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Speckle Interferometry of Metal-Poor Stars in the Solar Neighborhood. I

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Abstract—We report the results of speckle-interferometric observations of 109 high proper-motion metal-poor stars made with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. We resolve eight objects—G102-20, G191-55, BD+19° 1185A, G89-14, G87-45, G87-47, G111-38, and G114-25—into individual components and we are the first to astrometrically resolve seven of these stars. New resolved systems included two triple (G111-38, G87-47) and one quadruple (G89-14) star. The ratio of single-to-binary-to-triple-to-quadruple systems among the stars of our sample is equal to 71:28:6:1.

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1. INTRODUCTION

Stars of the halo and thick disk of our Galaxy are old metal-poor objects with large spatial velocities [1, 2]. The studies of these stars can be used to impose constraints on the physical conditions during the early stages of the formation of our Galaxy. Binary and multiple stars are the best candidate objects to be used for studying the process of star formation at the time of formation of our Galaxy, because they bear more information about this process compared to single stars. This information is coded both in the orbital parameters (eccentricity, semi-major axis) and physical parameters of the components (component luminosities and the mass function).

The authors of early papers dedicated to the study of the multiplicity of the old population of the Galaxy [3, 4] concluded that the fraction of binary and multiple systems among these objects is very low compared to the corresponding fractions for younger stars of the Galactic disk, which are richer in heavy elements. However, the picture has changed in the last two decades. In series of papers opened by [5] is shown that the binary-to-single star ratio for halo and thick-disk stars is comparable to the corresponding ratio for the overwhelming majority of stars in the solar neighborhood. Such studies are based on the analysis of stellar spectra [6, 7] using the data on visual binaries and common proper motion pairs [8, 9].

We still have insufficient data about the multiple old stars in the solar neighborhood with orbital semi-major axes in the interval from $\sim$1 to $\sim$100 AU observable with adaptive optics and speckle-interferometric facilities. We point out the paper by Zinnecker et al. [10] who report the results of observations of population II stars using the techniques of speckle interferometry, adaptive optics, and direct imaging. To expand the database on such objects and determine the properties of the components of multiple systems, we began speckle-interferometric observations of metal-poor objects with large proper motions located in the close vicinity of the Sun. In this paper we report the results of observations of 109 halo and thick-disk stars made during the period from April through December, 2006.

The paper has the following layout: Section 2 describes the sample of stars studied; Section 3 analyzes the methods of observations and reduction of the data obtained; Sections 4 and 5 list the results of observations and additional information about the resolved stars, respectively; Section 6 discusses the multplicity of the stars studied, and the last section gives the conclusions.

2. THE SAMPLE

We selected our program stars from the CLLA catalog [11]. This catalog is actually a sample of A- to early K-type dwarfs from the *Lowell Proper Motion Catalog* [12, 13], which contains mostly Northern-Hemisphere stars brighter than 16 magnitude with proper motions exceeding 0.26 ″/year.

We selected a total of 223 stars from the CLLA catalog based on the following three criteria:

1. $[m/H] < -1$;
2. $\delta > -10°$;
3. $m_V < 12$.

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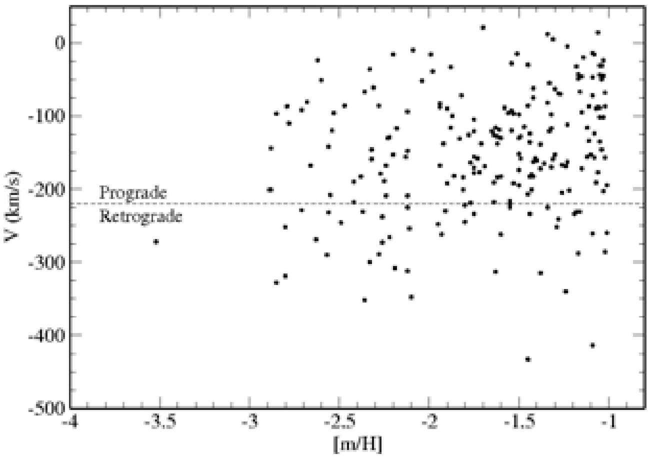

Fig. 1. Distribution of the stars of the sample by metallicity [m/H] and V component of spatial velocity. The dashed line separates stars moving in prograde and retrograde orbits.

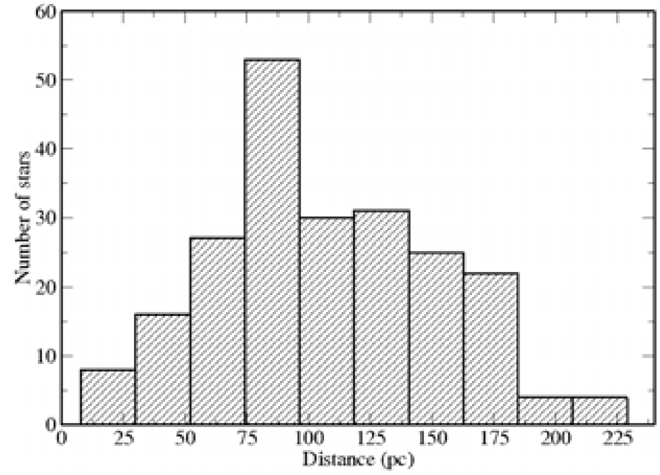

Fig. 2. Distribution of heliocentric distances of the stars of the sample (we adopt the distances from the CLLA catalog).

We use the data of the CLLA catalog to make several figures illustrating some of the main characteristics of our sample. Figure 1 shows the distribution of our selected stars on the "metallicity — V-component of the spatial velocity" plane, which demonstrates that our stars belong to different components of the Galaxy. The left-hand part of the diagram is occupied by halo objects — metal-poor stars with high velocity dispersion. The upper right corner is populated by stars belonging to the metal-weak tail of the thick disk. About 20% of all stars (45 objects) move in retrograde orbits. Figure 2 shows the distribution of the heliocentric distances of the stars of our sample. We used the photometric distances from the CLLA catalog. Arifyanto et al. [14] compared the photometric parallaxes with the corresponding trigonometric parallaxes measured by *Hipparcos* [15] for stars of the catalog considered and showed that there is a small discrepancy between the heliocentric distances determined using different methods. However, we did not correct the photometric distances in any way. Fig. 3 shows the distribution of the metallicities of the stars studied. The $[m/H] < -3$ metallicity interval is represented by only one star, G64-12, with $[m/H] = -3.52$. Half of the stars studied have metallicities in the interval $[m/H] = [-1.58; -1)$. As is evident from the distribution of stellar temperatures (Fig. 4), these are F-, G-, and K-type stars.

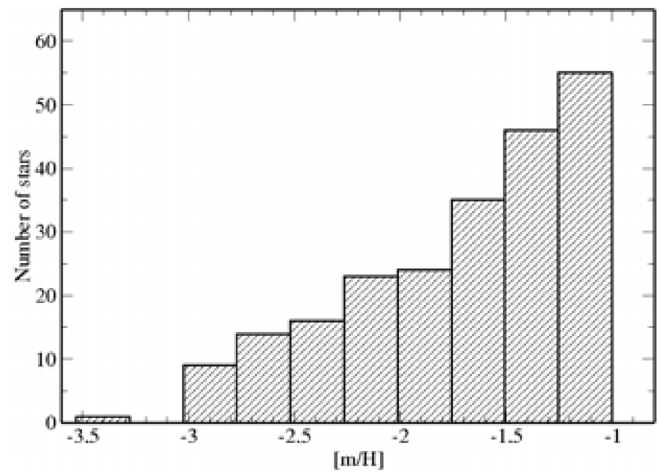

Fig. 3. Distribution of the metallicities of the stars of the sample (we adopt the metallicities from the CLLA catalog).

3. OBSERVATIONS AND DATA REDUCTION

We performed speckle-interferometry of 109 stars of the sample with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS): in April (one star), May (five objects), June (six objects), and December, 2006 (97 objects). Before December 2006 observations were made using a facility described by Maksimov et al. [16]. Its detector consists of a fast 1280×1024 Sony ICX085 CCD combined with a three-stage image intensifier with electrostatic focusing. In December we used a new facility based on an EMCCD (a CCD with internal electron gain) with higher quantum efficiency and better linearity. Both facilities are capable of detecting objects with component magnitude differences up to 4^m.

We recorded speckle interferograms in filters with the parameters of 545/30 nm (the first and the second numbers give the central wavelength and half bandwidth of the filter, respectively), 550/20, 800/110, and 800/100 nm with exposures ranging from five to 20 milliseconds. In December 2006 we obtained 500

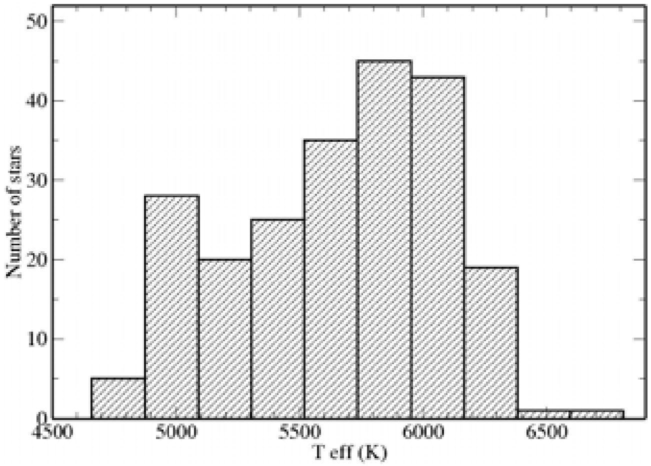

Fig. 4. Distribution of the temperatures of the stars of the sample (we adopt the temperatures from the CLLA catalog).

short-exposure images for each of most of the objects. For each of the remaining objects 2000 exposures are accumulated.

A description of the technique used to determine the relative positions and component magnitude differences from the power spectra of speckle interferograms averaged over the set can be found in [17]. The diffraction limit of the resolution is equal to 0.022″ in the 545/30 and 550/20 nm filters and 0.033″ in the 800/110 and 800/100 filters. The measured position angles and angular separations ρ are accurate to 0.3–2.8° and 1 to 5 mas, respectively. The errors of measured θ and ρ depend on a number of parameters: component separation, magnitude difference, and seeing β. The accuracy of the component magnitude difference determined from the power spectrum is also a function of the same parameters. It usually varies from 0.05^m to 0.2^m for $m_V = 8 - 10$ objects.

4. RESULTS OF OBSERVATIONS

The main results of this work are listed in Tables 1 and 4.

We resolved into components the following eight objects: G102-20, G191-55, BD+19° 1185A, G89-14, G87-45, G87-47, G111-38, and G114-25. We astrometrically resolved seven among these eight objects for the first time and found new components in five objects: G191-55, G89-14, G87-47, G111-38, and G114-25. We were the first to astrometrically resolve the well-known spectroscopic binary G102-20 [7]. We are also the first to establish the astrometric binarity of the G87-45 system whose spectrum exhibits signatures of three components [7]. The astrometric binarity of the resolved object BD+19° 1185A was earlier discovered by *Hipparcos* [15].

Table 2 gives some data on resolved systems. The last column of this table summarizes the results of all available astrometric and spectroscopic observations of the objects studied including the speckle-interferometric observations performed with the 6-m telescope of SAO RAS.

5. ADDITIONAL DATA ON RESOLVED STARS

In this section we summarize additional data on the resolved stars. For some objects we list two distances determined from photometric [11] and trigonometric [15] parallaxes. It is evident that the distance determined using the former method is underestimated, because it does not take into account the luminosity of the additional component. On the other hand, the additional component also introduces certain error in the measured trigonometric parallaxes, especially for short-period systems.

G102-20 ($05^h40^m09\overset{s}{.}7$ $+12°10'41''$; HIP 26676). This known SB1-type spectroscopic binary with a 26-year period [7] and a heliocentric distance of ≈ 70 pc [15] was resolved speckle-interferometrically for the first time.

G191-55 ($05^h57^m28\overset{s}{.}6$ $+58°40'49''$; BD+58° 876; TYC 3762-1904-1). It is an F8-type binary [18] located at a heliocentric distance of ≈ 93 pc [11].

BD+19° 1185A ($06^h03^m14\overset{s}{.}9$ $+19°21'39''$; HIP 28671). It is a G0V-type object [18]. The binary nature of this star with $\rho = 223$ mas was discovered by *Hipparcos*. Its heliocentric distance is estimated at $d \approx 42$ [11] and $d \approx 66$ pc [15]. This is a triple system given the presence of a distant companion ($\rho \approx 7''$) BD+19° 1185B.

G89-14 ($07^h22^m31\overset{s}{.}5$ $+08°49'13''$; HIP 35756; WDS 07224+0854) is a new quadruple system. We resolved it as a pair with a separation of 0.99″. Allen et al. [8] provide evidence suggesting that the system may contain a physically bound component at a distance of 34″. At the same time, G89-14 is an SB1-type spectroscopic binary with a period of 190 days [7]. The star is at a heliocentric distance of ≈ 94 pc [15].

G87-45 ($07^h32^m58\overset{s}{.}7$ $+31°07'00''$; TYC 2453-763-1). It is a G2-type star [18] known as an SB2-type spectroscopic binary with a period of 51 days [19]. The spectrum of this star exhibits signs of a third component [7], which we must have resolved. The distance to the star is $d \approx 123$ pc [11].

G87-47 ($07^h35^m34\overset{s}{.}1$ $+35°57'11''$; HIP 36936). A new triple system whose distance is estimated at

$d \approx 62$ [11] and $d \approx 100$ pc [15]. The system is known as an SB1-type spectroscopic binary with a period of 13 days. The Hipparcos catalog lists it as an object with stochastic astrometric solution. We found a third component. For this object we could determine the position of the secondary only with an uncertainty of $\pm 180°$.

G111-38 ($07^h49^m32\overset{s}{.}0$ $+41°28'08''$; HIP 38195; WDS 07495+4128). A new triple system. Hipparcos resolved it as a binary with $\rho = 2.154''$. We resolved one of the components. The distance to the system is estimated at $d \approx 50$ pc [11] or $d \approx 200$ pc [15]. The spectral type of the system is G5 [18].

G114-25 ($08^h59^m03\overset{s}{.}4$ $-06°23'46''$; HIP 44111). A new binary of spectral type F7 [18]. Its heliocentric distance is $d \approx 131$ pc [11].

6. MULTIPLICITY OF STARS

6.1. Distant Components

For 109 of the objects considered we used additional data on the spectroscopic multiplicity of these stars [6, 7] and the data on distant components from the WDS [20] catalog. Whereas spectroscopic and interferometric components appear to be undoubtedly physically bound, one must treat wide visual companions more carefully. We found a total of 43 WDS components (in some cases several components for one object), most of which we rejected as accidental optical projections. Table 3 lists the data on the all found wide components. The first column gives the names of the stars studied and the second column, all the WDS components found. For the components found to be physically bound to the corresponding stars columns 3 and 4 give the component separation and magnitude difference, respectively. We adopt the latter from the WDS catalog and they may differ slightly from the quantities given in the corresponding references. The '+' and '−' signs in column 5 (Status) mark the components, which we consider to be possibly physically bound to the main star and physically unbound optical pairs, respectively. A question mark in this column indicates that we are not sure about our decision. The last column gives the references to the papers, which contain data on the corresponding pair and confirm or disprove its physical relationship. In all cases these are two papers [8, 9] dedicated to wide pairs of population II stars and the Hipparcos catalog [15]. Additional $\star$ symbol in this column indicates that our observations confirm the presence of the given component. If no references are given, it means that we made our own decision about the physical association based on the data provided by the WDS catalog. To this end, we analyzed the component magnitude difference and the change of the component separations over the time periods covered by observations. As a result, we left only 12 objects among the initial 43 WDS components and used them to compute the ratios of the number of systems of different degree of multiplicity.

6.2. Ratio of the Systems of Different Degree of Multiplicity

To compute the ratio of the number of systems of different degree of multiplicity among the stars studied, we use all the data that we gathered on the observations of these systems using different methods. Of the 109 stars considered 24 are spectral binaries [6, 7]; one star (G87-45) is a spectral triple [7]; seven stars are speckle-interferometric binaries, and one star (G111-38) is a speckle-interferometric triple. Twelve stars have companions listed in the WDS catalog. It goes without saying that there are components detected using different methods. For example, the G102-20 binary with a period of 26 years [7] was found both spectroscopically and using speckle interferometry. Similarly, the outer pair in the triple system G111-38 ($\rho \approx 2''$) can be detected both using speckle interferometry and visually.

The resulting ratio of the number of single, binary, triple, and quadruple systems discovered using all methods among the stars of our sample is equal to 71:28:6:1. The corresponding estimate for F7- to G9-type disk stars uncorrected for unresolved binaries [21] is equal to 51:40:7:2. We point out an important difference between the two samples compared. Whereas our sample consists of stars selected by magnitude and spatial velocities, the sample used in [21] is only distance limited (all its stars are located within 22 pc of the Sun).

7. CONCLUSIONS

We selected for observations with high angular resolution a total of 223 high proper motion metal-poor objects from the CLLA catalog [11]. Our speckle-interferometric observations of 109 stars made with the 6-m telescope of SAO RAS allowed us to resolve eight stars into components and we were the first to astrometrically resolve seven objects. Additional data on spectral and astrometric multiplicity allowed us to estimate the ratio of the number of single, binary, triple, and quadruple systems to be 71:28:6:1.

In the next paper of this series we will continue to publish the results of our speckle-interferometric observations of the star sample presented.

Table 1. Speckle-interferometric measurements of resolved objects

Name of the system/ subsystem	$\rho('')$	$\Theta(^\circ)$	$\triangle m$	Filter
G102-20	0.120±0.006	308.0±2.8	3.24±0.11	550/20
G191-55	0.814±0.002	125.1±0.3	2.00±0.01	800/100
BD+19° 1185A	0.115±0.001	183.6±0.7	1.77±0.02	550/20
G89-14	0.989±0.005	0.8±0.4	4.14±0.06	800/100
G87-45	0.285±0.002	271.3±0.5	2.01±0.04	550/20
G87-45	0.285±0.002	270.7±0.4	1.76±0.02	800/100
G87-47	0.078±0.003	54.0*±2.1	1.74±0.03	800/100
G111-38AB	0.084±0.001	7.9±0.7	0.78±0.01	550/20
G111-38AB	0.084±0.001	7.8±1.3	0.75±0.01	800/100
G111-38AC	2.133±0.005	200.0±0.3	1.34±0.01	550/20
G111-38AC	2.133±0.005	200.0±0.3	1.10±0.01	800/100
G111-38BC	2.216±0.005	199.5±0.3	0.57±0.02	550/20
G111-38BC	2.216±0.005	199.5±0.3	0.36±0.03	800/100
G114-25	0.781±0.005	323.7±0.5	3.83±0.16	800/100

* The position of the secondary component is known with an uncertainty of ±180°.

Table 2. Additional data on resolved stars

Name of the system/ subsystem	Coordinates (2000.0)	m_V	[m/H]*	Total multiplicity of the system
G102-20	$05^h40^m09\overset{s}{.}7$ $+12°10'41''$	10.22	−1.17	2
G191-55	$05^h57^m28\overset{s}{.}6$ $+58°40'49''$	10.47	−1.94	2
BD+19° 1185A	$06^h03^m14\overset{s}{.}9$ $+19°21'39''$	9.32	−1.47	3
G89-14	$07^h22^m31\overset{s}{.}5$ $+08°49'13''$	10.40	−1.90	4
G87-45	$07^h32^m58\overset{s}{.}7$ $+31°07'00''$	11.44	−1.49	3
G87-47	$07^h35^m34\overset{s}{.}1$ $+35°57'11''$	10.34	−1.34	3
G111-38	$07^h49^m32\overset{s}{.}0$ $+41°28'08''$	8.7	−1.04	3
G114-25	$08^h59^m03\overset{s}{.}4$ $-06°23'46''$	11.92	−2.28	2

* Metallicities adopted from the CLLA catalog [11].

Table 3. WDS components for stars of the sample

Name	WDS companion	$\rho('')$	$\triangle m$	Status	References
G172-16	00386+4738OSO 7	8.4	5.85	+	[9]
G2-38	01270+1200LDS3282	24.6	5.5	+	[8]
G172-61	01344+4844ES 2587			–	[9]
G71-33	01452+0331LDS3306			–	
G74-5	02104+2948BUP 29AB			–	
	02104+2948BUP 29AC			–	
	02104+2948BUP 29AD			–	
G37-26	03084+2620OSO 14			–	[9]
G246-38	03313+6644OSO 15			–	[9]
G95-57A/G95-57B	03470+4126STF 443AB	7.4	0.62	+	[8]
	03470+4126STF 443AC			–	
	03470+4126FOX 135CD			–	[9]
HD 25329	04033+3516OSO 16			–	[9]
G99-31W	05449+0915HDS 769			–	[15]
BD+19° 1185A	06032+1922HDS 823Aa	0.2	2.12	+	[15], ⋆
	06032+1922LDS6195AB	6.9	4.06	+	[8]
G88-10	07104+2421OSO 19			–	[9]
G89-14	07224+0854GIC 72AB			–	[8]
	07224+0854ALC 2BC	34.0	6.3	+	[8]
G112-43/G112-44	07437-0004HJ 2413	11.8	1.58	+	[8]
G111-38	07495+4128A 2468AB	2.2	1.27	+	[15], ⋆
	07495+4128LDS 900AB-C			–	
G90-25	07536+3036BUP 108			–	[9]
G251-54	08110+7955LDS1668AB	110.5	5.4	+	[9]
	08110+7955PWS 3AC			–?	
	08110+7955OSO 21AD			–	[9]
G40-14	08161+1942LDS3781	98.0	7.6	+	[8]
G113-22	08170+0001LDS3782			–	
G9-36	08580+2428OSO 23AB			–	[9]
	08580+2428OSO 23AC			–	[9]
G115-49	09053+3848OSO 24			–	[9]
G120-15	11063+3113TDS7665AB	7.6	0.68	+?	
	11063+3113OSO 36AC			–	[9]
G10-4	11110+0625OSO 37			–	[9]

Table 3. (Contd.)

Name	WDS companion	ρ ($''$)	$\triangle m$	Status	References
G66-22	14433+0550OSO 58	3.2	3.19	+	[9], ⋆
G23-14	19518+0537OSO 112			–	[9]
G143-33	20084+1503OSO 117AB			–	[9]
	20084+1503OSO 117AC			–	[9]
	20084+1503OSO 117AD			–	[9]
	20084+1503OSO 117AE			–	[9]
	20084+1503LDS1033AF			–	
G125-64	20090+4252OSO 118AB			–	[9]
	20090+4252OSO 118AC			–	[9]

Table 4. Unresolved stars

Name	Filter ($\lambda/\Delta\lambda$, nm)	Epoch
G172-16	800/100	2006.9463
G33-30	800/100	2006.9437
G2-38	800/100	2006.9438
G172-58	800/100	2006.9462
G172-61	550/20; 800/100	2006.9462
G173-10	550/20; 800/100	2006.9463
G2-50	800/100	2006.9438
G71-33	800/100	2006.9438
G245-32	550/20	2006.9443
G133-45	800/100	2006.9467
G71-55	800/100	2006.9438
G72-60	800/100	2006.9468
G74-5	550/20	2006.9468
G74-30	800/100	2006.9467
G36-47	800/100	2006.9468
G37-26	550/20	2006.9468
G5-19	550/20	2006.9468
G221-7	550/20	2006.9442
G5-35	800/100	2006.9468
G246-38	800/100	2006.9442
G79-42	800/100	2006.9468
G79-43	800/100	2006.9468

Table 4. (Contd.)

Name	Filter ($\lambda/\Delta\lambda$, nm)	Epoch
G79-56	800/100	2006.9468
G95-57A	550/20	2006.9414
G95-57B	550/20	2006.9414
HD 25329	550/20	2006.9414
G82-18	800/100	2006.9415
G84-29	550/20	2006.9415
G191-23	800/100	2006.9448
G86-39	800/100	2006.9415
G86-40	550/20; 800/100	2006.9416
G96-48	800/100	2006.9417
G99-31W	550/20; 800/100	2006.9417
G102-27	550/20	2006.9471
G99-48	800/100	2006.9471
G101-34	800/100	2006.9471
G192-28	800/100	2006.9448
G105-50	800/100	2006.9471
G192-43	800/100	2006.9448
G87-13	800/100	2006.9417
G108-48	800/100	2006.9445
G107-50	800/100	2006.9475
G87-27	550/20; 800/100	2006.9472
G88-10	800/100	2006.9472

Table 4. (Contd.)

Name	Filter (λ/Δλ, nm)	Epoch
G108-58	800/100	2006.9445
G88-27	800/100	2006.9472
G90-3	800/100	2006.9472
G88-32	800/100	2006.9418
BD-1° 1792	800/100	2006.9446
G112-43	800/100	2006.9446
G112-44	800/100	2006.9446
G90-25	550/20; 800/100	2006.9473
G251-54	800/100	2006.9475
G234-24	800/100	2006.9475
G40-8	800/100	2006.9446
G234-28	800/100	2006.9448
G40-14	800/100	2006.9446
G113-22	800/100	2006.9446
G194-22	800/100	2006.9448
BD+25° 1981	550/20; 800/100	2006.9473
G46-5	800/100	2006.9474
G115-34	800/100	2006.9473
G9-36	800/100	2006.9473
G114-26	550/20	2006.942
G115-49	800/100	2006.9473
G46-31	800/100	2006.9476
G41-41	800/100	2006.9476
G195-34	800/100	2006.9422
G48-29	800/100	2006.9476
G116-45	800/100	2006.9473
G161-73	800/100	2006.9476
G43-3	545/30	2006.2759
G53-41	800/100	2006.9421
G44-30	800/100	2006.9422
G58-23	800/100	2006.9422
G196-48	800/100	2006.9422
G58-25	550/20	2006.9422
G146-76	800/100	2006.9477

Table 4. (Contd.)

Name	Filter (λ/Δλ, nm)	Epoch
G253-41	550/20; 800/100	2006.9422
G120-15	800/100	2006.9449
G10-4	800/100	2006.9449
BD+36° 2165	800/100	2006.9449
HD 97916*	550/20	2006.945
G56-30	800/100	2006.9449
G254-24	800/100	2006.9423
G147-62	800/100	2006.945
G121-12	800/100	2006.9477
G176-53	800/100	2006.9423
G122-51	550/20	2006.945
G66-22	545/30; 800/110	2006.3747
G166-45	545/30	2006.3747
G16-13	545/30	2006.3748
G16-20	545/30	2006.3749
G153-21	545/30	2006.3749
G170-47	545/30	2006.4488
G23-14	800/110	2006.4517
G23-20	800/110	2006.4517
G24-3	800/110	2006.4518
G143-33	800/110	2006.4518
G125-64	800/110	2006.4518
G171-15	800/100	2006.9463

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This work makes use of the SIMBAD database [18] and WDS catalog [20].

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