

1. Most of the halo stars were born in globular clusters or dwarf galaxies, which were then accreted and destroyed in the gravitational potential of the Milky Way (Bell et al. 2008).

2. The halo stars are genetically bound with our Galaxy. The accretion of globular clusters and dwarf galaxies observed today (Ibata et al. 1995) produces only a small fraction of halo stars. The kinematical structures detected in the stellar halo (Helmi et al. 1999; Bell et al. 2008) are a consequence of the Galaxy’s gravitational potential inhomogeneities and a manifestation of various resonances.

Any scenario of the stellar halo formation has to impose certain restrictions on the rate of binary and multiple systems and on their characteristics, e.g., on the distributions of orbital periods, component mass ratios, eccentricities. Particularly, a high percentage of binary and multiple halo field stars indicates that the formation of a stellar halo via the destruction of globular clusters is unlikely in our Galaxy since the relative number of binaries in globular clusters (Sollima et al. 2007) is smaller than that of metal-poor field stars. It is currently not clear how the dynamical evolution of globular clusters influences binary frequency (Ivanova et al. 2005; Hurley et al. 2007; Sollima 2008); therefore, the scenario of the halo field subdwarfs forming through a dissociation of globulars cannot be fully discarded.

The question of the differences between stellar streams is terms of binary and multiple systems requires further accumulation of observational data. Our material does not contradict either an assumption of the parity of binary and multiple stars’ frequency in different streams or the hypothesis of their dynamical origins (e.g., Famaey et al. 2008).

Some of the detected speckle interferometric pairs, G76-21, G63-46, G28-43, G217-8, G130-7, G102-20, BD+19°1185A, and G87-47, with presumably short orbital periods, are suitable for monitoring for orbit calculations and mass determination of the metal-poor stars. These studies can contribute to a calibration of the mass–luminosity relation and to the verification of the theories of dynamical evolution.

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Facility: BAT (Speckle interferometer).

APPENDIX

IMPACT OF GALACTIC STRUCTURE ON SPATIAL DISTRIBUTION OF SAMPLE STARS IN THE SOLAR NEIGHBORHOOD

To be able to estimate the number of stars in a given volume by an extrapolation of the calculated quantity of stars in a smaller volume, we have to take into account the structure of the Galaxy. A null hypothesis is that in the volume of 250 pc from the Sun, the amount of thick disk stars is 1000 times bigger than that...
within 25 pc. We assume a uniform distribution of halo stars on the scale of 100 pc$^3$ in the solar vicinity. Let us consider how an exponential decrease in the number density with an increase in the distance from the Galactic plane in the sample of thick disk stars affects the null hypothesis.

Let us introduce a $k = N_1/N_0$ coefficient, where

$$N_1 = \int_{-\infty}^{20} (25^2 - (z - 20)^2) \times e^{-|z|/H} \, dz. \quad (A1)$$

The $N_1$ is proportional to the quantity of the thick disk stars within 250 pc from the Sun. We assume that the Sun is located at a distance of 20 pc above the Galactic plane (Humphreys & Larsen 1995). The quantity of stars located within 25 pc from the Sun is proportional to

$$N_0 = \int_{-5}^{45} (25^2 - (z - 20)^2) \times e^{-|z|/H} \, dz. \quad (A2)$$

A true quantity of the stars in these volumes can be obtained by the multiplication of $N_1$ or $N_0$ on $\pi \times r_0$, where $r_0$ is the number density of thick disk stars at the Galactic plane ($z = 0$). Apparently, in the case of the uniform distribution of stars in space, $k$ is equal to 1000. All values in these formulae are expressed in parsecs. The location above the Galactic plane is designated by $z$. The thick disk scale height $H$ varies from 1000 to 1500 pc. For our calculations, we took $H = 1048$ pc (Veltz et al. 2008). After integrating the right-hand parts of Equations (A1) and (A2), we obtain $k = 933$. Therefore, the deviation from the homogeneous number density distribution of thick disk stars within 250 pc from the Sun is approximately 7%. The median metallicity of the stars in our sample is $|m/H| \approx -1.6$. The percentage of the metal-weak thick disk tail stars in the range of $-1.6 < [\text{Fe/H}] < -1$ may reach 60%–70% (Morrison et al. 1990; Beers & Sommer-Larsen 1995). Nevertheless, while considering our sample, the Galactic structure in the solar neighborhood can be neglected.

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