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A CCD SEARCH FOR WIDE METAL-POOR BINARY STARS: APPROACHING THE METAL-DEPLETED SUBSTELLAR LIMIT

M. R. Zapatero Osorio[1] and E. L. Martín[2]

RESUMEN

Hemos explorado los alrededores dentro de un radio de $25''$ en torno a 473 estrellas de tipo espectral G a M y pobres en metales, y hemos utilizado los filtros ópticos $(VR)I$ con telescopios de pequeño diámetro. Aproximadamente un 10% de la muestra ha sido investigada hasta separaciones angulares de $90''$. Las estrellas seleccionadas con metalicidades en el rango $-3.5 \leq$[Fe/H]≤ 0.0 provienen de los catálogos de Carney–Latham. Hemos aplicado técnicas fotométricas y astrométricas para detectar a las verdaderas compañeras de las estrellas. Identificamos 13 nuevas compañeras estelares por movimiento propio, y recuperamos 29 compañeras conocidas previamente con brillos hasta 8 magnitudes más débiles que las estrellas primarias. Las masas de estas compañeras se estiman entre $0.5\,M_{\odot}$ y $0.1\,M_{\odot}$, muy cerca de la frontera subestelar para bajas metalicidades. Las separaciones orbitales están entre $\sim$32 y $\sim$57000 UA. Nuestros resultados indican que un 15% de las estrellas pobres en metales tienen compañeras estelares en grandes órbitas, de forma análoga a las estrellas G y M de la secuencia principal y las estrellas T Tauri. Búsquedas similares llevadas a cabo con telescopios de la clase 4-m descubrirán enanas marrones deficientes en metales alrededor de estrellas. Su seguimiento espectroscópico habrá de llevarse a cabo con telescopios e instrumentación de la clase 10-m, como el GTC.

ABSTRACT

We explored the regions within a radius of $25''$ around 473 nearby, low-metallicity G- to M-type stars using $(VR)I$ optical filters and small-aperture telescopes. About 10% of the sample was searched up to angular separations of $90''$. Target stars with metallicities in the interval $-3.5 \leq$[Fe/H]≤ 0.0 were selected from the surveys by Carney–Latham. We applied photometric and astrometric techniques to detect true physical companions to these stars. We identified 13 new proper motion stellar companions and retrieved 29 previously known companions that are up to 8 magnitudes fainter than their primary stars in the I-band. The masses of these companions are estimated to be between $0.5\,M_{\odot}$ and $0.1\,M_{\odot}$, i.e., close to the substellar borderline for low metallicities. Projected orbital separations are between $\sim$32 and $\sim$57000 AU. Our results indicate that about 15% of the metal-poor stars have stellar companions in wide orbits, which is in agreement with the binary fraction observed among main sequence G- to M-type stars and T Tauri stars. Similar searches conducted with 4-m class telescopes will lead to the discovery of low-metallicity brown dwarfs around stars. Their spectroscopic follow-up requires 10-m class telescopes and instrumentation like that of the GTC.

Key Words: **BINARIES: VISUAL — STARS: LATE-TYPE — STARS: STATISTICS — STARS: SUBDWARFS**

1. INTRODUCTION

Since the discovery of the first brown dwarfs (Rebolo, Zapatero-Osorio & Martí 1995; Nakajima, Oppenheimer, Kulkarni et al. 1995), many efforts have been devoted to study substellar objects (unable to fuse hydrogen stably in their interiors) as companions to stars. To date, there are many brown dwarfs orbiting solar-metallicity, nearby stars that have been found using different searching techniques, like radial velocity surveys and Adaptive Optics direct imaging surveys. They are orbiting their primary stars at a wide range of orbital sizes, from $a \leq 5$ AU up to several thousands AU. Free-floating brown dwarfs with presumably solar composition are also common in the galactic disk.

However, it has been suggested that metallicity plays an important role in the formation of planets in close-in orbits ($a \leq 5$ AU), based on the fact that the percentage of stars with detected extrasolar planets rises with iron abundance (Fischer & Valenti 2003). The role of metallicity at larger orbits has not been investigated so far. Here, we have conducted a CCD-based imaging search for wide metal-poor stellar companions using optical filters and small-aperture telescopes (Zapatero Osorio &

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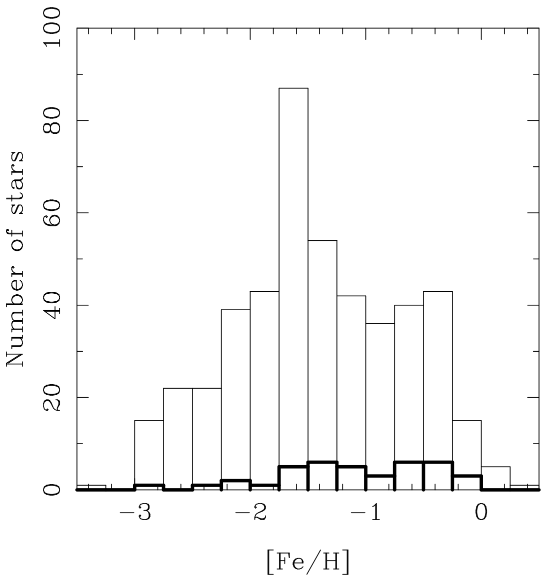

Fig. 1. The metallicity distribution of our sample is plotted as a thin line. The metallicity distribution of the stars with wide companions is displayed with a thick line.

Martín 2004). The smallest companions found in our exploration have masses close to the substellar borderline and brightnesses near the survey sensitivity limit. If we extrapolate the results of our search to the brown dwarf domain, about 15% of the metal-poor stars may harbor substellar companions at wide orbits ($a \geq 30$ AU). According to state-of-the-art evolutionary models, these can be detected photometrically with intermediate-size telescopes, but require 10-m class telescopes for detailed characterization.

2. SAMPLE, OBSERVATIONS AND ANALYSIS

The great majority of the 473 low-metallicity stars of our sample has been selected from the Carney, Latham, Laird & Aguilar (1994) survey. These stars, with spectral types G, K and M, show high proper motions (typically $\geq 0.1'' \, \mathrm{yr}^{-1}$), and their atmospheric metal content has been measured to be in the range [Fe/H] = [−3.5, 0.0]. We plot in Fig. 1 the metallicity distribution of our entire sample. About 46% of the sample have distances available in the Hipparcos database. The target stars lie between 10 and 1000 pc; the most metal-depleted stars are typically located farther away than the most metal-rich stars.

Imaging observations have been carried out using 1024 × 1024 CCD cameras mounted on 1-m and 2-m class telescopes located at Teide Observatory (0.80-m IAC80 telescope), and Roque de los Muchachos Observatory (2.5-m NOT and 1.0-m JKT telescopes). Images in the I-band filter were collected during 1994, 1995, 1996, 2002 and 2003. Exposure times ranged between a few seconds to 600 s, depending on the brightness of the targets and the telescope diameter. These integration times did not yield deep images. However, these data are intended to detect objects typically between 0 and 5 mag fainter than the target stars (completeness). In some cases, less luminous objects are seen (maximum dynamical range is 9 mag). We note that this program was usually carried out as a backup observing program whenever the seeing was rather poor ($\geq 2''$) or there were many clouds. This allows us to resolve separations larger than 30 AU for roughly solar metallicities and larger than 200 AU for [Fe/H] = −3.

We performed differential photometry and relative astrometry of all star-like sources that are found within a radius of $25''$ from the low-metallicity source. For about 10% of our sample, we also investigated up to $1\farcm5$. Common proper motion visual binaries are recognized because the members of a system should keep a rather constant separation and position angle within intervals of years, while changing their apparent location with respect to background sources. Target stars with nearby red companion candidates were observed at different epochs years apart, allowing us to identify common proper motion pairs. We also used red images provided by the Digitized Sky Surveys to complete our astrometric study. In addition, we searched the literature and SIMBAD for identifying wide binaries with large or with very small separations, which we cannot resolve in our data.

Of the 473 stars in the original sample, we detected 29 previously known binaries and multiple systems with separations between $0\farcs17$ and $17'$, and 13 new proper motion companions with separations between $2''$ and $1\farcm9$. The photometry and astrometry of the new companions are listed in Table 1. We also provide the 2MASS JHK_s near-infrared photometry when available. Companions with separations of less than $4''$ are not fully resolved by the 2MASS survey.

We also obtained low-resolution optical spectra (3860–1000) Å) of eight new companions using the 4.2-m WHT and 3.5-m TNG telescopes (Roque de los Muchachos Observatory). For these companions, we derived subdwarf spectral types esdK7.2–sdM3.0 (error bar of half a subclass). The spectra of significantly metal-poor companions are dominated by strong MgH and CaH molecular absorptions. At the resolution of our data, spectra appear featureless redward of 8000 Å, except for the Ca II triplet, which remains detectable down to esdM3. The molecular

TABLE 1

NEW PROPER MOTION STAR COMPANIONS

Companion	[Fe/H]	$\Delta(V)$	$\Delta(R)$	$\Delta(I)$	J	H	K_s	ρ ($''$)	PA (deg)	Sep (AU)	d (Hip) (pc)	d[a] (pc)
G 009-047 B	−1.93	8.70	8.23	8.05	14.05	13.37	13.19	81.93	229.5	30800	375.94	13
G 059-032 B	−0.23	–	–	–	14.11	13.72	13.22	112.03	108.7	5381	48.05	58
G 090-036 B[b]	−1.62	3.44	2.97	2.61	–	–	–	1.67	47.4	369	–	221
G 093-027 B	−1.23	2.7:	2.2:	1.8:	11.47	10.83	–	3.52	101.3	275	–	78
G 116-009 B[b]	−1.46	4.00	3.57	3.03	15.33	14.71	14.57	10.08	90.5	2712	–	269
G 128-077 B	−1.36	2.87	2.05	1.89	13.53	12.96	12.83	9.18	138.3	1533	–	167
G 172-016 B	−1.64	5.85	5.34	4.84	13.99	13.41	13.19	8.30	154.5	822	–	99
G 176-046 D[b]	−1.67	4.89	4.76	3.89	–	–	13.50	4.80	152.9	610	–	127
G 188-022 B	−1.45	6.93	6.21	5.45	13.47	13.03	12.86	5.08	308.3	553	108.81	89
G 204-049 B	−0.97	4.3:	3.7:	3.1:	–	–	–	2.7:	72:	235:	–	87
G 214-001 B	−2.03	5.74	4.95	4.59	14.51	14.08	13.95	5.14	353.0	802	–	156
G 216-045 B	−0.52	8.56	7.49	6.22	15.02	14.45	14.14	31.45	43.9	4151	–	132
G 273-152 B	−0.60	$\leq$5.7	4.42	3.57	–	–	–	3.84	277.6	307	80.06	65

[a] Distance from Carney et al. (1994), except for G 009-047 B.

[b] See also Martín et al. (1995), and Gizis & Reid (1997).

features between 6000 and 8000 Å are quite sensitive to temperature changes, in contrast to the blue spectra.

3. DISCUSSION

Our survey suggests that about one third of the stellar wide companions were missed in previous proper motion searches.

The optical and near-infrared color-magnitude diagrams depicting the location of the total of 42 companions identified in our survey are shown in Fig. 2. We also included 10-Myr isochrones from Baraffe, Chabrier, Allard & Hauschildt (1997) for two different abundances, $[\mathrm{Fe/H}] = -1$ and -2. Most of the new companions have metallicities in this metal range. To convert apparent magnitudes into absolute magnitudes, we assumed that companions are located at the same distance than the primaries. As seen from Fig. 2, the models nicely reproduce the trend described by the observations.

We estimated the masses of the companions by comparing their locii in color-magnitude diagrams (e.g., Fig. 2) with evolutionary tracks. The most likely masses are between 0.1 and 0.54 $M_\odot$. A few less massive metal-depleted stars have been recently identified in the field by means of proper motion measurements. Lépine, Shara & Rich (2003) reported on the finding of a low-metallicity star with spectral type sdM8.0: LSR 1425+7102. For comparison purposes, we plot its 2MASS photometry as an asterisk in Fig. 2. Its location in the figure suggests that the atmospheric metal abundance of this star is around $[\mathrm{M/H}] = -1$ (i.e., all metals are depleted by a factor of 10 as compared to the Sun). From the comparison with model calculations, its mass is likely between 0.085 and 0.09 $M_\odot$, rather close to the substellar borderline for this metallicity (i.e, 0.083 $M_\odot$, Baraffe et al. 1997). We do not detect in our survey objects as cool as this one because the images are not deep enough.

Figure 3 illustrates the projected separation of the 42 common-proper-motion companions to G-, K- and M-type subdwarfs as a function of metallicity. Separations range from a few tens of AU up to about 57000 AU. Metal-poor, low-mass stars are found in wide binary systems with orbital sizes that resemble those of solar-metallicity binary stars of similar masses (e.g., Poveda, Herrera, Cordero & Lavalley 1994). This result agrees with the very recent and extensive spectroscopic work of Latham, Stefanik, Torres et al. (2002). We do not find significant difference in the orbital separations of metal-depleted binaries and solar-metallicity multiple stars.

Poveda et al. (1994) provided a catalog of wide binaries and multiple stars in the solar vicinity with separations larger than 25 AU. The great majority of the stars in their catalog (98.5%) has solar metallicity. According to these authors, the fraction of wide binaries in the solar neighborhood is 15–20%. The metallicity distribution of our companion stars

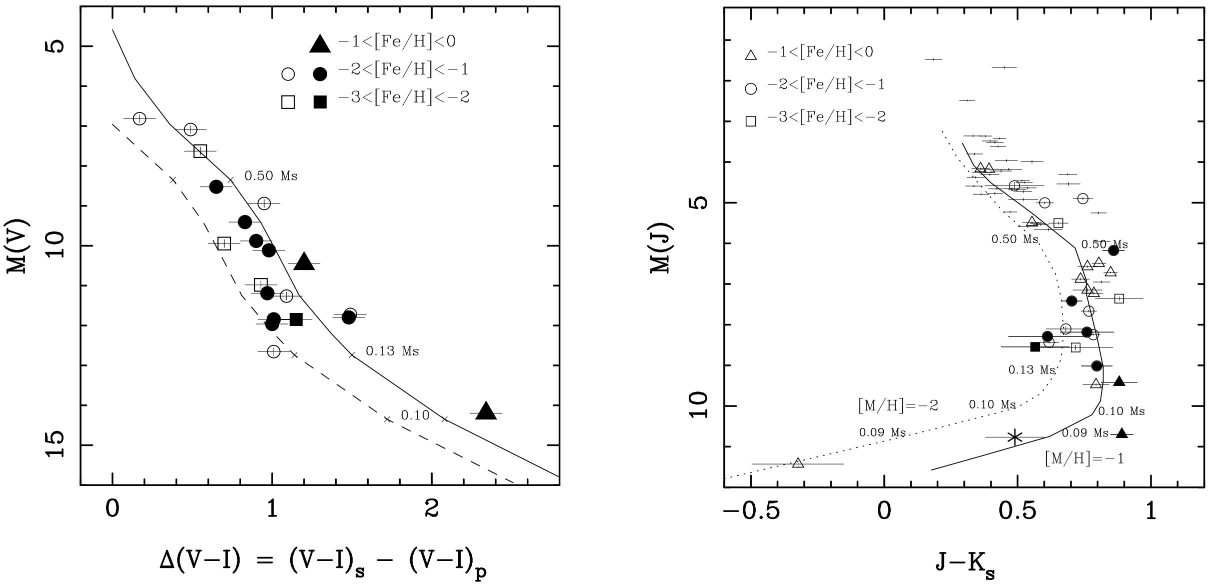

Fig. 2. Color-magnitude diagrams of low-metallicity stellar companions. New discoveries are plotted as filled symbols, and previously known companions are plotted as open symbols. *(Left panel)* The x-axis represents the $(V-I)$ color difference between the companion and the primary star. Overplotted is the 10-Myr isochrone (Baraffe et al. 1997) for the metallicity $[\mathrm{Fe/H}] = -1$. For the color difference, primaries of $0.8\,M_\odot$ (solid line) and $0.6\,M_\odot$ (dashed lines) are considered. For the sake of clarity, previously known companions with metal abundances below -1 are excluded from the diagram. *(Right panel)* Primaries are also plotted as no symbols with error bars. The 10-Myr isochrones for two different metallicities are included. The field low-metallicity star LSR 1425+7102 is plotted as an asterisk. The faint end of the isochrones indicates the location of the substellar limit for each metallicity.

(thick line) is compared to the distribution of the sample targets in Fig. 1. Although it is not very obvious from the figure, we have confirmed that the two distributions are different. To further illustrate this, we evaluated the binary fraction of stars with visible companions in our survey as a function of metal content. For binary fraction, we used the number of multiple systems relative to the total number of stars per interval of metallicity. The results are depicted in Fig. 4 (solid line). There is a marked decrease toward very low metallicities: while 12–16% of the most metal-rich stars ($[\mathrm{Fe/H}] \geq -1$) harbor wide companions, less than 5% of the most metal-deficient stars ($[\mathrm{Fe/H}] \leq -2$) are found in wide binaries.

Nevertheless, Fig. 4 needs to be corrected for the fact that the most metal-depleted stars in our survey are located farther away than the most metal-rich stars. Hence, we explored the widest orbits of the very low-metallicity stars, while closer regions were surveyed around more metal-rich sources. We corrected the "direct" binary fraction for this effect by taking into account the different orbital sizes that our survey has explored as a function of metallicity, and normalizing at $[\mathrm{Fe/H}] = [-1, 0]$. The resulting "corrected" binary frequency is plotted as a dashed line in Fig. 4. We note that this correction is based on the assumption that companions have similar orbits throughout all metallicities. This assumption is supported by Fig. 3, where it is obvious that this assessment is true for the interval $[\mathrm{Fe/H}] = [-1.5, 0]$. The corrected binary fraction is nearly flat, and suggests that 13–15% of the low-metallicity stars harbor wide, low-mass stellar companions with mass ratios in the range 0.13–1.0 and separations larger than 30 AU. This overall binary frequency is in agreement with the binary fraction observed among main sequence G- to M-type stars in the solar neighbourhood (Poveda et al. 1994) and young T Tauri stars of star-forming regions ($14 \pm 1.8\%$, Brandner, A'calá, Kunkel et al. 1996). This suggests that metallicity is not a key parameter in the stellar formation of wide binary (and multiple) systems.

If we extrapolate the results of our survey to the substellar domain, about 15% of the G- to M-type metal-depleted stars may have brown dwarf companions located at separations ≥30 AU. Surveys similar to the one described here can lead to their detection. The substellar borderline oc-

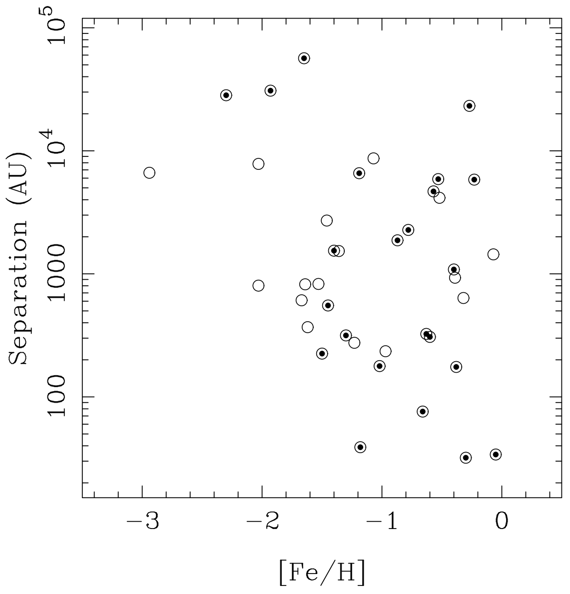

Fig. 3. Projected separation against metallicity. Encircle dots stand for stars with Hipparcos distances. The apparent lack of small separations at very low metallicities is a bias resulting from the larger distances at which these stars are located.

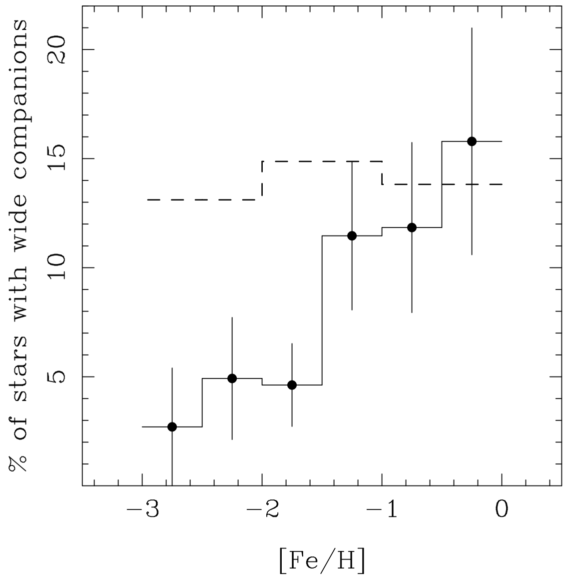

Fig. 4. The frequency of low-metallicity wide companions is plotted as a solid line. Vertical errors are Poissonian. The "corrected" frequency is plotted as a dashed line.

curs at M(I) = 13.93 mag and M(J) = 11.57 mag for [M/H] = −1 and age = 10 Gyr (Baraffe et al. 1997; Chabrier & Baraffe 1997). For younger ages, the star–brown dwarf frontier occurs at brighter magnitudes. The most massive brown dwarfs are expected to be about 1 magnitude fainter in J and to show cool atmospheres with temperatures below 1000 K; their peak of emission will lie mostly between the R and H wavelengths (Saumon, Bergeron, Lunine et al. 1994; Allard & Hauschildt 1995). These values are within the capabilities of mid-size telescopes and their optical and near-infrared instrumentation. These telescopes can detect nearby, metal-depleted brown dwarfs in direct images. As compared to solar-metallicity brown dwarfs of similar mass, the models predict that low-metallicity substellar objects are significantly bluer in the infrared colors (due to the increasing collision-induced absorption of molecular hydrogen with increasing density and decreasing temperature). However, given the very faint nature of evolved metal-poor brown dwarfs (substellar objects progressively become fainter), their spectroscopic follow-up requires 10-m class telescopes to achieve a relatively detailed characterization of their properties. GTC and its Day-One instrumentation (OSIRIRS and ELMER) offer an extraordinary opportunity to observe metal-depleted brown dwarf candidates.

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