HR 6060: The Closest Ever Solar Twin?

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Abstract

We show that the photometric and spectroscopic data of the G2V type star HR 6060 (18 Sco) makes it the best ever solar twin (Porto de Mello & da Silva 1997). This result is a by-product of a detailed abundance survey of 25 chemical elements in 15 nearby G-type stars, with very high S/N, high resolution spectra. Atmospheric parameters were determined from the excitation & ionization equilibria of 106 Fe I lines and 12 Fe II lines, theoretical fitting of Hα profiles and the calibrations of T_{eff} against (B-V), (b-y), $(R\text{-}I)_J$ and β colors. The best previously claimed solar twin is 16 Cyg A, with the same T_{eff} and [Fe/H] as the Sun but being older, brighter, with lower gravity and a quieter chromosphere (Friel et al. 1993). HR 6060 shares with the Sun the same T_{eff}, log g, [Fe/H], microturbulence, projected rotation velocity, chromospheric activity and Li and Be abundances. Its galactic orbit is also very similar to the Sun's. Yet its luminosity (HIPPARCOS), and thus its age, is very slightly higher than the Sun's: its abundance pattern, also, is curiously non-solar. Additionally, we have inferred a new, very precise solar (B-V) from the database of our spectroscopic survey.

1 Detailed Spectral Analysis

We performed a detailed, rigorously differential spectral analysis with respect to the Sun. Stellar spectra with resolving power R = 29,000 have been acquired at the 4m CTIO telescope. The continuum sinal-to-noise ratio ranges from S/N = 300 (λ4500) to S/N = 1600 (λ6400). Solar gf values were generated from Ganymede spectra, observed with the same instrumental setup as the stellar spectra, and a modified MARCS atmospheric model (Edvardsson et al. 1993). For the Sun, we adopted: T_{eff} = 5.777 K, log g = 4.44 and ξ = 1.20 Km/s. The results for HR 6060 are: $T_{eff} = (5817 \pm 30)$ K (Fe excitation), $T_{eff} = (5768 \pm 40)$ K (Hα), $T_{eff} = (5771 \pm 60)$ K (colors), log g = (4.45 ± 0.12) dex (Fe ionization), [Fe/H] = $(+0.05 \pm 0.05)$ dex and $\xi = (1.22 \pm 0.05)$ Km/s. The weighted mean value is T_{eff} = (5789 K $\pm$ 24) K. Internal errors in the atmospheric parameters are: σ (T_{eff}) = 30 K, σ(log g) = 0.12 dex, σ([Fe/H]) = 0.05 dex and σ (ξ) = 0.05 Km/s. The internal mean uncertainty in the [X/Fe] ratios is $\sigma = 0.06$ dex. In figure 1 we plot the individual Fe I line abundances against lower excitation potential. The high quality and robustness of the results, as well as the absence of systematic effects, are appreciated. In figure 2 we compare for the Sun (Moon) and HR 6060 the observed Hα profiles, obtained at the Observatório do Pico dos Dias (CNPq/LNA/Brazil), with R = 20,000 and S/N = 200: they are seen to be indistinguishable even at the line core.

In figure 3 we show the abundance pattern of HR 6060, with respect to the Fe abundance, for 24 chemical elements. The abundance distribution in HR 6060 is solar but for the slight overabundance of Sc and V and of the heavier elements. In figure 4 we compare a short range of the solar and stellar blue spectra: the similarity between the Sun and HR 6060 is striking even in this spectral range, which is particularly sensitive to metal abundance differences. In figure 5 we compare the Fe I line strengths of the Sun and HR 6060. The line strengths in the two objects are the same within the 1% uncertainty. The next best solar twins, the 16 Cyg A and B pair, have Fe lines 3% stronger than in the Sun (figures 6a,b) according to the data of Friel et al. (1993). The data of Hardorp (1982) at 20 Å resolution, in the $\lambda\lambda$3640-4100 range, imply HR 6060 and 16 Cyg A to be weaker-lined than the Sun, 16 Cyg B having exactly solar-like features. Our and Friel et al.'s much higher-resolution data do not correspond to Hardorp's data, suggesting errors in his near UV line difference magnitude indices of up to 0.05^m.

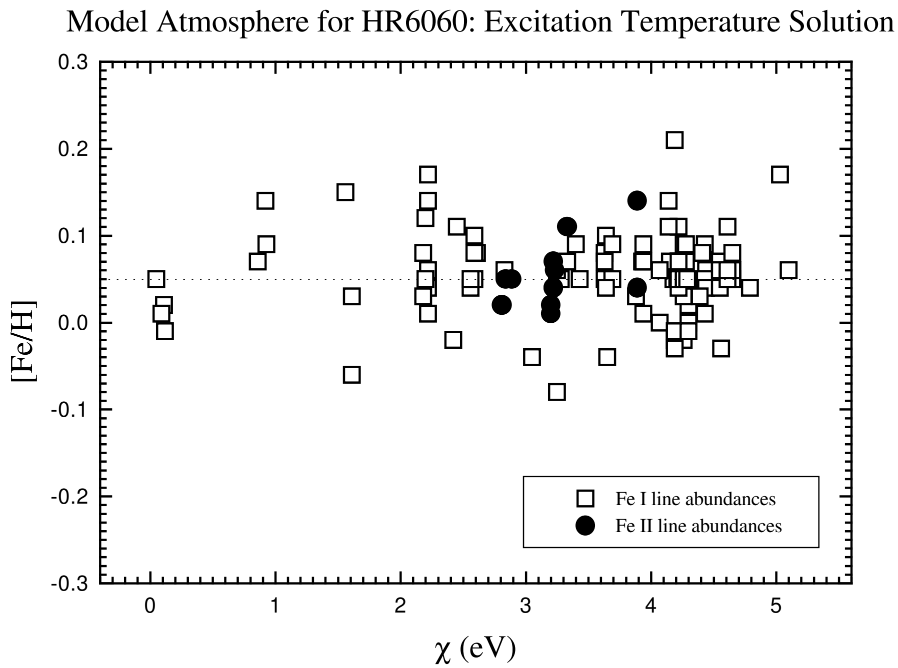

Figure 1.

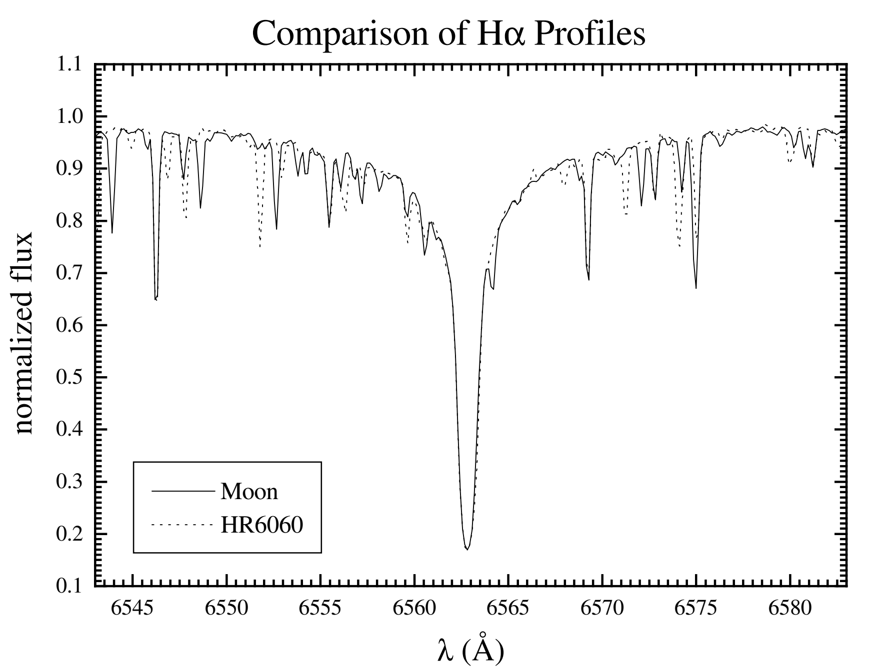

Figure 2.

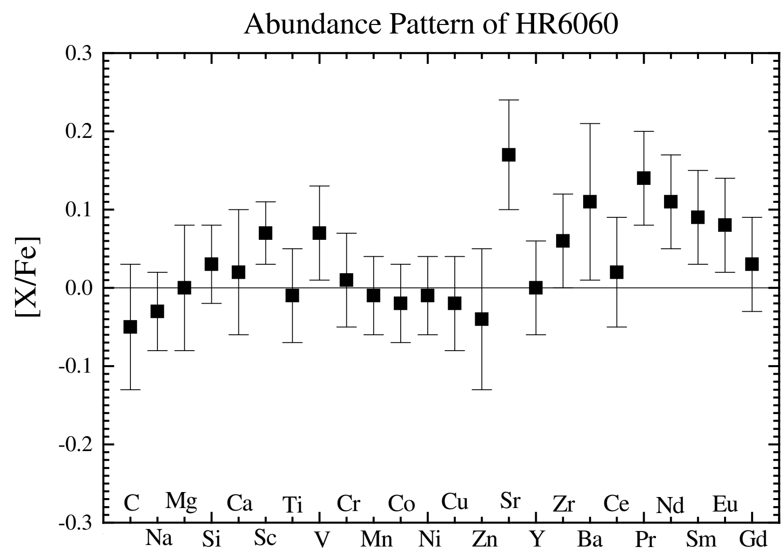

Figure 3.

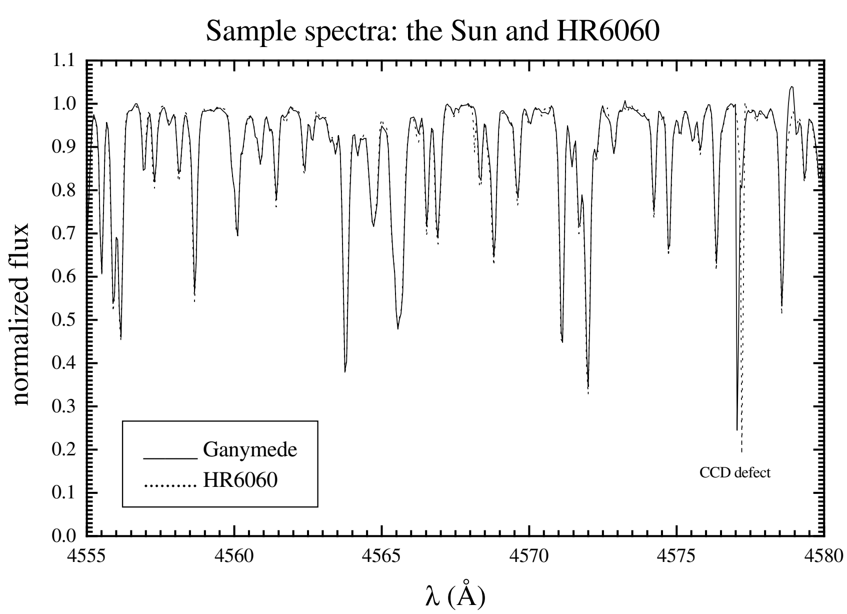

Figure 4.

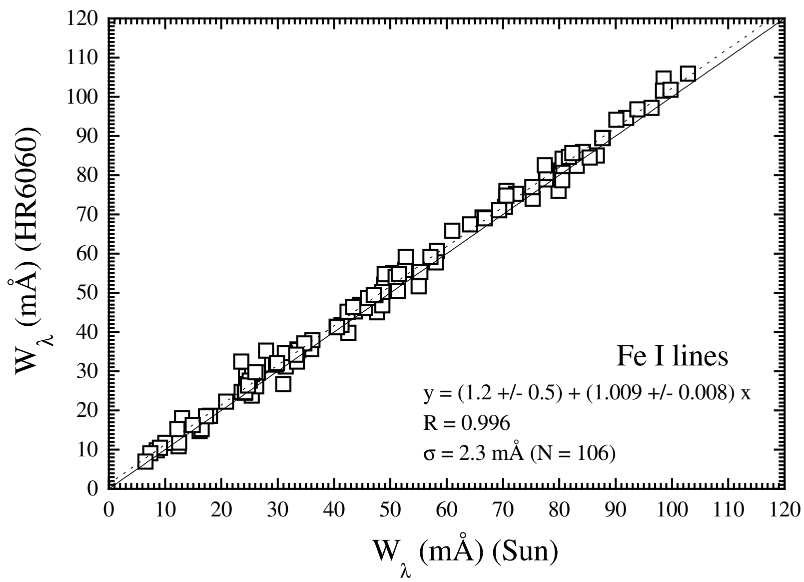

Figure 5.

2 Chromospheric Activity, Rotation, Light Elements

Available Mount Wilson HK indices (Duncan et al 1991.) imply the same degree of chromospheric activity in the Sun (<S> = 0.177) and HR 6060 (<S> = 0.174). The Hα line core residual fluxes are exactly the same in the two stars (figure 2), also implying the same degree of activity. Our estimated projected rotation velocity for HR 6060 is $v$sin i $\leq$ 3,0 Km/s, from a selected set of Fe I lines with very clean profiles. The abundances in HR 6060 of log N(Li) $<$ 1.4 (Soderblom 1983) and log N(Be) = 1.15 $\pm$ 0.15 (Boesgaard & King 1993) are solar: log N(Li)$_\odot$ = 1.16 $\pm$ 0.10 and log N(Be)$_\odot$ = 1.30 $\pm$ 0.10 (Grevesse & Noels 1993) (all these values in the log N(H) = 12.00 scale). The Li depletion data suggests that HR 6060 has about the same age of the Sun. 16 Cyg A also shows the same Li depletion as the Sun, as contrasted to the slightly cooler and more Li depleted star 16 Cyg B (Friel et al. 1993). Both 16 Cyg stars are however appreciably less active with <S> $\sim$ 0.150 (Duncan et al 1991). Friel et al. (1993) also found appreciably deeper cores in the Ca II infrared triplet lines for the 16 Cyg pair, with respect to the Sun.

3 Evolutionary State, Age

The HIPPARCOS parallax gives 14.0 pc as the distance to HR 6060. Assuming the same bolometric correction for the Sun and HR 6060, log (L/L$_\odot$) = +0.020 $\pm$ 0.008 results. In figure 7 the Sun, HR 6060 and the 16 Cyg stars are compared in a HR diagram. One infers the same mass for the Sun and HR 6060. Taking into account that the Sun does not lie over the 4.5 Gyr isochrone, the inferred age of HR 6060 is $\sim$ 6.0 Gyr. Morell et al.'s (1992) analysis of the [Th/Nd] cosmochronometer pair arrived at the same [Th/Nd] abundance ratio — and hence the same age — for the Sun and HR 6060. The 16 Cyg stars are therefore appreciably older and more evolved than both the Sun and HR 6060: this is confirmed by their lower gravity (Friel et al. 1993).

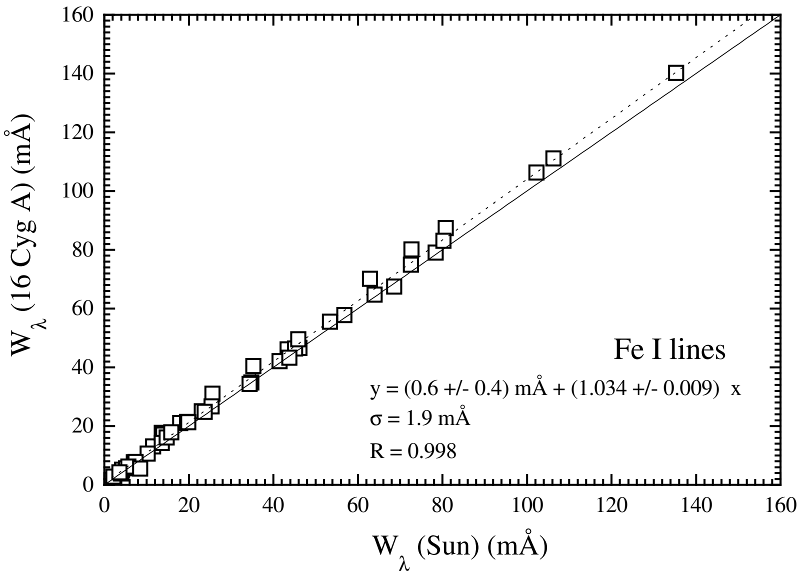

Figure 6a.

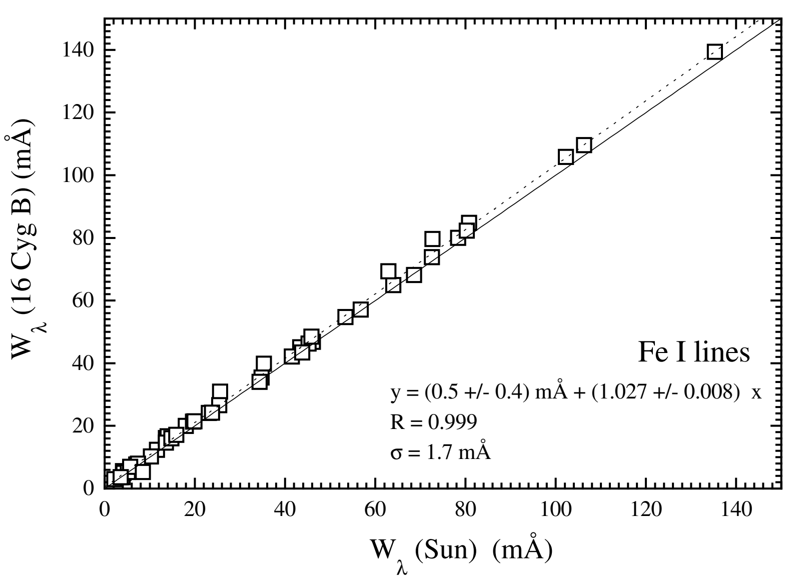

Figure 6b.

4 Galactic Kinematics

Woolley et al.'s (1970) galactic orbital parameters for HR 6060, by adopting for the Sun a mean galactocentric distance of $R_{m\odot} = 8.0$ Kpc, imply R_m(HR 6060) = 7.8 Kpc. These same authors provide as orbital eccentricities e(HR 6060) = 0.12 and $e_\odot = 0.07$. Cayrel de Strobel (1996), in her large review of the solar analogue subject, gives as kinematical parameters: $(U',V',W')_\odot = (+9,+12,+7)$, $(U',V',W')_{HR6060} = (+38,-4,-18)$. HR 6060 is therefore a typical middle aged, thin disk star, never venturing much either outside the solar circle or the galactic plane — just like the Sun.

5 The Solar Colors

We derived the solar (B-V) from our detailed spectral data, by plotting the observed colors of the [Fe/H] = +0.0 stars of our sample (augmented by 16 Cyg A and B) against their mean (Hα, Fe excitation & ionization, photometric) effective temperatures. We have deduced $(B-V)_\odot = +0.647 \pm 0.006$ (figure 8), in excellent agreement with the results of Neckel (1986), $(B-V)_\odot = +0.650$, Gray (1995), $(B-V)_\odot = +0.648$, and Cayrel de Strobel (1996), $(B-V)_\odot = +0.642$. In the diagrams one sees that HR 6060 and 16 Cyg A are about equally similar to the Sun in their (B-V) color.

6 Conclusion

We conclude that, for low resolution work, either HR 6060 or 16 Cyg A can successfully act as a solar proxy in the night sky. For higher resolution observations, or if one is interested in very fine differences in stellar atmospheric parameters, however, HR 6060 is the most solar-like star discovered to date.

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References

Boesgaard & King 1993, AJ, 106, 2309
Cayrel de Strobel 1996, A&AR, 7, 243
Duncan et al 1991., ApJS, 76, 383
Edvardsson et al. 1993, A&A, 275, 101
Friel et al. 1993, A&A, 274, 825
Gray 1995, PASP, 107, 120
Grevesse & Noels 1993, Origin and Evolution of the Elements,
Hardorp 1982, A&A, 105, 120
Morell et al. 1992, A&A, 259, 543
Neckel 1986, A&A, 159, 175
Porto de Mello & da Silva 1997, ApJ Letters, 482, L89
Soderblom 1983, ApJS, 53, 1
Woolley et al. 1970, Roy. Obs. Ann., 5

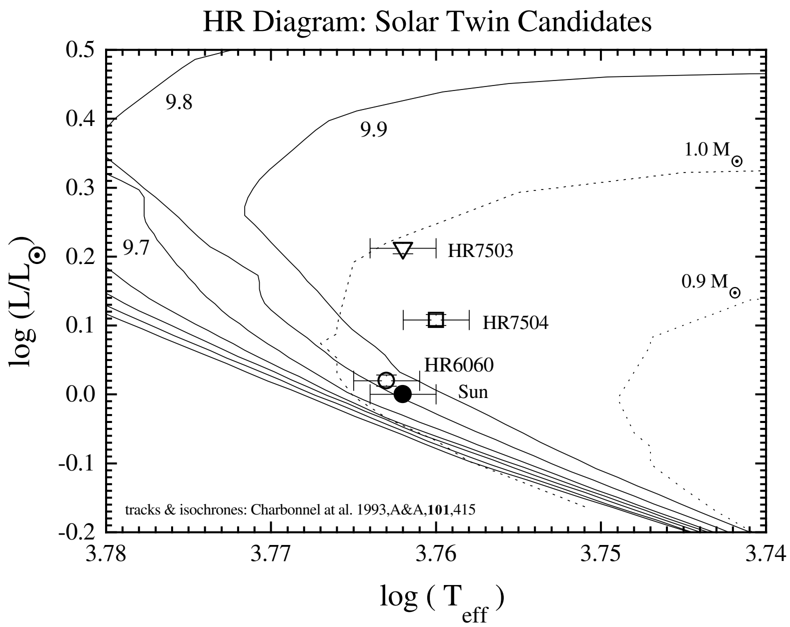

Figure 7.

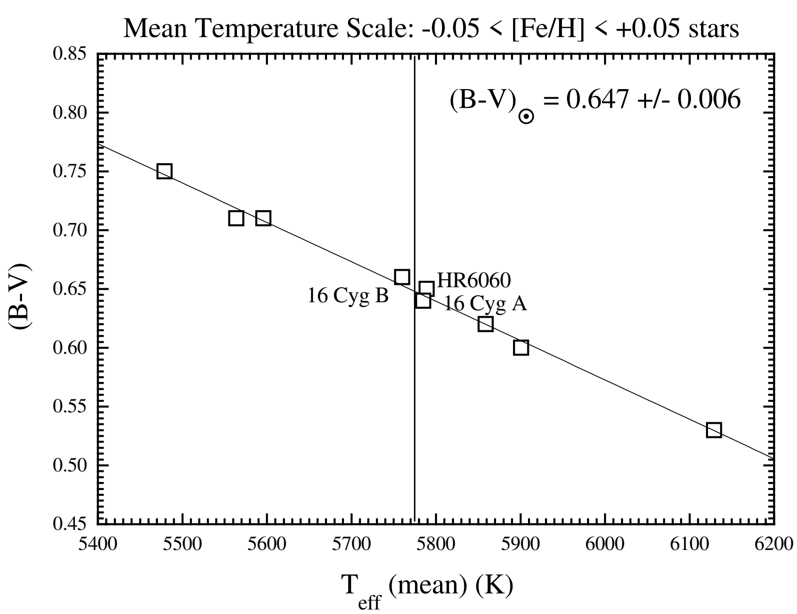

Figure 8.