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The Top Ten solar analogs in the ELODIE library*

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Abstract. Several solar analogs have been identified in the library of high resolution stellar spectra taken with the echelle spectrograph ELODIE. A purely differential method has been used, based on the χ^2 comparison of a large number of G dwarf spectra to 8 spectra of the Sun, taken on the Moon and Ceres. HD 146233 keeps its status of closest ever solar twin (Porto de Mello & da Silva 1997). Some other spectroscopic analogs have never been studied before, while the two planet-host stars HD 095128 and HD 186427 are also part of the selection. The fundamental parameters found in the literature for these stars show a surprising dispersion, partly due to the uncertainties which affect them. We discuss the advantages and drawbacks of photometric and spectroscopic methods to search for solar analogs and conclude that they have to be used jointly to find real solar twins.

Key words. stars: fundamental parameters – Sun: fundamental parameters

1. Introduction

The Sun is the best-known star: its fundamental parameters (radius, mass, age, luminosity, effective temperature, chemical composition) are known with a good accuracy, as well as its internal structure, activity, velocity field and magnetic field. Consequently the Sun is used as the fundamental standard in many astronomical calibrations. One of the motivations to identify stars that replicate the solar astrophysical properties is the necessity to have other reference stars, observable during the night under the same conditions as any other target. The pioneers of the subject (Hardorp 1978; Cayrel de Strobel et al. 1981) were also involved in resolving the problem of the photometric indexes of the Sun, inherent to the impossibility to observe it as a point-like source. In the last decade the motivation of finding such stars has been increased by an exciting challenge: the search for planetary systems that could harbour life. Solar analogs are straightforward targets for this hunt.

The first searches of solar analogs were performed by photometric and spectrophotometric techniques. Hardorp (1978) compared UV spectral energy distributions of nearly 80 G dwarfs to that of the Sun and found 4 stars that had a UV spectrum indistinguishable from solar: HD 028099 (Hy VB 64), HD 044594, HD 186427 (16 Cyg B), HD 191854. Neckel (1986) established a list of bright stars with *UBV*-colours close to those of the Sun and confirmed the photometric resemblance of Hy VB 64 and 16 Cyg B to the Sun. With the advance of techniques in high resolution spectroscopy and solid state detectors, and with the progress in modelling stellar atmospheres, measurements of ($T_{\rm eff}$, $\log g$, [Fe/H]) became of higher precision allowing the search for solar analogs by comparing their atmospheric parameters to those of the Sun. G. Cayrel de Strobel made a huge contribution to the subject with the detailed analysis of many candidates (Cayrel de Strobel et al. 1981; Cayrel de Strobel & Bentolila 1989; Friel et al. 1993) and a review of the status of the art (Cayrel de Strobel 1996). She also introduced the concepts of solar twin, solar analog and solar-like star. Porto de Mello & da Silva (1997) presented the star HD 146233 (18 Sco) with physical properties extremely close to those of the Sun, as the "closest ever solar twin".

A workshop on Solar Analogs was held in 1997 at the Lowell Observatory to provide a solid basis to the hunt of solar analogs. After many discussions on the performances of different methods, a list of the best candidates was established, in which 4 stars received the agreement of almost all participants: HD 217014 (51 Peg), HD 146233 (18 Sco), HD 186408 (16 Cyg A), HD 186427 (16 Cyg B).

In this paper, we take advantage of a large and homogeneous dataset of high resolution echelle spectra which are compared directly to solar spectra, independently of any model or photometric measurements. The eye is replaced by a more reliable criterion, approximatively the reduced χ^2, computed over ~32 000 resolution elements. This purely differential method allowed us to identify several stars whose optical spectrum looks closely like the Sun's, the best one being HD 146233.

We describe in Sect. 2 our observational material and differential method, and we give the list of our Top Ten solar analogs.

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* Based on observations made at the Observatoire de Haute-Provence (France).

We have searched the literature for their colour indexes and atmospheric parameters and calculated absolute magnitudes from Hipparcos parallaxes. We discuss the uncertainties which affect these data and compare them to that of the Sun (Sect. 3). In Sect. 4, we examine qualitatively their Li content and give information on their activity and age. In Sect. 5 we discuss several stars, having similar colours and absolute magnitude or similar atmospheric parameters as the Sun but slightly different spectra.

2. ELODIE spectra and the TGMET code

All the spectra used in this paper were extracted from the library of stellar spectra collected with the echelle spectrograph ELODIE at the Observatoire de Haute-Provence by Soubiran et al. (1998) and Prugniel & Soubiran (2001). The performances of the instrument mounted on the 193 cm telescope, are described in Baranne et al. (1996). ELODIE is a very stable instrument, built to monitor radial velocity oscillations of stars with exoplanets, at a resolving power of 42 000 in the wavelength range 3850–6800 Å. The stability of the system makes it possible to compare spectra taken at different epochs. Spectrum extraction, wavelength calibration and radial velocity measurement by cross-correlation have been performed at the telescope with the on-line data reduction software.

The current version of the Elodie library includes 1962 spectra available in the Hypercat database[1], most of the spectra having a signal to noise ration (S/N) at 550 nm greater than 100. We have selected 208 spectra of G dwarfs with the following criteria: $0.55 < B-V < 0.75$ ($(B-V)_{\odot} \simeq 0.65$) and $4 < M_V < 5.6$ ($M_{V\odot} \simeq 4.82$). Absolute magnitudes have been computed from Hipparcos parallaxes, the selected stars having relative errors smaller than 10%. The list includes 8 spectra of the Sun (Table 1).

The stellar spectra were compared to solar ones with the TGMET code developed by Katz et al. (1998). TGMET is a minimum distance method which measures similarities between spectra in a quantitative way. The TGMET comparison between 2 spectra includes the following steps:

- straightening of each order;
- removal of bad pixels, cosmic hits and telluric lines;
- wavelength adjustment;
- mean flux adjustment by weighted least squares, order by order.

The wavelength adjustment shifts the comparison spectrum to the radial velocity of the solar spectrum and resamples it to the same wavelenghts. It implies an interpolation between wavelengths which is performed with the quadratic Bessel formula. The flux fitting of the comparison spectrum to the solar spectrum assumes that the 2 spectra differ by a simple factor (the 2 stars having roughly the same temperature it is not necessary to introduce a slope). Once the two spectra have been put on a common scale, a distance between them can then be computed. As explained in Katz et al. (1998), instead of adopting the real reduced χ^2 of the fit as the distance between 2 spectra, which would imply taking into account the noise on each pixel, the response curve was chosen as the weighting function. This distance was adopted after many tests and was proven to produce the most satisfactory results, especially at high S/N. Its advantage is that it gives a similar weight to the continuum and to the wings and bottom of absorption lines, contrary to a weighting function based on the photon noise.

[1] www-obs.univ-lyon1.fr/hypercat/11/spectrophotometry.html

Table 1. List of the solar spectra used in this study.

Hypercat number	Date of observation	Object	*FWHM* km s^{-1}	S/N at 550 nm
00903	14/01/1998	Moon	11.061	381.4
00904	22/12/1999	Moon	11.050	268.5
00905	22/12/1999	Moon	11.050	139.6
00906	22/12/1999	Moon	11.061	156.5
00907	27/03/2000	Ceres	11.017	117.5
00908	24/01/2000	Moon	11.057	200.0
00909	24/01/2000	Moon	11.054	224.9
01964	22/08/2000	Moon	12.126	404.3

Katz et al.'s algorithm includes a convolution step which is not included in the present work. A convolution should be performed in order to put the 2 compared spectra at exactly the same resolution. A difference in resolution between two spectra is the result either of a variation of the instrumental resolution between the two exposures or of intrinsic physical properties of the observed stars like rotation, macroturbulence or binarity which enlarge their spectral profile. But as we are looking for solar twins, these intrinsic properties are important in the criterion of similarity and should not be erased. Moreover ELODIE is a very stable instrument and its resolution does not vary significantly with time. It can be seen in Table 1 that all of our solar spectra have a resolution of 11 km s^{-1} (*FWHM*), except the spectrum 01964 which is sligthly degraded (12 km s^{-1}). These considerations led us to supress the convolution step in the TGMET algorithm.

In practice we have limited the comparison to the wavelength range 4400–6800 Å (orders 21 to 67) and eliminated the under-illuminated edges of the orders. Finally distances between spectra have been computed over nearly 32 000 wavelengths. Table 2 gives an example of the TGMET output, for solar spectra 00903 (S/N = 381.4) and 00907 (S/N = 117.5). The output in the two cases is consistent, with however some differences: HD 088072 is within the 20 closest neigbours of 00903 but not of 00907, the opposite is the case for HD 071148 and HD 042618. These differences, probably related to observing conditions, are smoothed when combining the TGMET results obtained for the 8 solar spectra, the combination being performed by averaging the distances, order by order, giving a different weight to several orders (see below). The score obtained by each solar analog was our criterion of closeness to the Sun, leading the final Top Ten list: HD 146233, HD 168009, HD 010307, HD 089269,

Table 2. The 20 closest spectra of the solar spectra 00903 and 00907, deduced by the TGMET code.

No.	Star	S/N	Distance	No.	Star	S/N	Distance
	00903				00907		
01964	Sun	404.3	2.220	00903	Sun	381.4	1.158
00909	Sun	224.9	2.332	00909	Sun	224.9	1.175
00908	Sun	200.0	2.410	01964	Sun	404.3	1.183
00490	HD 146233	236.8	2.789	00908	Sun	200.0	1.188
00906	Sun	156.5	2.910	00490	HD 146233	236.8	1.243
00905	Sun	139.6	3.110	00906	Sun	156.5	1.250
01633	HD 168009	204.9	3.305	00905	Sun	139.6	1.275
00904	Sun	268.5	3.392	01633	HD 168009	204.9	1.329
00907	Sun	117.5	3.474	00904	Sun	268.5	1.382
01187	HD 047309	119.7	3.841	00039	HD 010307	198.4	1.457
01188	HD 047309	108.8	3.864	01634	HD 168009	134.6	1.458
01634	HD 168009	134.6	3.875	01187	HD 047309	119.7	1.471
00039	HD 010307	198.4	3.937	00346	HD 071148	117.0	1.472
00895	HD 089269	225.9	3.978	00895	HD 089269	225.9	1.478
00258	HD 047309	100.9	4.176	01188	HD 047309	108.8	1.493
00387	HD 088072	86.5	4.236	00400	HD 095128	181.9	1.555
00699	HD 186427	139.9	4.283	00258	HD 047309	100.9	1.557
00400	HD 095128	181.9	4.336	00981	HD 010307	162.9	1.560
00981	HD 010307	162.9	4.342	01125	HD 042618	132.5	1.591
00038	HD 010145	153.2	4.346	00699	HD 186427	139.9	1.594

HD 047309, HD 095128, HD 042618, HD 071148, HD 186427, HD 010145.

Figure 1 shows the fit of HD 146233 to spectrum 00903, for order 39 including the MgI triplet and order 64 including the H_α line. For order 39, the fit has been performed on 773 points; the mean difference between the solar flux and the fitted fluxes of HD 146233 is 3 electrons with a standard deviation of 1157 electrons, corresponding to 1% of the mean flux (108 772 electrons). For order 64, the difference is also 1% (743 points, mean difference of −57 electrons, standard deviation of 2166 electrons, mean flux of 210 319 electrons).

Figure 2 shows for the Top Ten solar analogs their distance to the solar spectrum 00903, order by order. It is very clear from Fig. 2 that HD 146233 is very similar to the Sun and that HD 168009 is not very far behind. The closeness of these 2 stars is confirmed for the 7 other solar spectra. The largest discrepancies occur for order 63 (648–652.5 nm). The examination of this order indicates that it is polluted by telluric lines which were not completely removed. Telluric lines unfortunatly affect also order 64 which is our best indicator of temperature thanks to the H_α line. The dispersion obtained on order 64 is much higher than that on order 31 which includes the H_β line. However, the H_β line being at the edge of the order it has a lower weight in the fit because of under-illumination. A large dispersion on order 39, which includes strong features due to the MgI triplet, is also seen for each solar spectrum. This region is known to be very sensitive to the 3 atmospheric parameters ($T_{\rm eff}$, $\log g$, [Fe/H]) and consequently powerful for discriminating solar twins. These considerations led us to adopt a higher weight of 3 on order 39, a half weight on order 64 and a null weight on order 63 when combining the information on all the orders.

3. Atmospheric parameters and photometry

We report in this section colour indexes available in the literature for our Top Ten solar analogs and visual absolute magnitudes deduced from their Hipparcos parallaxes (Table 4). We also review recent determinations of their atmospheric parameters. These data are compared to those of the Sun, and uncertainties which affect them are discussed. Finally we report their occurrence in previous studies of solar analogs.

The $B-V$ and $U-B$ colours come from the General Catalogue of Photometric Data (Mermilliod et al. 1997), except for HD 047309 for which we have taken the $B-V$ colour from Tycho2 (Høg et al. 2000) transformed to the Johnson system. The $b-y$ colours are extracted from the catalogue by Hauck & Mermilliod (1998).

The photometry of the Sun is a matter of debate. Neckel (1986) has determined $(B-V)_\odot = 0.650 \pm 0.005$, $(U-B)_\odot = 0.195 \pm 0.005$, $M_{V\odot} = 4.82 \pm 0.025$, values which are adopted as basic solar data in Allen's Astrophysical Quantities (Cox 2000). Cayrel de Strobel (1996) gives a compilation of solar $(B-V)$ colours measured by different techniques and

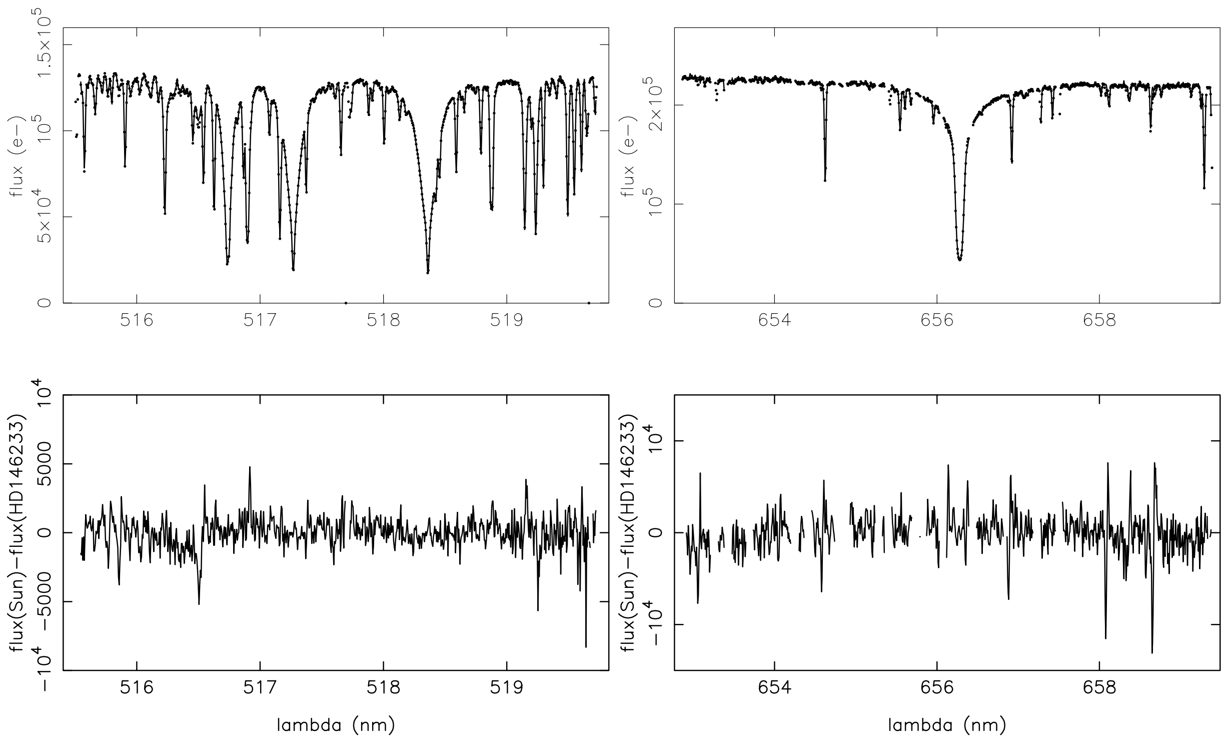

Fig. 1. Comparison of one of the solar spectra (dots) with HD 146233 (continuous line) in the spectral region of the MgI triplet and H_α line.

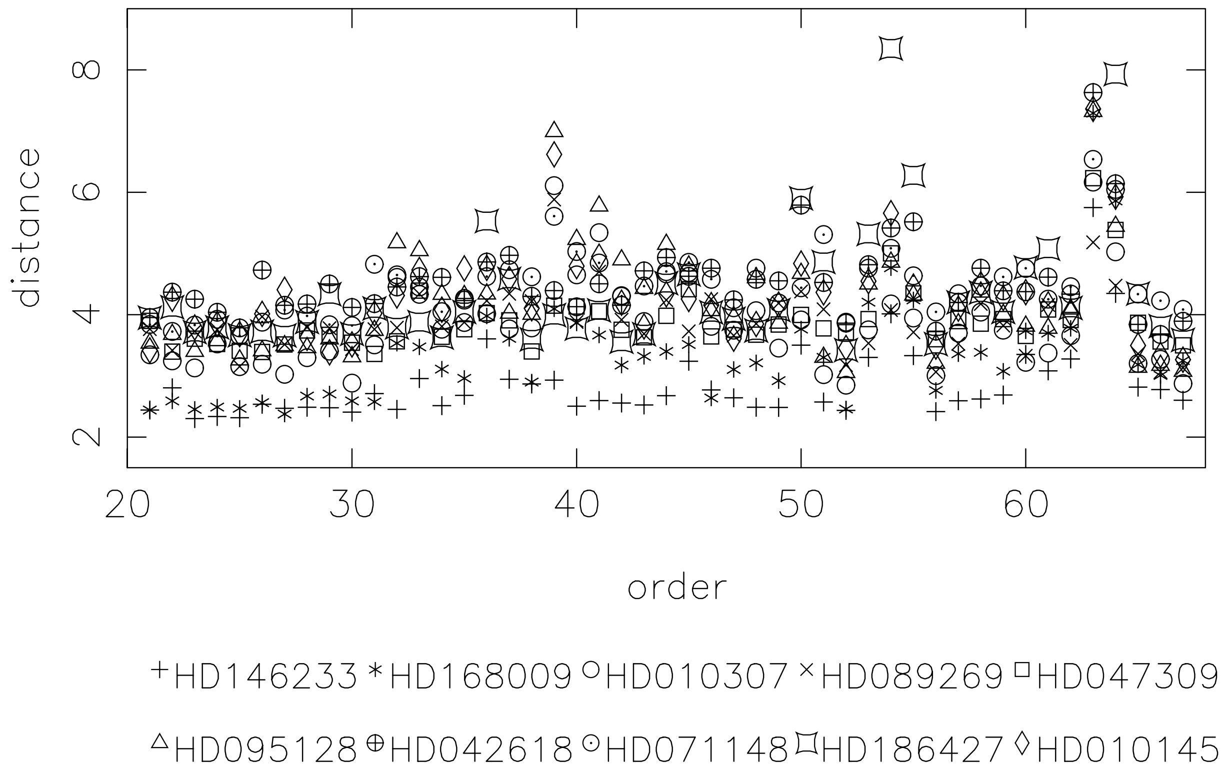

Fig. 2. Distance of the Top Ten solar analogs to solar spectrum 00903, order by order.

determines from the relations colour vs. $T_{\rm eff}$: $(B-V)_\odot = 0.642 \pm 0.004$, $(b-y)_\odot = 0.404 \pm 0.005$. Porto de Mello & da Silva (1997) obtain with a similar method: $(B-V)_\odot = 0.648 \pm 0.006$, $(U-B)_\odot = 0.178 \pm 0.013$. We list in Table 4 a reasonable range of values for the Sun's colours and absolute magnitudes.

3.1. HD 146233

HD 146233 (18 Sco) was adopted at the Solar Analogs workshop at Lowell Observatory as one of the best solar twins. Our study confirms with independent data and methods the result of Porto de Mello & da Silva (1997) quoting HD 146233 as THE closest ever solar twin. In the optical range, its spectrum is indistinguishable from that of the Sun (Fig. 1). Before that, Hardorp (1978) using UV spectrophotometry mentioned this star as a solar analog but with the comment "spectrum similar to solar, some absorption features weaker". However, this study was based on a single low-resolution spectrum. This discrepancy is discussed by Porto de Mello & da Silva (1997) and by Cayrel de Strobel (1996).

Only 2 determinations of atmospheric parameters are available for this star, in very good agreement, giving solar values within the error bars. HD 146233 seems to be more luminous than the Sun by 0.05 mag. Its parallax is very accurate (π = 71.30 ± 0.89 mas), but one may legitimely wonder if its photometry is sufficiently accurate to consider this excess of luminosity real. As a matter of fact HD 146233 is part of the Catalogue of suspected variables by Kukarkin et al. (1981) who found a possible amplitude of 0.11 mag. V magnitudes, measured by several authors between 1957 and 1978 and available in the GCPD (Mermilliod et al. 1997), range effectively between V = 5.48 and V = 5.56. The average V = 5.504 ± 0.015 was used to compute an absolute magnitude of M_V = 4.77. Thus if HD 146233 is slightly variable, a higher luminosity than the Sun cannot be clearly established. But more recently HD 146233 was identified by Adelman (2001) to be part of the 681 most photometrically stable stars during the 5 years of the Hipparcos mission, with an amplitude of 0.01 mag. Its median magnitude in the Hipparcos system is $H_{\rm p}$ = 5.6265 ± 0.0005. According to the photometric transformation calibrated by Harmanec (1998), the corresponding apparent visual magnitude is V = 5.493 ± 0.003 which confirms its higher luminosity.

3.2. HD 168009

HD 168009 has been quite well studied but has never been mentioned as a good solar analog, despite its being part of the list of "bright stars with UBV-colours close to those of the Sun" established by Neckel (1986). According to its spectroscopic gravity and absolute magnitude, HD 168009 is more luminous than the Sun. Its absolute magnitude M_V = 4.52 is quite reliable and relies on a parallax of π = 44.08 ± 0.51 mas. Several estimations of its apparent visual magnitude are in good agreement: V = 6.295 according to the GCPD, V = 6.309 according to Simbad, V = 6.307 according to Tycho2. Its $B-V$ colour index is slightly more uncertain: $B-V$ = 0.635 according to the GCPD, $B-V$ = 0.604 according to Simbad, $B-V$ = 0.646 according to Tycho2, but suggests however a higher temperature than the Sun. This is confirmed by several recent estimates of $T_{\rm eff}$ available in the literature and spanning values from 5719 K (Chen et al. 2000) to 5833 K (Blackwell & Lynas-Gray 1998) with a mean value of 5801 K. This large dispersion is a good illustration of the lack of a common temperature scale, even for bright nearby stars. HD 168009 is also part of a catalogue of high precision near infrared photometry by Kidger & Martin-Luis (2003) who give J = 5.133, H = 4.840, K = 4.783, values which differ by less than 0.005 mag from those measured by Alonso et al. (1998). A colour index $V-K$ = 1.512 leads to $T_{\rm eff}$ = 5730 K with the relation established by Alonso et al. (1996b).

The abundance of several elements (O, Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Ni, Ba) have been measured by Chen et al. (2000) to be solar within the error bars. Ba, Eu and Sr abundances have also been measured by Mashonkina & Gehren (2001), leading to the same conclusion.

3.3. HD 010307

Like HD 168009, HD 010307 seems to be hotter and more luminous than the Sun. Allende Prieto et al. (1999) quote a mass of 0.94 $M_\odot$ and an astrometric gravity of $\log g$ = 4.29, in very good agreement with the averaged spectroscopic gravity of $\log g$ = 4.26 quoted in Table 4. HD 010307 is in fact a binary system which was resolved by Henry et al. (1992), the low mass companion being 1000 times fainter. According to a detailed analysis of Hipparcos data by Martin et al. (1998) the system has a total mass of (0.931 ± 0.178) $M_\odot$, a primary mass of (0.795 ± 0.159) $M_\odot$ and a secondary mass of (0.136 ± 0.053) $M_\odot$. At a distance of 12.6 pc (12.4 pc when the binarity is considered), it is the nearest of our Top Ten solar analogs. It is a well studied star with many measurements in good agreement of its apparent visual magnitude and $B-V$ colour, and it is part of the catalogue of the least variable stars compiled by Adelman (2001) despite its binarity. We notice that the temperature given by Chen et al. is similar to that of the Sun but significantly lower than given by other authors, as was also the case for HD 168009. Hardorp (1978) mentioned HD 010307 with the comment "some aborption features appreciably weaker than solar" which is in agreement with a higher temperature.

Cayrel de Strobel (1996) and Fesenko (1994) have included HD 010307 in their list of solar analogs but not with a high rank. It was only mentioned to "deserve study" in the conclusions of the Lowell Workshop.

3.4. HD 089269

Very few papers mentioning HD 089269 are available in the literature. It was never recorded as a solar analog despite its colour index $B-V$ = 0.654 being similar to that of the Sun. Its visual magnitude V = 6.633 combined to its trigonometric parallax π = 48.45 ± 0.85 mas leads to an absolute magnitude M_V = 5.06 indicating that it is less massive than the Sun. Mishenina et al. (2004) find it 100 K colder than the Sun and significantly more metal poor. The good score obtained with TGMET indicates that, globally, the combined effects of temperature and iron abundance may give similar absorption features as in the Sun.

3.5. HD 047309

HD 047309 is unknown as a solar analog. The only data are Strömgren photometry, and data from Hipparcos and Tycho2.

Contrary to HD 089269, it seems to be slightly hotter, more luminous and metal-rich. It is also the most distant of our sample at 42.4 pc.

3.6. HD 095128

We come back to well a known star with HD 095128 (47 UMa) known to have two giant planets orbiting around it. Consequently it has been very well studied. Its temperature is significantly higher than that of the Sun. Again the temperature given by Chen et al. is the lowest of the list with 5731 K whereas Santos et al. (2003) find the highest temperature, with 5925 K. The 2 colour indexes $B - V = 0.606$ and $b - y = 0.391$ confirm a higher temperature than the Sun. Despite the large dispersion in $T_{\rm eff}$, the dispersion in [Fe/H] is low, with an average exactly solar. HD 095128 is more luminous than the Sun. Allende Prieto et al. (1999) quote a mass of 0.96 $M_{\odot}$ and an astrometric gravity of $\log g = 4.23$, in good agreement with the averaged spectroscopic gravity of $\log g = 4.28$ quoted in Table 4. It shows that HD 095128 has already evolved from the main sequence.

3.7. HD 042618

The only mention of HD 042618 is by Fesenko (1994) in his solar type star study. The 2 available estimates of its temperature differ by 120 K, but $B - V = 0.632$ suggests that the hottest one, 5775 K, is the most likely. The cold temperature scale adopted by Reddy et al. (2002) implies a low metallicity of [Fe/H] = −0.16, which might be closer to the solar one in fact. It is not very clear however, because its absolute magnitude $M_V = 5.05$ combined with a solar temperature would not be compatible with being on the solar composition ZAMS.

3.8. HD 071148

Like HD 042618, HD 071148 was recorded by Fesenko (1994) but did not receive much attention as a solar analog. Its effective temperature is subject to a controversy between partisans of a low temperature scale (Reddy et al. 2002; Chen et al. 2003) giving a temperature of about 5710 K and Mishenina et al. (2004) giving a temperature 140 K higher. Again we find that the colour indexes indicate that this star is probably slightly hotter than the Sun. The 3 authors agree on the fact that its metallicity is nearly solar.

Interestingly, the radial velocity of HD 071148 has been monitored during several years by Naef et al. (2003) who found that it is constant within 10 m s^{-1}, ruling out the presence of a low mass companion.

3.9. HD 186427

HD 186427 (16 Cyg B) is one of the best solar twin candidates of the Lowell Fall Workshop and also a planet-host star. Its UV spectrum was qualified as "indistinguishable from solar" by Hardorp (1978), a similarity confirmed by Fernley et al. (1996). There is a remarkable agreement between the 10 authors who have estimated its temperature, colder than the Sun by only ~20 K. Only Laws & Gonzalez (2001) and Gonzalez (1998) used a significantly lower temperature scale. HD 186427 differs from the Sun mainly by its higher metal content, and by a higher luminosity.

3.10. HD 010145

HD 010145 has never been mentioned as a solar analog and was little studied before. The recent spectroscopic analysis performed by Mishenina et al. (2004) shows that it is colder than the Sun by 100 K, but with a similar gravity and metal content. It is the coldest of our Top Ten together with HD 089269, the latter one having bluer colour index consistent with its lower metallicity. HD 010145 has a lower luminosity than the Sun, indicating either a lower age or a lower mass.

4. Li content, activity, ages

In this section we compare qualitatively the Li content of our Top Ten solar analogs with that of the Sun. The solar photosphere is known to be highly depleted in Li, as is the case for many solar type stars. This depletion is however subject to various interpretations, involving rotation, convection, or the presence of a planetary system. The correlation of age with Li depletion has also been often discussed but not fully established.

The ^{7}Li doublet resonance lines at 670.78 nm and 670.79 nm are well placed in the middle of the 66th order of the ELODIE spectra. In Fig. 3, for each of our Top Ten, the Li region was superposed on the solar spectrum, showing that 6 of them are depleted in Li like the Sun whereas the 4 others show a pronounced Li feature. The most pronounced feature concerns HD 071148 and HD 010307. A weaker feature is also present in the spectra of HD 095128 and HD 146233.

More clearly than the Li content, the chromospheric activity of a solar type star is directly connected to its age. Thus it would have been extremely interesting to look at the chromospheric activity revealed by the central depth of the Ca II H and K lines, and of the Ca II triplet lines at 852 nm. Unfortunatly the NIR Ca II triplet is not in the spectral range of ELODIE and the H and K lines appear on the border of the 2nd and 3rd orders which are underilluminated. The core of the H_{α} line is also an indicator of chromospheric activity, but we were not able to detect any significant difference of depth, even for the 4 stars having a higher Li content. According to Soderblom (1985), HD 071148, HD 010307 and HD 095128 show CaII emission strengths and rotation similar to the Sun, suggesting a weak activity. Hall & Lockwood (2000) found an activity cycle in HD 146233 with an amplitude slightly greater than that of the Sun. Thus these 4 stars presenting a pronounced Li feature do not seem to be enormously more active than the Sun. Two other analogs are part of Soderblom's study, HD 010145 and HD 168009; they do not exhibit evidence of a higher activity than the Sun.

Several of our Top Ten had their age estimated by Ibukiyama & Arimoto (2002): 7.02 Gyr for HD 168009, 7.32 Gyr for HD 010307, 6.92 Gyr for HD 095128, 6.65 Gyr for HD 071148. According to Cayrel de Strobel & Friel (1998),

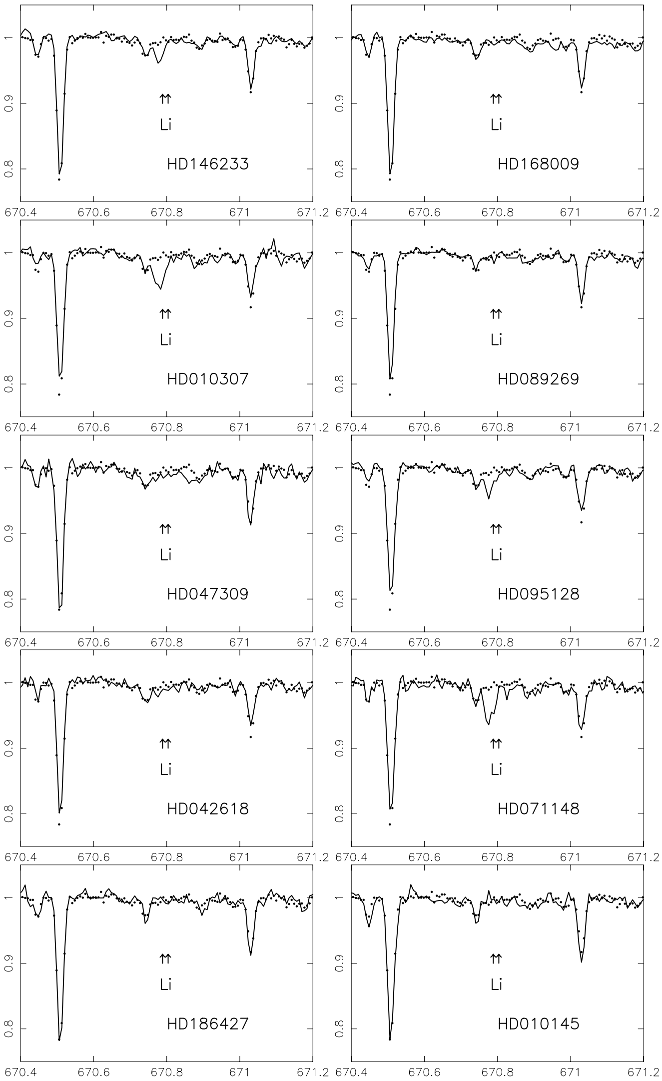

Fig. 3. Comparison between the Li I 670.7 nm region of the Sun (spectrum 00903, dotted line) and of each Top Ten solar analog.

HD 146233 has an age of 6 Gyr. Thus one can find stars older than the Sun which have a higher Li content.

5. Solar analogs selected by other methods

The ELODIE library includes the spectra of several stars which were considered in previous studies as high rank solar analogs. We will focus here on HD 217014 (51 Peg), HD 028099 (Hy VB 64) and HD 186408 (16 Cyg A).

With our purely differential method HD 186408 is within the 20 best solar analogs among our list of 208 dwarfs. A dozen recent determinations of its atmospheric parameters are available and give on average $T_{\rm eff}$ = 5780 K, $\log g$ = 4.26, [Fe/H] = +0.07. Its visual absolute magnitude is M_V = 4.29, to be compared to M_V = 4.56 for its companion HD 186427 and $M_{V\odot}$ = 4.82 showing that HD 186408 is more massive and evolved.

HD 217014 and HD 028099 obtained a lower score in the TGMET output despite their similar effective temperature and gravity to the Sun. These 2 stars have also been very much studied, especially HD 217014 because of its planet. The latest determination of its atmospheric parameters led to $T_{\rm eff}$ = 5805 K, $\log g$ = 4.51, [Fe/H] = +0.21 (Santos et al. 2003). Thus stronger metallic lines explain that it is not a good spectroscopic analog of the Sun. HD 028099 was found to have $T_{\rm eff}$ = 5800 K, $\log g$ = 4.40, [Fe/H] = +0.10 by Paulson et al. (2003). This star is not considerably more metal rich than the Sun, but it is known to be younger and to have a high chromospheric activity. Looking closely at its spectrum shows that its lines are not as deep as those in the solar spectrum.

We have also searched for photometric solar analogs in the ELODIE library by selecting stars having the same colours and absolute magnitude as the Sun. Four stars fall in the narrow range $4.6 < M_V < 5.0, 0.63 < B-V < 0.68, 0.16 < U-B < 0.23, 0.40 < b-y < 0.42$: HD 001835 (BE Cet), HD 076151, HD 146233, HD 159222. HD 076151 in not in our Top Ten but it is at the 14th position. It is a well studied star, with recent determinations of its atmospheric parameters in good agreement, giving on average $T_{\rm eff}$ = 5774 K, $\log g$ = 4.39, [Fe/H] = +0.06. It was also one of the good solar twin candidates discussed by Cayrel de Strobel (1996). However, this star is younger than the Sun (3.04 Gyr estimated by Ibukiyama & Arimoto 2002), with a stronger activity and faster rotation (Pizzolato et al. 2003) and presents a pronounced Li feature. In combination with a higher metal abundance, this may explain why it was not at higher rank in the TGMET output. HD 001835 is a variable star of the BY Dra type which renders its photometry suspect. It was also discussed by Cayrel de Strobel (1996) as a good solar analog for the temperature and gravity but not for Li, chromospheric activity and age. Its young age is assessed by its membership of the Hyades moving group and its high activity is confirmed by Pizzolato et al. (2003). It is also more metal-rich than the Sun ([Fe/H] = +0.13 estimated by Mishenina et al. 2004) and its distance to the solar spectra computed by TGMET is very large. Its activity is clearly seen in its H_α line, which is shallower than in the Sun. HD 159222 the 11th star in the TGMET output. It is thus a good photometric and spectroscopic solar analog. Moreover its age is also very similar (4.56 Gyr estimated by Ibukiyama & Arimoto 2002). Several determinations of $T_{\rm eff}$ are available for this star, showing an impressive dispersion: 5708 K by Blackwell & Lynas-Gray (1998), 5770 K by Alonso et al. (1996a), 5834 K by Mishenina et al. (2004), 5852 K by di Benedetto (1998).

We have also observed that many spectra were polluted by telluric lines in the red orders, and that order 39 including the MgI triplet was a powerful discriminator of solar resemblance. We have thus performed the TGMET comparison of the 8 solar spectra with the library using only this order. This has greatly modified the order of our list, HD 146233 keeping however its highest rank. The five closest stars are part of the Top Ten list: HD 146233, HD 047309, HD 168009, HD 042618 and HD 186427. The 4 stars of the Top Ten list with the lowest temperatures (HD 010145 and HD 089269) and the highest temperatures (HD 010307 and HD 095128) are pushed away. Five new stars appear in the 10 closest solar analogs: HD 195034, HD 159222 (also a good photometric analog), HD 187123, HD 186104, HD 005294. The photometric analog HD 076151 is at the 11th position.

Table 3. Fondamental data for solar analogs mentioned in Sect. 5. Only the most recent determination of atmospheric parameters is listed. The second column indicates how the star was selected as a solar analog (P: photometry, L: Lowell workshop, Mg: TGMET on the Mg I triplet region).

Star name	Method	$B-V$	$b-y$	$U-B$	M_V	$T_{\rm eff}$	log g	[Fe/H]	Source
HD 186408	L	0.645	0.410	0.187	4.29	5803	4.20	+0.02	Mishenina et al. (2004)
HD 217014	L	0.665	0.416	0.224	4.53	5805	4.51	+0.21	Santos et al. (2003)
HD 028099	L	0.660	0.411		4.75	5800	4.40	+0.10	Paulson et al. (2003)
HD 076151	P	0.662	0.413	0.217	4.83	5776	4.40	+0.05	Mishenina et al. (2004)
HD 001835	P	0.659	0.409	0.226	4.84	5790	4.50	+0.13	Mishenina et al. (2004)
HD 005294	Mg	0.650	0.401	0.174	5.03	5779	4.10	-0.17	Mishenina et al. (2004)
HD 159222	P+Mg	0.637	0.406	0.172	4.67	5834	4.30	+0.06	Mishenina et al. (2004)
HD 186104	Mg	0.631	0.412		4.62	5753	4.20	+0.05	Mishenina et al. (2004)
HD 187123	Mg	0.619	0.405		4.43	5855	4.48	+0.14	Santos et al. (2003)
HD 195034	Mg	0.610	0.408		4.84				

The parameters of the solar analogs discussed in this section are listed in Table 3. All of them, except HD 005294, are more metal-rich than the Sun.

6. Discussion

It is interesting to note that, despite the great similitude of the optical spectrum of our Top Ten solar analogs to that of the Sun, their atmospheric parameters can differ significantly. Effective temperatures span ±100 K on both sides of the solar value, log g values span the interval [4.09; 4.58] and [Fe/H] span the interval [−0.23; +0.11]. Several interpretations can explain this dispersion. On the one hand, authors do not use the same temperature scale and model atmospheres. Temperature scales can differ by more than 150 K as we have seen. It is very important that authors agree on temperatures because this parameter has a strong impact on abundance determinations. Uncertainties which affect the stellar parameter determinations have been discussed by Asplund (2003) to be of the order of 50 K to 100 K in $T_{\rm eff}$, 0.2 dex for log g and 0.1 dex for [Fe/H]. On the other hand, we cannot expect finding a perfect twin having all its parameters exactly solar, especially in an incomplete sample. Finally, temperature and metallicity have contrary effects on the overall spectrum which may compensate in some cases (ex. HD 089269 or HD 187123). It is also possible that other effects act on the spectra. Observing conditions and telluric lines are the most obvious, but intrinsic stellar properties also have an influence on the spectrum. We have mentioned chromospheric activity and rotation, but the abundance of other elements than iron, turbulent motions, spots on the stellar surface may be different than in the Sun. For instance, when using TGMET only in the MgI triplet region, the Mg abundance of the star may have a strong weight.

Colour indexes of the Top Ten solar analogs also span intervals as large as 0.073 in $B-V$, 0.032 in $b-y$, 0.099 in $U-B$, and absolute magnitudes range from $M_v = 4.31$ to $M_v = 5.06$. Figure 4 represents their distribution in $T_{\rm eff}$ vs. colour and HR diagrams together with the other analogs discussed in Sect. 5 and the rest of the ELODIE library, restricted to $-0.25 <$ [Fe/H] $< +0.15$. The Strömgren index $b-y$ is clearly the one which presents the lowest dispersion in its relation with $T_{\rm eff}$. Like atmospheric parameters, magnitudes and colours are affected by uncertainties and a lack of homogeneity. Absolute magnitudes are computed from excellent parallaxes but averages of old and inhomogeneous apparent magnitudes. Tycho2 (Høg et al. 2000) is a recent photometric catalogue of good quality but its B and V passbands do not correspond to the Johnson standard system and transformations, also affected by calibration uncertainties, have to be used. A small fraction of the dispersion may also be due to interstellar absorption, even if our targets are closer than 50 pc. But we interpret the larger part of the dispersion to mean that our incomplete sample of 208 G dwarfs includes stars of various ages and states of evolution resulting in a variety of astrophysical properties, because the ELODIE library was built to represent the stellar content in the solar neighbourhood, not solar analogs.

We have seen in previous sections that good photometric analogs are not always good spectroscopic analogs. HD 001835 is a good example of a star having similar colours and absolute magnitude as the Sun but which is considerably different in respect to its age, activity and metal content. Thus photometry is not able to discriminate between these effects whereas high resolution spectroscopy can. In contrast the direct comparison of high resolution spectra used alone classify as solar analogs stars having a large range of atmospheric parameters. We conclude that a good strategy to find other solar twins than HD 146233, and perhaps better ones, would be to select photometric analogs in large catalogues, then select with Hipparcos those that have a similar absolute magnitude to the Sun, then submit their high resolution spectrum to the TGMET comparison. We have scanned the GCPD, Strömgren and Hipparcos catalogues with the drastic criterion used in Sect. 5 to identify photometric analogs and found only 27 candidates, 4 being already in the ELODIE library, 15 others observable with ELODIE. We plan to observe them soon in order to complete this work.

Table 4. Fondamental data for our Top Ten solar analogs. Our adopted atmospheric parameters in bold characters are the mean values from the literature. The second column is the averaged TGMET distance of the corresponding star to the 8 solar spectra.

Star name	TGMET score	$B-V$	$b-y$	$U-B$	Distance in pc	Absolute magnitude	$T_{\rm eff}$	log g	[Fe/H]	Source ($T_{\rm eff}$, log g, [Fe/H])
Sun		0.64–0.66	0.40–0.41	0.17–0.20	0	4.80–4.84	5777	4.44	0.00	–
HD 146233	2.019	0.651	0.401	0.174	14.0	4.77	5799	4.40	+0.01	Mishenina et al. (2004)
							5789	4.49	+0.05	Porto de Mello & da Silva (1997)
							5794	**4.44**	**+0.03**	
HD 168009	2.195	0.635	0.410	0.115	22.7	4.52	5826	4.10	–0.01	Mishenina et al. (2004)
							5719	4.08	–0.07	Chen et al. (2000)
							5826	–	–	di Benedetto (1998)
							5833	–	–	Blackwell & Lynas-Gray (1998)
							5781	–	–	Alonso et al. (1996a)
							5801	**4.09**	**–0.04**	
HD 010307	2.516	0.616	0.389	0.113	12.6	4.45	5881	4.30	+0.02	Mishenina et al. (2004)
							5776	4.13	–0.05	Chen et al. (2000)
							5825	4.33	–0.04	Gratton et al. (1996)
							5874	–	–	Alonso et al. (1996a)
							5898	4.31	–0.02	Edvardsson et al. (1993)
							5848	**4.26**	**–0.02**	
HD 089269	2.602	0.654	0.420	0.156	20.6	5.06	5674	4.40	–0.23	Mishenina et al. (2004)
							5674	**4.40**	**–0.23**	
HD 047309	2.628	0.623	0.412	–	42.4	4.47	5791	–	–	Kovtyukh et al. (2003)
							5791	4.40	+0.11	Mishenina priv. com.
							5791	**4.40**	**+0.11**	
HD 095128	2.758	0.606	0.391	0.126	14.1	4.31	5887	4.30	+0.01	Mishenina et al. (2004)
							5861	4.29	+0.05	Laws et al. (2003)
							5925	4.45	+0.05	Santos et al. (2003)
							5788	4.31	+0.03	Zhao et al. (2002)
							5731	4.16	–0.12	Chen et al. (2000)
							5892	4.27	0.00	Zhao & Gehren (2000)
							5892	4.27	0.00	Fuhrmann et al. (1998)
							5800	4.25	+0.01	Gonzalez (1998)
							5892	4.27	0.00	Fuhrmann et al. (1997)
							5811	4.09	0.00	Gratton et al. (1996)
							5882	4.34	+0.01	Edvardsson et al. (1993)
							5860	**4.28**	**0.00**	

Table 4. continued.

Star name	TGMET score	$B-V$	$b-y$	$U-B$	Distance in pc	Absolute magnitude	$T_{\rm eff}$	log g	[Fe/H]	Source ($T_{\rm eff}$, log g, [Fe/H])
Sun		0.64–0.66	0.40–0.41	0.17–0.20	0	4.80–4.84	5777	4.44	0.00	–
HD 042618	2.857	0.632	0.404	0.127	23.1	5.05	5775	–	–	Kovtyukh et al. (2003)
							5653	4.58	–0.16	Reddy et al. (2002)
							5714	**4.58**	**–0.16**	
HD 071148	2.907	0.625	0.399	0.120	21.8	4.65	5850	4.25	0.00	Mishenina et al. (2004)
							5716	4.34	+0.03	Chen et al. (2003)
							5703	4.46	–0.08	Reddy et al. (2002)
							5756	**4.35**	**–0.02**	
HD 186427	2.934	0.662	0.416	0.200	21.4	4.56	5752	4.20	+0.02	Mishenina et al. (2004)
							5765	4.46	+0.09	Santos et al. (2003)
							5685	4.26	+0.07	Laws & Gonzalez (2001)
							5760	4.40	+0.06	Deliyannis et al. (2000)
							5700	4.35	+0.06	Gonzalez (1998)
							5773	4.42	+0.06	Feltzing & Gustafsson (1998)
							5766	4.29	+0.05	Fuhrmann et al. (1997)
							5752	–	–	di Benedetto (1998)
							5767	–	–	Alonso et al. (1996a)
							5753	4.33	+0.06	Friel et al. (1993)
							5753	**4.35**	**+0.06**	
HD 010145	3.003	0.689	0.421	0.212	36.7	4.87	5673	4.40	–0.01	Mishenina et al. (2004)
							5673	**4.40**	**–0.01**	

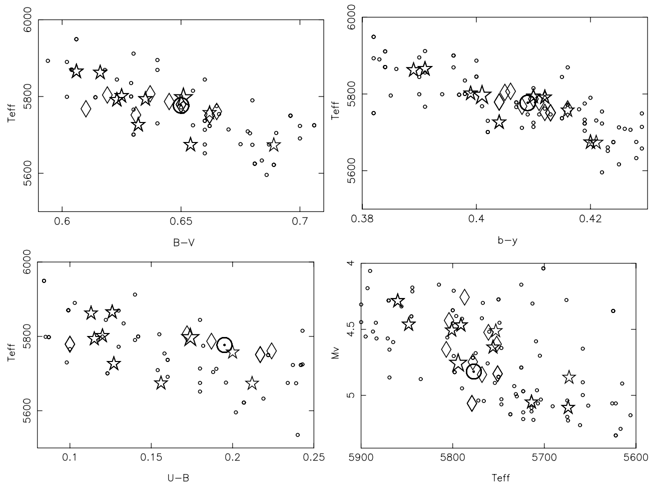

Fig. 4. Distribution of the ELODIE library (small dots), the Top Ten solar analogs (stars), other solar analogs (Sect. 5, diamonds) and the Sun in $T_{\rm eff}$ vs. colour and HR diagrams. The solar twin HD 146233 is shown with a larger symbol.

7. Conclusion

We have presented the 10 stars of the ELODIE library which exhibit the closest optical spectrum to the Sun at a resolution of 42 000. They have colours, absolute magnitudes, atmospheric parameters and Li content which span a range of values larger than expected. It is surprising that a star like HD 089269, colder, more metal poor and less luminous than the Sun is at the 4th position, whereas HD 076151, having similar colours, absolute magnitude and atmospheric parameters is only at the 14th position. Activity may play an important role in discrimination. We have shown for instance that the good photometric analog HD 001835 was a very bad spectroscopic analog because of its high activity. One also has to take into account, when comparing colours, absolute magnitudes and atmospheric parameters to those of the Sun, that these quantities are affected by significant uncertainties. Effective temperatures are particularly in question, with determinations for the same star differing by nearly 200 K in some cases. Our method consisting in measuring distances between spectra is powerful but it is also affected by uncertainties due to observing conditions, especially the pollution by telluric lines, which may perturb the order of the classification.

Among our Top Ten, several stars have never been mentioned before as solar analogs and have been very little studied. They are good candidates for planet hunting, especially HD 047309 which is slightly more metal rich than the Sun. Two of our solar analogs, HD 095128 and HD 186427, are already known to have planets. HD 159222 and HD 076151 are also good candidates because they are good spectroscopic analogs (in the Top 15) and good photometric analogs.

The conclusion of this work is that none of the methods to search for solar twins is satisfactory when used by itself. The methods that have been already used are the comparison of colour indexes, of absolute magnitudes, of UV spectral energy distributions, of atmospheric parameters and of high resolution optical spectra. All these methods are affected by uncertainties and none of them is able to describe sufficiently all the stellar properties. Combining them is the best way to minimize their drawbacks, uncertainties and insufficiencies. Finally HD 146233 is the only star in the ELODIE library which merits the title of solar twin because it has passed the filter of all methods. It is not however a perfect twin and differs from the Sun by its higher Li content, slightly higher age (6 Gyr against 4.6 Gyr for the Sun) and higher luminosity ($M_V = 4.77$ against $M_{V\odot} = 4.82$).

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