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uvby Photometry of stars with planets

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Abstract. The use of Strömgren $uvby$ photometry is proposed as a simple tool for the estimation of effective temperatures and metallicities in stars discovered to have planets. Previous photometric calibrations are tested with available spectroscopic measurements and their application to stars without high-resolution spectroscopy allowed the determination of metal abundances for 12 additional stars with planets. Their previously suggested relative metal-rich nature, when compared with similar field stars, is discussed as well as the possible relation of the stellar metal abundance with the mass of the planet.

Key words: stars: abundances – stars: fundamental parameters – stars: formation – stars: late-type

1. Introduction

Until few years ago, the Sun was the only star known to have a planetary system. The discovery of an increasing number of extra-solar planets now offers the possibility of analysing general characteristics of planets (masses, periods, etc.) and their distribution, or the search for special signatures of the planet formation process in their parent stars. A fair amount of work has been devoted to the first kind of problems, while the second has recently shown unexpected results from a detailed analysis of high-resolution spectra of stars with planets by González and collaborators (see González 1999, and references cited therein). The spectroscopic data apparently show that stars with planetary systems are in average more metal rich than single stars having similar temperature, age and galactic position. In fact, the Sun is known since long ago to be more metal abundant than other analog stars. These results were interpreted as a consequence of the formation process of the planets. But not all cases did actually show such a metal excess since some stars, also suspected of having giant planets, were found to be metal defficient. Only a statistical distribution of the metallicities, when compared to nearby field stars, as given e.g. by Favata et al. (1997), allowed the mentioned conclusion.

The problem is of course worth giving further attention to it. Both, because statistical arguments need a large sample to be tested, and because the conclusion, if confirmed, is of high relevance for the formation of planetary systems and the search for further candidates. Within this context, the information provided by intermediate-band photometry was considered to be relevant due to the possibility to derive effective temperatures, closely linked to the spectroscopic measurement of relative abundances, as well as to estimate the values of the metallicities themselves. With this well-known tool, a larger sample than until now available, of stars with planets and high-resolution spectroscopy, can be analysed. Even more, an easy method is provided to explore candidate stars in connection with ongoing massive surveys for the detection of new extra-solar planets. The purpose of the work presented in this paper was twofold. Firstly, to test the validity of available photometric calibrations for solar-type stars in estimating effective temperatures and metallicities by comparison with available spectroscopic data. Secondly, the obtention of metal abundances for the largest possible sample of stars known to have planets from the analysis of their *uvby* Strömgren photometry in order to derive further global information about their suggested metallicity anomalies.

2. The photometric data

The catalogue maintained by Jean Schneider at the Paris Observatory (http://www.obspm.fr/planets) was used to compile the list of stars to be studied. In this catalogue, as by December 1999, 27 stars are referenced with confirmed companions having minimum masses ($m \sin i$) below the limit of 13 times the value for Jupiter, which some authors adopt as the border between brown dwarfs and giant planets (no deuterium burning). This separation is not well established and only minimum masses are available so that values close to the limit may not be relevant. In fact, the star with the more massive companion, HD 114762, may actually contain a brown dwarf rather than a giant planet.

Strömgren $uvby$ photometry was extracted from the SIMBAD database, basically corresponding to Hauck & Mermilliod (1998). For the faint GJ 876 and the evolved HD 177830, no $uvby$ photometry was available and therefore only 25 stars have been analyzed. The $uvby$ colour indices are given in Table 1, ordered according to increasing mass of the lightest planet. In the case of HD 210277 the best photometry, rather than average values, was adopted because of the higher scatter of data in the literature. Since all stars in the sample are nearby, in fact

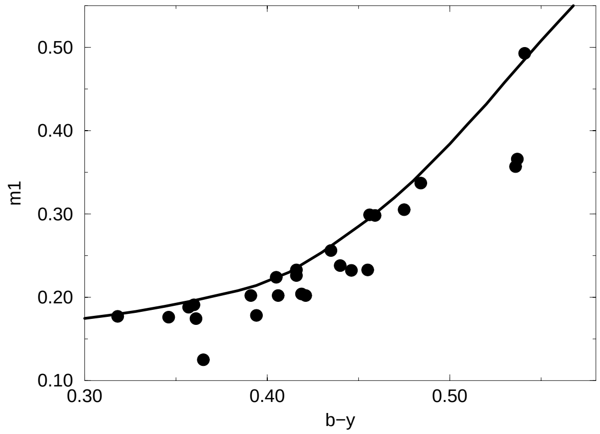

Fig. 1. The $(b-y)-m_1$ diagram for the sample of stars with planets. Crawford's (1975) standard relation for F-type dwarfs and Olsen's (1984) relation for G-K dwarfs are plotted with a continuous line.

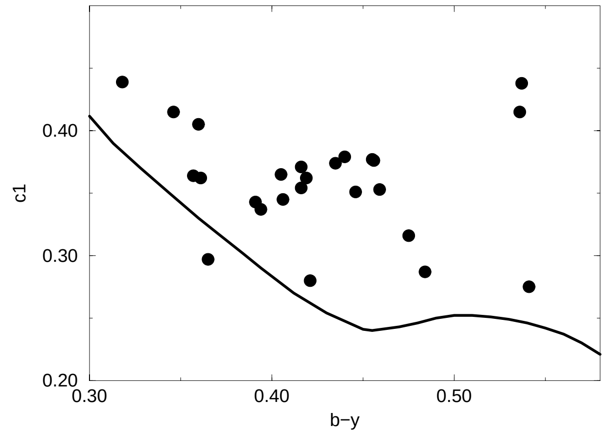

Fig. 2. The $(b-y)-c_1$ diagram for the stars with planets. Symbols and curve as in Fig. 1.

Table 1. *uvby* Photometry

HD	Name	b-y	m_1	c_1	δm_1	δc_1
75289		0.360	0.191	0.405	0.005	0.075
217014	51 Peg	0.416	0.233	0.371	0.002	0.105
187123		0.405	0.224	0.365	0.000	0.087
209458		0.361	0.174	0.362	0.023	0.033
9826	υ And	0.346	0.176	0.415	0.014	0.068
192263		0.541	0.493	0.275	−0.008	0.029
75732	55 Cnc	0.536	0.357	0.415	0.116	0.168
37124		0.421	0.202	0.280	0.040	0.018
130322		0.475	0.305	0.316	0.025	0.072
143761	ρ CrB	0.394	0.178	0.337	0.036	0.047
217107		0.456	0.299	0.376	−0.004	0.136
210277		0.459	0.298	0.353	0.002	0.112
186427	16 Cyg B	0.416	0.226	0.354	0.009	0.088
134987		0.435	0.256	0.374	0.006	0.123
17051		0.357	0.188	0.364	0.007	0.030
95128	47 UMa	0.391	0.202	0.343	0.010	0.049
145675	14 Her	0.537	0.366	0.438	0.110	0.191
195019		0.419	0.204	0.362	0.035	0.098
13445	GJ 86	0.484	0.337	0.287	0.012	0.039
120136	τ Boo	0.318	0.177	0.439	0.003	0.056
168443		0.455	0.233	0.377	0.060	0.137
222582		0.406	0.202	0.345	0.023	0.068
10697		0.440	0.238	0.379	0.031	0.132
117176	70 Vir	0.446	0.232	0.351	0.047	0.107
114762		0.365	0.125	0.297	0.074	−0.027

closer than 50 pc, no reddening was considered and observed photometric indices were adopted as intrinsic.

In Figs. 1 and 2, the location of stars with planets in the $(b-y)-m_1$ and $(b-y)-c_1$ diagrams, respectively, is shown. With a continuous line is indicated the standard calibration for dwarf stars given by Crawford (1975), in his Table I, for late F-type stars and the preliminary one by Olsen (1984) for G and K dwarfs, given in his Table VI. The position of the stars in Fig. 1 is found to be in good agreement with the calibration curves, from late F to early K stars. In fact, they are close to the Hyades reference curve, indicating small values of δm_1 and therefore relatively large metallicities, at least similar to the Sun. Only in the case of HD 114762, with the lowest m_1 index, a clear evidence of low metallicity is found.

The $(b-y)-c_1$ diagram, in Fig. 2, shows that the distribution of stars with planets corresponds, in average, to slightly more evolved regions than main sequence dwarfs in the sample by Olsen (1984). HD 114762 shows a small c_1, as expected for low metallicity stars. The relatively large values of c_1 for most of the stars should have not been unexpected if stars with planets need time to form them and get rid of their accretion disks. It is now well supported that the optical thickness of protoplanetary disks decreases as a function of time – see e.g. Spangler et al. (1999) – suggesting that searches for terrestrial planets should concentrate in older stars. This is moreover supported by observational evidences showing that stars with planets are slower rotators than average main sequence stars.

The differences in the m_1 and c_1 indices with respect to the adopted standard calibrations for all the stars with planets are given in Table 1. They are defined, as usual, by $\delta m_1 = m_1(std) - m_1(obs)$ and $\delta c_1 = c_1(obs) - c_1(std)$, where standard values are derived from the observed $(b-y)$ index using the Hyades reference curve. These differences contain the most interesting astrophysical information and will be used in Sect. 3. In the spectral region of our interest, $(b-y)$ is known to be an indicator of temperature, δm_1 denotes the abundance of metals, and δc_1 shows evolution up to a $(b-y)$ of approximately 0.5. It is worth mentioning also that the behaviour of the δm_1 parameter as a function of $(b-y)$ derived from Fig. 1 does not show the same trend observed by Giménez et al. (1991) for chromospherically active stars, indicating that they are relatively non-active and δm_1 can be safely used as a metal abundance indicator.

3. Astrophysical parameters

The calibration given by Saxner & Hammarbäck (1985), Sect. 4.4, as a function of $(b-y)$ and metallicity, was used to estimate the effective temperatures of late F and early G type

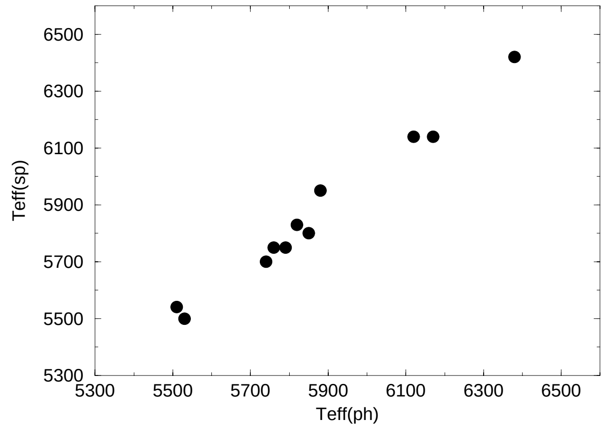

Fig. 3. Comparison between the effective temperatures determined by means of $uvby$ photometry (ph) and high-dispersion spectroscopy (sp).

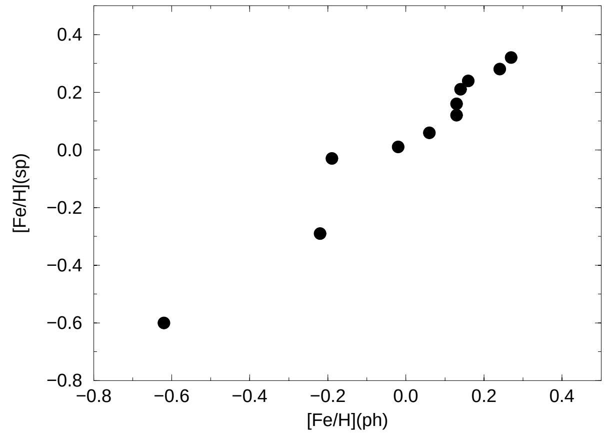

Fig. 4. Comparison between the metallicities derived by means of $uvby$ photometry (ph) and high-dispersion spectroscopy (sp).

dwarfs in our sample, with $(b-y) < 0.37$. For cooler stars, the calibration by Olsen (1984) was adopted, following Eq. (6) for $(b-y) < 0.51$ and Eq. (9) for larger values. The obtained temperatures, for stars in Table 1 are given in Table 2. It should be pointed out that the adopted calibrations are only valid for normal metallicities, approximately within the range -0.50 < [Fe/H] < 0.20 for Saxner & Hammarbäck (1985), and -0.83 < [Fe/H] < 0.39 for Olsen (1984). Most improvements in later calibrations have been made to extend their validity to Population II stars but no star in our sample has been found to have such large metal deficiencies.

As mentioned above, if no modification due to chromospheric activity is expected, the m_1 index should be a good indicator of metallicity in late-type stars. The calibration by Crawford (1975) was adopted for $(b-y) < 0.37$, as given in his Sect. VII, which is not correlated with δc_1. For later-type stars, the preliminary calibrations by Olsen (1984) were adopted according to his Eqs. (14) or (16) for $(b-y)$ smaller or, respectively, larger than 0.51. The resulting metallicities, expressed as $[Fe/H]$ with respect to the Sun, are also given in Table 2. Again, calibrations should be valid for stars in the solar neighborhood (Population I).

Concerning evolutionary status, the adopted calibrations are valid for dwarf stars and subgiants not far from the main sequence, but not for evolved subgiants and giants. In addition, no conclusion could be derived, either for temperatures or metallicities, for the two stars in our sample (55 Cnc and 14 Her) that show values of $\delta c_1 > 0.15$. In Table 2, the temperatures and metallicities derived from high-dispersion spectroscopy by González and collaborators are shown for comparison when available. The original determinations have been used instead of the slightly revised values in González (1999) in order to also have temperatures for comparison. Independent measurements of 51 Peg by Tomkin et al. (1997) show very good agreement with the results by González (1999).

The first thing to do is to check if the values derived from the photometry alone agree with the spectroscopic ones. This is certainly necessary given the preliminary nature of available calibrations of Strömgren photometry for G and K type stars, as well as the different possible approaches to the effective temperature determination. In Fig. 3 it is shown the comparison between the photometric effective temperatures and those obtained from the spectroscopy to fit atmosphere models for 11 stars in our sample. The correlation is certainly quite good and there are no systematic differences. If any, only HD 114762 presents a larger than average temperature difference which can be explained as due to its lower metallicity. The scatter of the

Table 2. Astrophysical Parameters

HD	Name	T_{ef} (ph)	[Fe/H] (ph)	T_{ef} (sp)	[Fe/H] (sp)
75289		6120	0.24	6140	0.28
217014	51 Peg	5760	0.14	5750	0.21
187123		5820	0.13	5830	0.16
209458		6060	0.02		
9826	υ And	6170	0.13	6140	0.12
192263		4840	0.11		
75732	55 Cnc			5250	0.45
37124		5590	−0.31		
130322		5340	−0.09		
143761	ρ CrB	5790	−0.22	5750	−0.29
217107		5560	0.25		
210277		5510	0.16	5540	0.24
186427	16 Cyg B	5740	0.06	5700	0.06
134987		5660	0.15		
17051		6130	0.22		
95128	47 UMa	5850	−0.02	5800	0.01
145675	14 Her			5300	0.50
195019		5690	−0.12		
13445	GJ 86	5280	−0.05		
120136	τ Boo	6380	0.27	6420	0.32
168443		6490	−0.23		
222582		5760	−0.08		
10697		5610	−0.03		
117176	70 Vir	5530	−0.19	5500	−0.03
114762		5880	−0.62	5950	−0.60

calibration curves shows uncertainties in the photometrically estimated temperatures of around 100 K.

Concerning metal abundances, the interagreement between the photometric values and those from the spectroscopy is also extremely good, as shown in Fig. 4. A small tendency nevertheless for smaller values derived from the photometric calibrations was detected. This discrepancy, of around 0.04 dex, though small, could indicate a problem in the determination of metallicities either from spectroscopy or photometry. The later is obviously responsible since it was also found a slight, but significant, correlation between the differences in metal abundance and δc_1, in the sense that the most discrepant values are also those with larger δc_1. In fact, the mentioned tendency disapears if the 3 stars with $\delta c_1 > 0.10$ are not used. The scatter in $[Fe/H]$ around the adopted calibrations is of the order of 0.15 dex.

For further check, we have used the temperature and metallicity (5597 K and +0.30) obtained by Randich et al. (1999) for HD 217107 in a recent spectroscopic survey of Pop I subgiant stars, and supported by Sadakane et al. (1999). A good agreement is found with the photometrically derived values as given in Table 2. The agreement in metallicity is even better if the photometric value is corrected for the mentioned difference of 0.04 that should be applied according to its δc_1. This star was not included in Figs. 3 and 4 to keep the comparison of the photometric results with a homogeneous sample of spectroscopic determinations. Moreover, for the best known solar analog, 18 Sco, with T_{eff} = 5790 K and $[Fe/H]$ = +0.05 according to Porto de Mello & da Silva (1997), we can use $uvby$ photometry ($b - y$ = 0.401, m_1 = 0.217, c_1 = 0.343) from Hauck & Mermilliod (1998) to estimate a temperature of 5800 K and a metallicity of +0.05, both in excellent agreement.

4. Conclusions

The overall general agreement between photometric and spectroscopic temperatures and metallicities allow for an extension of the sample of stars with planets having an estimation of their metal abundance. Though the two more metal-rich stars analyzed by González (1999) could not be studied with $uvby$ photometry, 12 new cases were added to the list, one of them (HD 217107) with external spectroscopic information. From these stars, four (HD 192263, HD 217107, HD 17051, and HD 134987) are found to be more metal abundant than the Sun. HD 192263 is a K-dwarf and calibrations are not yet well established because of the lack of enough high-resolution spectroscopic data. The 13 stars with spectroscopic measurements by González et al. give an average of $\langle [Fe/H] \rangle = +0.11 \pm 0.08$ (or $+0.17$ if the anomalous case of HD 114762 is not included), suggesting a tendency for metal-rich values. If we consider also the photometric information provided by the 12 additional cases (corrected for the δc_1 term when necessary), the average value becomes, $\langle [Fe/H] \rangle = +0.06 \pm 0.06$ (or $+0.09$ without HD 114762). Thus, the metal abundance of stars with planets is confirmed around the solar value, which is higher than normal when compared with other stars, as shown by Favata et al. (1997).

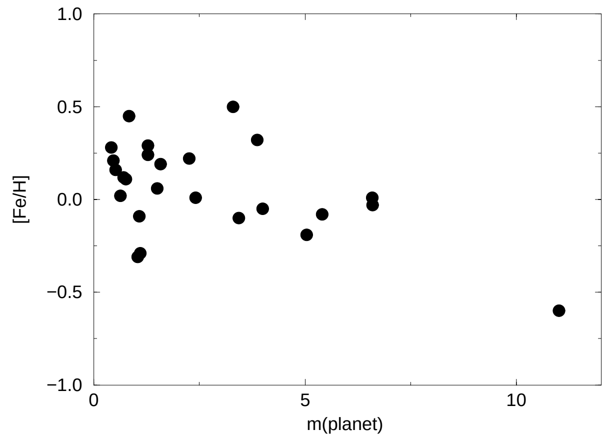

Fig. 5. Comparison of derived metallicities with the mass of the lightest planet of each star in units of Jupiter's mass.

Another interesting suggestion by González (1999) that, in stars with planets, metal abundance decreases with increasing mass of the planet is roughly seen in column 6 of Table 2, since masses for the lightest planet of each star were used to order entries in Tables 1 and 2. But they are minimum values only since no information about the orbital inclinations is available. Moreover, other physical parameters, for example distances between planet and central star, may have to be introduced.

In Fig. 5, the relation between metal abundances and the minimum mass of the planets is shown using not only stars with spectroscopic determinations but also the available photometric information. Little can be clearly seen in this figure other than the clustering of points around solar metallicity, essentially irrespective of the planet mass, and an isolated point denoting the lower metallicity star HD 114762 as an anomalous case. Fig. 5 thus supports the idea that HD 114762 may in fact be a different kind of object, a binary system with a brown dwarf rather than a star with a planetary companion. Anyhow, the sample is still too small to derive any definitive conclusion. This will certainly change in the near future when results from ongoing surveys allow for the study of a much larger number of stars with planets.

Summarizing, we have studied the application of standard $uvby$ Strömgren photometry to recently discovered late-type stars with giant planets. As a result, it has been found that effective temperatures and metallicities derived from $uvby$ photometry are in very good agreement with spectroscopic determinations. The conclusion is actually that the calibrations, essentially that by Olsen (1984), are good to predict effective temperatures and metallicities as derived from high-resolution spectra when the method used by González (1998) is adopted. This is a multiparametric determination of effective temperature, surface gravity, and depth-independent microturbulence parameter, using Kurucz (1993) model atmospheres, by means of Fe I and Fe II lines, and metallicity through a full array of absorption lines equivalent widths. A differential study with respect to the Sun is performed, which is valid for stars like those in the sample, avoiding many possible systematic errors. Olsen (1984) adopted the information provided by the catalogue of Cayrel de Strobel & Bentolila (1983) in his calibration thus assuming data derived from detailed high-resolution spectroscopic analyses. Other metallicity determinations have been obtained through the comparison with models adopting effective temperatures as derived from photometric information in the infrared – e.g. Favata et al. (1997), Laird et al. (1988) – and the adopted calibrations are expected to show systematic differences with respect to them.

Stars with planets were shown to be relatively evolved with respect to the ZAMS, or main sequence stars, and indications were found for the need of a small correction to the metallicity calibrations through δc_1. The enlarged sample of stars with metallicity determinations finally allows to confirm the larger average values for stars with planets than field stars with similar age and galactic location. The existence of a relation between metallicity and the planet mass is nevertheless still not established. This, if confirmed, might be due to the formation scenario or that we are dealing with different kind of objects.

The main interest of the present study is actually to open the possibility of using photometric data to derive effective temperatures and metallicities for a large sample of candidate stars. For the sample of 27 up to now known stars with planets, an increase from 13 to 25 stars with reliable determinations has been possible. We are presently carrying out a larger study of late-type stars in the G-K range in order to provide a more definitive calibration of $uvby$ photometry in terms of metal abundance than the currently adopted equations by Olsen (1984).

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