ASTROBIOLOGY
Volume 6, Number 2, 2006

Research Paper

Astrobiologically Interesting Stars Within 10 Parsecs of the Sun

GUSTAVO PORTO DE MELLO, EDUARDO FERNANDEZ DEL PELOSO,*
and LUAN GHEZZI

ABSTRACT

The existence of life based on carbon chemistry and water oceans relies upon planetary properties, chiefly climate stability, and stellar properties, such as mass, age, metallicity, and galactic orbits. The latter can be well constrained with present knowledge. We present a detailed, up-to-date compilation of the atmospheric parameters, chemical composition, multiplicity, and degree of chromospheric activity for the astrobiologically interesting solar-type stars within 10 parsecs of the Sun. We determined their state of evolution, masses, ages, and space velocities, and produced an optimized list of candidates that merit serious scientific consideration by the future space-based interferometry probes aimed at directly detecting Earth-sized extrasolar planets and seeking spectroscopic infrared biomarkers as evidence of photosynthetic life. The initially selected stars number 33 solar-type within the total population (excluding some incompleteness for late M-dwarfs) of 182 stars closer than 10 parsecs. A comprehensive and detailed data compilation for these objects is still lacking; a considerable amount of recent data has so far gone unexplored in this context. We present 13 objects as the nearest "biostars," after eliminating multiple stars, young, chromospherically active, hard x-ray-emitting stars, and low metallicity objects. Three of these "biostars"—Zeta Tucanae, Beta Canum Venaticorum, and 61 Virginis—closely reproduce most of the solar properties and are considered as premier targets. We show that approximately 7% of the nearby stars are optimally interesting targets for exobiology. Key Words: Stars—Astrobiology—Solar neighborhood—Solar-type stars. Astrobiology 6, 308–331.

THE HABITABILITY CONCEPT

The goal of this paper is to present a list of stars, among the stellar population within 10 parsecs (pc) of the Sun, which best qualify as adequate hosts to habitable planets. These stars are presumably prime targets for the remote spectroscopic detection, by way of future spaceborne nulling interferometer missions such as NASA's Terrestrial Planet Finder (Lawson *et al.*, 2004) and European Space Agency's Darwin DARWIN (see: http://ast.star.rl.ac.uk/darwin/), of biological activity in telluric planets that orbit nearby stars. The detection of these so-called "biomarkers"

Observatório do Valongo, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.
*Present address: Observatório Nacional, Rio de Janeiro, Brazil.

(des Marais *et al.*, 2002; Segura *et al.*, 2003) will undoubtedly be one of the major topics of the scientific agenda for decades to come (Tarter, 2001), and represents perhaps the surest and most expedient, technologically attainable (in the short term) promise of establishing with reasonable certainty the existence of life outside the Solar System.

Complex life, as we know it, is based on reasonably well-established properties. The essential ones are: a long-lived, solar-type star within definite constraints of luminosity; a rocky, internally hot planet able to sustain liquid water at its surface; a magnetic field able to shield the surface from biologically harmful, high-energy particles; a CO_2–H_2O–N_2 atmosphere with a climate-regulating, carbonate–silicate cycle by way of plate tectonics (Kasting, 1996; Franck *et al.*, 1999, 2000a,b; Kasting and Catling, 2003); and the foundation blocks of carbon chain chemistry, water oceans, and long-term stability. Such attributes stem from our immediate knowledge of life on Earth, but they must surely guide our strategy to search for life elsewhere.

Stability is difficult to define. The Cretaceous-Tertiary mass extinction, 65 million years ago (Myr), was probably triggered by a cometary impact (Alvarez *et al.*, 1980). The Permian-Triassic massive extinction 251 Myr ago, in which 96% of species vanished, bears the sign of massive volcanic eruptions and lava outflows that boosted greenhouse gas concentrations and, thus, warmed the Earth, wreaked havoc on the climate, and lowered the atmospheric O_2 levels to near anoxic levels (Benton and Twitchett, 2003). In contrast, Becker *et al.* (2004) have suggested that the massive Permian-Triassic extinction that affected nearly all life may have been caused by yet another impact of extraterrestrial origin. There is ample evidence of past global catastrophes with heavy impact on the biota. Notwithstanding, the Earth's biosphere can and did survive these events, and thus we may take stability as, at the very least, the ability to sustain such damage for $\sim$4 billion years ago (Gyr).

The real point in selecting nearby stars as targets for interferometric missions is the assessment of the probability of biomarker detection. Many authors have argued that a minimum time is necessary for sufficient oxygenation of the planetary atmosphere (*e.g.*, Catling *et al.*, 2005), but this is not necessarily concomitant with the evolution of complex metazoans. The so-called "Rare Earth" hypothesis (Ward and Brownlee, 2000) favors the rarity of complex biospheres such as Earth's, yet contends that the evolution of simple life should be common. It is as yet not clear how evolved a biosphere and, thus, a planetary atmosphere must be to allow biomarker detection. Segura *et al*. (2003) found that ozone was probably detectable on Earth as early as in the Proterozoic $\sim$2 Gyr ago, not long after aerobic photosynthesis first appeared. von Bloh *et al*. (2003) presented results for the evolution of a model biosphere composed of prokaryotes, eukaryotes, and complex metazoans, tying the biological with the geophysical evolution. Their results show that, depending on the choice of model parameters, complex life could appear almost simultaneously with eukaryotes, or lag behind them. The time scales of evolution of simple and complex life might thus overlap, leaving as the real issue not the complexity reached by putative biospheres, but the degree of atmospheric evolution that entails.

The whole issue of habitability hinges on the identification of those stars that can maintain a potentially habitable planet by providing an adequate radiation environment. Such stars occupy the so-called continuously habitable zone (CHZ) within which liquid water can exist at planetary surfaces. The interplay of stellar radiation and climate stability seems to be fundamentally linked to the homeostatic carbonate–silicate cycle by way of a feedback mechanism in which the atmospheric CO_2 concentration varies inversely with planetary surface temperature (Kasting *et al.*, 1993, and references therein; Franck *et al.*, 2000a,b). The process involves a reaction of the CO_2 concentration to the incoming stellar radiation, first by enhanced weathering, which in its turn sequesters a larger fraction of CO_2 out of the atmosphere. In this sense CO_2 concentrations decrease exactly as needed to counter a higher flux of radiation. Therefore the three variables—radiation input, surface temperature, and CO_2 concentration—tend to maintain an equilibrium state. This homeostasis depends on the atmospheric composition and the maintenance of weathering processes by plate tectonics. Thus the inner habitability edge is defined by loss of water via photolysis and hydrogen escape, with consequent ocean evaporation. The outer edge is defined by the formation of CO_2 clouds that cool the planet by lowering its albedo and the atmospheric convective lapse rate. As concerns planetary mass, McElroy (1972) has argued that a habitable planet must have at least a few times the mass of Mars to prevent the stripping off of its atmosphere of C, N, and O atoms by the action of the stellar wind in time scales of a few Gyr. Kasting *et al*. (1993) also have shown that, for planets larger than the Earth, the CHZ might be slightly wider. A reasonable upper limit might be a few Earth masses, since planets larger than this may retain such a high inventory of volatiles as to be completely covered by global oceans (Ward and Brownlee, 2000; Léger *et al*., 2004), which prevents the closing of the carbonate–silicate cycle by the absence of rock weathering. Such planetary mass considerations are most probably linked to the stellar metal content (Lineweaver, 2001; Santos *et al*., 2003, 2004; Fischer and Valenti, 2005) and details of the planetary condensation process, and remain highly speculative under our almost total ignorance of the mechanisms responsible for telluric planet formation.

DETAILED CRITERIA

The CHZ is to be found around mid-K to late-F stars (Huang, 1959; Kasting *et al*., 1993; Franck *et al*., 2000a,b). On the one hand, late K-type and M-type stars place their planets inside the tidal lock radius if they are to possess liquid water at the surface, whereby the planet rotates in the same time it revolves around the star, spelling potential disaster for climate stability (Dole, 1964; Kasting *et al*., 1993). These objects should be appreciably less conducive to the development of complex and long-term biospheres such as Earth's, since climate stability considerations should be very dissimilar because of the necessity of placing habitable planets near to, or inside, the tidal lock radius. Also, for these very cool stars, it is difficult to obtain metallicity from spectroscopic analysis because of severe crowding of the line spectra, which makes the measurement of line strengths unreliable. A poor knowledge of metallicity precludes the elimination of metal-poor stars, an essential aspect of our analysis, owing to the well-established connection of this parameter to the probability of forming planets (Santos *et al*., 2004; Fischer and Valenti, 2005). Actually the completeness of the metallicity data for these objects is much lower than for the FG stars, precluding a complete volume-limited analysis. Joshi *et al*. (1997) have argued that planets within a certain range of physical properties might be habitable in the CHZ of M-dwarfs if a sufficiently large CO_2 atmospheric concentration is present. In this case, a collapse of the atmosphere would be prevented in the darkside of a synchronously rotating planet. Notwithstanding, recent results have drawn attention to the fact that these objects maintain very high x-ray and ultraviolet fluxes near the saturation limit, as well as strong stellar winds, for 1–2 Gyr or even more (Lammer *et al*., 2005), and this would be especially damaging to Earth-like planets placed inside their very close-in CHZ. The extended high activity phase of these stars also leads to a more uncertain age evaluation from chromospheric activity than for the more massive stars. And, last but not least, planets in the CHZ of late-K and M-type stars must have considerably reduced rotation rates as compared with that of the Earth, and therefore very reduced magnetic moments. This exposes them to a higher flux of cosmic ray because of the absence of protection by an extended magnetosphere. Griessmeier *et al*. (2005) found that secondary cosmic rays might pose a significant threat to organisms on the surface of Earth-like planets in this situation, depending on atmospheric pressure. These considerations lead us to rank possible planets in late-K stars or M-dwarfs as much inferior targets.

Additionally, we specifically aim at producing a list of stars that are optimized for the detection of biomarkers in planets inside the CHZ, and not just the detection of the planets themselves. Within present knowledge, this results inevitably in a reduced list, favoring G- and F-type stars, but actually over 50% of the list is made up by K stars.

On the other hand, mid-F stars have wide habitable zones, but these move outward rapidly as the star evolves into subgiant status. Thus, the time the planet can remain within the CHZ is shorter than the $\sim$4 Gyr necessary for the evolution of complex life. Additionally, Catling *et al.* (2005) have suggested that the partial oxygen pressure of a planetary atmosphere must surpass a threshold of $\sim 10^3$–10^4 Pa to allow the accumulation of a sizable biomass, and the time scale for a sufficient oxygenation is long, $\sim$4 Gyr, comparable to stellar ages. This places yet another constraint against F-type stars, which might evolve too quickly, even when providing benign planetary conditions, to allow oxygenation to reach the threshold point.

In mass, these limitations, for solar metallicity stars, roughly translate into the interval $\sim$0.70–

1.20 solar masses, depending, not negligibly, on the stellar metallicity, as will be discussed below. These limits can be somewhat softened for stellar masses lower than 0.70 solar, if one accepts the possibility of a planet locking itself in orbital resonances that might preclude complete rotational synchronization, even though well before partial synchronization the planetary climate pattern would be appreciably disrupted. Masses larger than 1.20 solar may remain acceptable if allowance is made for a faster evolution of complex life than was the case on Earth. Yet, besides these well-accepted notions, quite a few other considerations have recently been increasingly considered as playing fundamental roles for the long-term existence of CHZs around such stars.

The stellar galactic orbit is a rarely mentioned factor of stability, which is drawing more interest as one regards how important it may be concerning the average interval between global catastrophes a planet may undergo. The Sun lies very near the so-called co-rotation radius (Balázs, 2000; Lépine *et al.*, 2001), where stars revolve around the Galaxy in the same period the density wave perturbations sweep across the galactic disk. In such a situation, the passages across the spiral arms and, consequently, the potential encounters with star-forming regions and giant molecular clouds are presumably minimized. The first are thought to present the danger of biologically lethal x- and gamma-ray irradiation episodes by supernova explosions (Gehrels *et al.*, 2003); the latter, to trigger heavy cometary bombardment in the inner planetary system by perturbing the Oort cloud dormant population (Clube and Napier, 1982). Leitch and Vasisht (2001) have presented some evidence on the correlation of past significant mass extinctions with crossings of the spiral arms by the Sun. Yet this issue is probably more complicated. When one considers stars that either lead or trail the pattern of density waves, by having small velocity components with respect to them, on the one hand they will cross the spiral arms more often than a star lying close to the co-rotation radius, but on the other hand they will also remain inside the arms and subjected to their dangers for a shorter time. It remains unclear as to which situation presents a longer exposure to the putative hazards of this crossing. Moreover, Lépine *et al.* (2003) have argued that, because of resonant interaction with the spiral arms gravity fields, stellar orbits may wander as much as a few kpc from their initial position in 1 billion years or less. In their model, the history of spiral arm passages of any given star may be considerably subjected to random fluctuation, introducing an unforeseeable element that implies that the long-term survival of biospheres might be closely linked to chance. A thorough analysis of the times and frequency of stellar passages across the spiral arms and of its objective dangers is yet to be addresssed.

Some galactic chemical evolution considerations are largely underappreciated as fundamental issues for providing a suitable habitable rocky planet. The Sun, for its age, is quite metal rich (Rocha-Pinto and Maciel, 1996), which makes it one of the earliest stars of its galactic orbit to reach metal content levels adequate to support complex life. Earth might well then belong to an early generation of habitable planets in the Galaxy. Metallicity as linked to age also comes into play at another point: a sizable fraction of Earth's internal heat comes from the decay of radioactive isotopes, such as ^{40}K, ^{235}U, ^{238}U, and ^{232}Th. Their bulk abundance in the Galaxy is synthesized by neutron capture processes in moderate or highly massive stars. Gonzalez *et al.* (2001) have suggested that the relative abundances of these radioisotopes to Fe (the element taken to represent the gross stellar metal content) is decreasing with time in the Galaxy and that future Earth-like planets will generate less radiogenic heating than the Earth does, which may be of consequence to their long-term ability to maintain active plate tectonics and climate regulation. These authors have further suggested, albeit rather speculatively, that there is a wide, but definite, statistical "galactic time window" for the formation of adequate telluric planets in the Galaxy and that past and future rocky planet candidates may be less suitable to complex life than the Earth. Also, stars with lower metal content than the Sun possess a higher abundance ratio of Mg-Si to Fe, according to known trends in galactic chemical evolution (Edvardsson *et al.*, 1993). This might also imply, for hypothetical telluric planets, a different mantle–core ratio, different liquid metallic core convection properties (and consequently a different magnetic field), and a different content of radiogenic isotopes (Gonzalez *et al.*, 2001).

A crucial parameter for the aim of the present study is the stellar age. Otherwise adequate stars may be found too close to the zero age main sequence (ZAMS), where any biosphere will necessarily be in its infancy. No complex metazoans or high O_2 content can reasonably be expected to have appeared in such planetary-star systems, and certainly no radiocommunicating civilization will exist. Alternatively, evolved stars may have outlasted their usefulness as abodes of life if the luminosity increase sustained from zero age to their present evolutionary status surpasses the capability of the planetary thermoregulating carbonate–silicate cycle. This situation is dependent upon planetary location inside the CHZ, yet for excessively evolved subgiant stars, the luminosity increase may be excessive even for planets situated, initially, in the outer limits of the stellar CHZ.

Previous efforts, mainly targeted at selecting nearby stars in terms of their suitability to search for extraterrestrial intelligence (SETI) programs, have not included the full set of criteria presented here (*e.g*., Blair *et al*., 1992; Henry *et al*., 1995), and have generally applied them with much less detail. Recently, Turnbull and Tarter (2003a,b) have applied most of the criteria presented above to the stellar sample of the *Hipparcos* catalogue (European Space Agency, 1997), exploring its full range in distance and producing a large catalogue of stars fulfilling the criteria of luminosity class, spectral type, metallicity, age as estimated from spectroscopic indicators of chromospheric activity, and galactic orbits inferred from velocity components. The present analysis, in contrast to theirs, is limited to those stars within 10 pc of the Sun, but is able to sieve the stars in considerably more detail with the inclusion of more data and less reliance on statistical considerations. For very nearby stars, the *Hipparcos* parallaxes allow luminosity determinations with uncertainties under 2%, and the location of their CHZ, at least for those parameters depending exclusively on the stellar luminosity, becomes very precise. These small luminosity errors also enable us to analyze each candidate star in the Hertzprung-Russell (HR) diagram appropriate to its metallicity, thus providing an independent estimate of its age, as well as an accurate evaluation of its state of evolution and increase in luminosity undergone since the stellar birth. The amount of increase in radiation any putative planet has suffered can be estimated for each case, a parameter that has been pointed out by Franck *et al*. (1999, 2000b) to have a strong bearing on the planetary biological productivity. The carbonate–silicate cycle forces the atmospheric CO_2 content to go steadily down as the star ages and brightens, and this essential stability mechanism eventually lowers the CO_2 content to a point at which photosynthesis becomes impossible even for the hardiest plants. This poses a definite upper constraint on the time scale within which even a suitable planet can sustain biological activity at its surface and, thereby, maintain detectable biomarkers in its thermal spectrum, a constraint that may prove to be more stringent than the luminosity evolution of the star itself.

The full set of criteria discussed above can be used to constrain rather tightly the nearby stars in terms of suitability for complex life. The level of detail presently attainable for the nearby stars allows definite quantitative statements on habitability, and their propinquity, a key issue for the interferometric planetary detection technique, will probably make them the first interesting targets for the coming infrared space-based interferometers. We aim here at characterizing which of the nearby solar-type stars can be expected to possess a reasonable CHZ and be old enough to have maintained a habitable planet within it in the last few Gyr, or at least to the point of allowing complex life and an O_2-rich atmosphere to have developed. It would certainly be more interesting to define complex life as a space-faring culture able to establish an astrophysical understanding of its surroundings and operate radiotelescopes. However, given the failure to detect any extraterrestrial non-natural signal, despite sustained efforts (Tarter, 2001), it is probable that no such culture is broadcasting with appreciable power within our present detection limits. Thus the prospect of life detection by the photosynthetic planetary spectral signature, with available techniques, is probably higher.

In the following sections of this paper we detail the criteria employed to select the stars, discuss the results and present the best candidates, and present our conclusions and perspectives for future work.

SAMPLE SELECTION, DATA COMPILATION, AND FUNDAMENTAL CRITERIA

In this section, we apply a sequence of criteria to the *Hipparcos* catalogue, removing unsuitable stars and producing a residual sample of stars that, as far as present knowledge warrants judgment, are potentially optimal hosts for habitable planets. As a first step we selected all *Hipparcos* stars within 10 pc of the Sun (Fig. 1), which totals 182 objects. The completeness of *Hipparcos* is 100% for $V \leq 9.0$; therefore, within 10 pc, it is expected to be complete to spectral types earlier than ~M0V, the ones relevant to our analysis. Objects closer than 10 pc that fail to be included to Fig. 1 owing to incompleteness of *Hipparcos* should then be exclusively late M-dwarfs (see RECONS at: http://www.chara.gsu.edu/RECONS/). The sample plotted in Fig. 1 is, as expected, numerically dominated by red dwarfs.

The box plotted in Fig. 1 is bounded by our initial limits of color index (*B-V*) and absolute magnitude M_V of what constitutes an astrobiologically *interesting* star, that is, a non-subgiant K2 to F8 star. These limits had to be experimented with. Without *a priori* knowledge of the stellar's metallicity, the colors are a poor guide to the effective temperature $T_{\rm eff}$, since a cooler and more metal-poor star can mimic the colors of a metal-normal star. The same effect takes place for a hotter and more metal-rich star (*e.g.*, Saxner and Hammarbäck, 1985). It will be shown below that the stellar $T_{\rm eff}$ and metallicity govern the uncertainty in the determination of age and evolutionary mass, with errors in luminosity being much less important. Initially we set as limits the values $+2.0 < M_V < +8.0$ and $+0.40 < (B\text{-}V) < +1.15$, only to find that, upon a systematic analysis, as a function of stellar metallicity, of the stars in the HR diagram, that very massive F-type stars appeared at the blue end of the selection, and very late-type K stars defined the red end. Besides, to be observable at all near the main sequence, such massive F-type stars necessarily need to be very young, chromospherically active stars, and this was systematically observed. Also, in the blue, high luminosity end of this selection box, a few subgiants too evolved to be of interest were kept. The limits were then modified iteratively until we arrived at the following box limits: $+4.0 < M_V < +6.5$ and $+0.50 < (B\text{-}V) < +1.05$. The high (*B-V*) limit, even for very metal-rich stars, which are redder at the same $T_{\rm eff}$, guarantees that no late-type K-dwarf will be selected. These limits should be adequate for the metallicity range to be found in the galactic thin disk, $-0.4 < [\mathrm{Fe/H}] < +0.4$ {we use throughout the usual spectroscopic notation $[A/B] = \log\ (A/B)\mathrm{star} - \log\ (A/B)_{\mathrm{Sun}}$}, and will be employed in a subsequent paper in the analysis of the astrobiologically interesting stars within 10 pc and 15 pc of the Sun, for which the relevant data still lack considerably in completeness, as will be discussed below.

Including the Sun, 34 stars are kept inside the box of Fig. 1. We searched the literature for data on the following: binarity (Warren and Hoffleit, 1987; Batten *et al.*, 1989; Duquennoy and Mayor, 1991; Mason *et al.*, 2002); magnetohydrodynamic activity, measured by the Ca II H and K lines chromospheric flux and the x-ray luminosity (Noyes *et al.*, 1984; Duncan *et al.*, 1991; Baliunas *et al.*, 1995; Henry *et al.*, 1996; Hünsch *et al.*, 1998, 1999; Strassmeier *et al.*, 2000; Schmitt and Liefke, 2004); and effective temperature $T_{\rm eff}$ and metallicity [Fe/H] (Cayrel de Strobel *et al.*, 2001; Taylor, 2003). The *SIMBAD* database was also scrutinized for completeness up to 2005.

All the relevant data are compiled in Table 1, where we also give additional remarks on each object. The solar-type star sample comprises stars

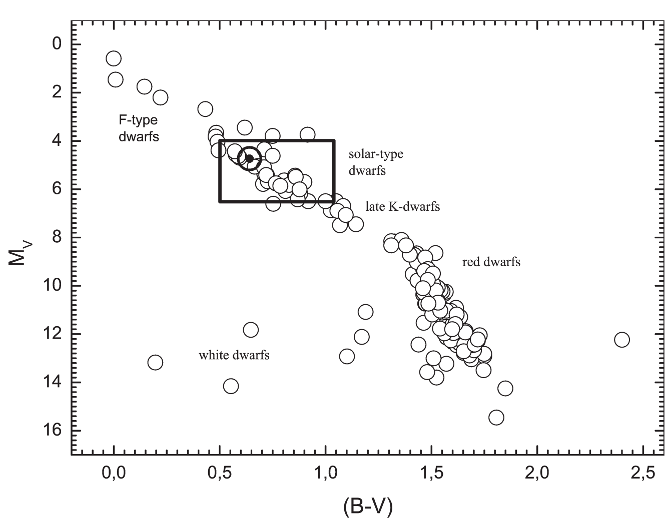


FIG. 1. Observational HR diagram, from *Hipparcos* data, of stars within 10 pc of the Sun. The black box isolates the parameter range $+4.0 < M_V < +6.5$ and $+0.50 < (B\text{-}V) < +1.05$ (see text) and contains the initial candidates of astrobiologically interesting stars.

TABLE 1. ESSENTIAL DATA FOR THE 33 SOLAR-TYPE STARS WITHIN 10 PC OF THE SUN THAT ARE CANDIDATES FOR ASTROBIOLOGICALLY INTERESTING STARS, WITH THE SUN INCLUDED AS THE FIRST ENTRY

HD[a]	*Name*	*Distance (pc)*	*Type*	T_{eff} *(K)*	*[Fe/H]*	*Log* $L/L_{\odot}$	L_x *(erg/s)*	*log* R'_{HK}[b]	*Remarks*	*Source*
—	Sun	—	G2V	5,777	+0.00	+0.00	3.8	−4.85	—	—
1581	ζ Tuc	8.6	F9V	5,970	−0.07	+0.07	—	−4.83	—	Castro *et al.* (1999)
4614	η Cas	6.0	G0V	5,900	−0.25	+0.07	2.6	−4.94	Binary	Cunha *et al.* (1995)
4628	—	7.5	K2V	4,910	−0.27	−0.47	0.9	−4.88	—	Zbornil and Byrne (1998)
6582	μ Cas	7.6	G5V	5,390	−0.83	−0.29	—	−4.92	Binary, metal poor	Zhao and Gehren (2000)
10360	—	8.1	K0V	5,045	−0.19	−0.40	—	−4.85	Binary	Santos *et al.* (2001)
10476	107 Psc	7.5	K1V	5,200	+0.03	−0.30	—	−4.87	—	Heiter and Luck (2003)
10700	τ Cet	3.6	G8V	5,320	−0.50	−0.26	0.2	−4.91	Metal poor	Castro *et al.* (1999)
10780	—	10.0	K0V	5,350	+0.07	−0.23	22	−4.60	Near ZAMS	Heiter and Luck (2003)
16160	—	7.2	K3V	5,100	−0.03	−0.52	1.7	−4.94	—	Heiter and Luck (2003)
20630	κ Cet	9.2	G5V	5,600	+0.04	−0.07	77.1	−4.42	Near ZAMS	Cayrel de Strobel and Bentolila (1989)
20794	82 Eri	6.1	G8V	5,360	−0.54	−0.13	0.5	−4.93	Metal poor	François (1986)
22049	ε Eri	3.2	K2V	5,180	−0.09	−0.40	20.7	−4.46	Near ZAMS	Drake and Smith (1993)
26965	o^2 Eri	5.0	K1V	5,185	−0.26	−0.32	4.1	−4.85	Triple	Bodaghee *et al.* (2003)
32147	—	8.8	K3V	4,825	+0.34	−0.50	1.5	−4.99	—	Thorén and Feltzing (1998)
39587	χ1 Ori	8.7	G0V	5,929	−0.02	+0.01	120	−4.46	Binary, near ZAMS	Castro *et al.* (1999)
100623	—	9.5	K0V	5,400	−0.26	−0.38	—	−4.86	—	Flynn and Morell (1997)
101501	61 UMa	9.5	G8V	5,600	+0.00	−0.18	16.2	−4.50	Near ZAMS	Heiter and Luck (2003)
102365	—	9.2	G5V	5,643	−0.28	−0.07	—	−4.90	—	Porto de Mello (1996)
109358	β CVn	8.4	G0V	5,860	−0.21	+0.06	0.6	−4.85	—	Fuhrmann *et al.* (1998)
114710	β Com	9.2	G0V	5,952	+0.00	+0.12	11.5	−4.75	Near ZAMS	Gratton *et al.* (1996)
115617	61 Vir	8.5	G5V	5,587	+0.00	−0.07	—	−4.96	—	Porto de Mello (1996)
128620	α Cen A	1.3	G2V	5,857	+0.23	+0.21	2.2	−4.76	Binary	del Peloso *et al.* (2005a)
128621	α Cen B	1.3	K1V	5,300	+0.20	−0.22	2.2	−5.16	Binary	Chmielewski *et al.* (1992)
131156	ξ Boo	6.7	G8V	5,500	−0.15	−0.16	87.3	−4.32	Binary, near ZAMS	Ruck and Smith (1995)
149661	12 Oph	9.8	K2V	5,300	+0.01	−0.29	14.5	−4.55	Near ZAMS	Flynn and Morell (1997)
155885	36 Oph B	6.8	K1V	5,140	−0.35	−0.12	19.2	−4.50	Triple, near ZAMS	Cayrel de Strobel *et al.* (1989)
156274	41 Ara	8.8	G8V	5,305	−0.35	−0.27	1.9	−4.95	Binary	Perrin *et al.* (1988)
165341	70 Oph	5.1	K0V	5,260	−0.25	−0.13	28.3	−4.57	Binary, near ZAMS	Zboril and Byrne (1998)
185144	σ Dra	5.8	K0V	5,310	−0.21	−0.31	4.1	−4.81	—	Clegg *et al.* (1981)
190248	δ Pav	6.1	G7IV	5,588	−0.38	+0.11	1.8	−4.97	—	del Peloso *et al.* (2005a)
191408	—	6.1	K2V	4,890	−0.58	−0.48	—	−5.04	Metal poor	Abia *et al.* (1988)
192310	—	8.8	K3V	5,125	+0.05	−0.36	1.7	—	—	Bodaghee *et al.* (2003)
219134	—	6.5	K3V	5,100	+0.10	−0.47	0.4	−5.08	—	Heiter and Luck (2003)

The first four columns are, respectively, the HD number, name, distance (in pc), and spectral type; the fifth and sixth columns are the T_{eff} (in Kelvin) and metallicity, respectively; the seventh column is the logarithm of the stellar luminosity with respect to the Sun; the eighth and ninth columns are the x-ray luminosities (in 10^{27} erg/s) and the logarithm of the chromospheric flux in the Ca II H and K lines (in erg/cm/s) (see text for sources); the 10^{th} column provides remarks under which each object was disregarded as an astrobiologically interesting target by our criteria; and the 11^{th} column provides the source of metallicity and T_{eff}. Variability data from *Hipparcos* are given under Remarks.

[a]For HD 1581, low average HK flux and a quiet Ca II K line profile are observed (Pasquini, 1992). The Hα lux is low and also compatible with an age of a few Gyr. It is listed among the least variable stars in the *Hipparcos* catalogue (Adelman, 2001). Endl *et al.*, (2002) found its radial velocity as constant within ~22 m/s, ruling out "hot

jupiters" for this object. For HD 4614, a binary system (period 480 years) with component A more evolved than the Sun and with masses of 0.95 and 0.62 (Fernandes *et al*., 1998) solar masses is found. It has low L_x and HK flux, and an age of 3–4 Gyr (Fernandes *et al*., 1998). *Hipparcos* data list a separation of 12.49″ and magnitude difference $\Delta m = 3.78$. Component A has been reported to be a spectroscopic binary, but this is not confirmed. *Hipparcos* data report unsolved photometric variability. For HD 4628, monitoring of its HK chromospheric flux (Duncan *et al*., 1991) indicates a uniformly low activity level, in excellent compatibility with a low L_x and long rotational period. For HD 6582, a spectroscopy binary with a period of 22 years and orbital eccentricity of 0.58 (Russell and Gatewood, 1984) is seen, with low HK flux. For HD 10360, it is a binary (period = 484 years) with a pair of very similar K0V dwarfs. *Hipparcos* data list a separation of 11.26″ and magnitude difference $\Delta m = 0.0$, with low HK flux. *Hipparcos* data report duplicity-induced variability. For HD 10476, it is listed as a binary, unresolved by speckle interferometry (Hartkopf and McAlister, 1984), but given as single in the Washington Double Star catalog (Mason *et al*., 2002). The HK lux is lower than solar. For HD 10700, chromospheric very low HK and Hα fluxes combine to suggest an age appreciably larger than solar. For HD 10780, high L_x and HK flux indicate a very young star. It is listed in the Washington Double Star catalog as a possible binary, but *Hipparcos* data confirm that the $V = 8.5$ magnitude nearby star has dissimilar proper motion components, ruling out a possible physical connection between these objects. For HD16160, it has very low L_x and HK flux lower than solar, yet Cutispoto *et al*. (2002) have detected HK emission with a central reversal in their analysis of fast-rotating stars, which is strong evidence of chromospheric activity and youth. Endl *et al*. (2002) have found its radial velocity constant within 10 m/s, ruling out "hot jupiters." For HD 20630, it has very high L_x and HK flux, with a short rotational period of 9.4 days; a high Hα flux is compatible with an age of ~1 Gyr. The Washington Double Star catalog gives component A as a spectroscopic binary. *Hipparcos* data report a photometric period of 9.09 days, in good agreement with the rotational period. For HD 20794, it has very low L_x and HK flux. For HD 22049, it has extremely high HK flux, high L_x, and a rotational period of 11 days; Hα is compatible with an age of a few hundred million years, a very young star. It is an astronomic binary with a period of 25 years according to the Bright Star Catalogue (Warren and Hoffleit, 1987), which was unconfirmed by Batten *et al*. (1989). A planetary companion has been detected (Hatzes *et al*., 2000) with a period of 2,502 days, minimum mass of 0.86 Jupiter masses, semimajor axis of 3.3 AU, and orbital eccentricity of 0.60. It is a possible microvariable (*Hipparcos*). For HD 26965, a triple system has been found: component B is a white dwarf, component C is a red dwarf with strong x-ray emission, and component A has L_x and HK flux similar to solar. There is an unsolved variable (*Hipparcos*). For HD 32147, it has very low L_x and HK flux. For HD 39587, it is a binary with a M-dwarf (period = 14.2 years), with mass of the secondary of approximately 0.15 solar masses (Irwin *et al*., 1992), and is a member of the 0.3-Gyr-old Ursa Major moving group (Castro *et al*., 1999). It has very high activity level in x-ray, HK, and Hα and a rotational period of 5.4 days, indicating probably a very young star. It has a possible microvariable (*Hipparcos*). For HD 100623, it has an activity level similar to the Sun's. For HD 101501, it has high L_x and HK flux and a rotational period of 17 days, indicating a young star. It has an unsolved variable (*Hipparcos*). For HD 102365, it has very low HK flux and Hα flux much lower than solar. Endl *et al*. (2002) have found its radial velocity as constant within ~15 m/s, ruling out "hot jupiters" for this object. For HD 109358, it has HK flux and L_x lower than solar. The Washington Double Star catalog lists a companion 0.1″away, citing data probably from McAlister (1978), and probably in error (M.C. Turnbull, personal communication, 2005), since this author gives a negative result for HD 109358. Batten *et al*. (1989) give it single status. The Washington Double Star catalog data probably refer to the first suggestion by Abt and Levy (1976) that this star might have a spectroscopic companion; this suggestion was convincingly refuted by Morbey and Griffiin (1987). For HD 114710, its HK flux places it at the boundary of active and inactive stars. Its x-ray luminosity is appreciably higher than the Sun's, yet its Hα flux is slightly lower than solar. These data, together with a rotational period of 12 days and a high lithium abundance of log N(Li) =2.60 (Mallik, 1998), place it very probably as appreciably younger than the Sun. The Washington Double Star catalog considers it a possible long-period spectroscopic binary. For HD 115617, it has Hα slightly higher than solar and HK lower than solar. For HD 128620 (α Centauri A), it is an astrometric binary (period = 81.2 years) with masses of 1.17 (A) and 1.09 (B) solar masses (Pourbaix *et al*., 1999), Hα flux slightly higher than solar, and HK flux and L_x lower than solar. It shows duplicity-induced variability (*Hipparcos*). For HD 128621 [α Centauri B (see HD 128620)], it has Hα flux higher than solar and HK flux and L_x lower than solar. It shows duplicity-induced variability (*Hipparcos*). For HD 131156, it is a binary (period = 151 years) with masses of 0.89 (A) and 0.79 (B) solar masses, very high L_x, HK, and Hα flux for spectra of the combined components, and rotational periods of 6.2 (A) and 11.5 (B) days. *Hipparcos* data list a separation of 7.07″ and magnitude difference $\Delta m = 2.27$, and report unsolved variability. For HD 149661, it has high L_x, high HK flux, and a rotational period of 21.3 days, indicating a young star. For HD 155885, it is a member of a triple system of K-dwarfs (period = 549 years), with a rotational period of 22.9 days (A), high L_x, and high HK flux, indicating a young star. *Hipparcos* data list a separation of 4.74″ and magnitude difference $\Delta m = 0.01$ and report duplicity-induced variability. For HD 156274, it is a binary, companion M-dwarf, with published periods ranging from 693 to 2,205 years. It has Hα flux equal to the Sun's, but is a very inactive star in L_x and HK. *Hipparcos* data list a separation of 8.66″ and magnitude difference $\Delta m = 3.22$ and report unsolved variability. For HD 165341, it is a spectroscopic binary with two K-dwarfs (period = 88 years, eccentricity = 0.50). It has a very high activity level, with a rotational period of 19.7 days (A). *Hipparcos* data list a separation of 1.59″ and magnitude difference $\Delta m = 1.84$ and report periodic photometric variability at 1.96 days. For HD 185144, it has low L_x and low HK flux. It is listed among the least variable stars in the *Hipparcos* database. For HD 190248, it has low L_x, low HK flux, and Hα flux slightly higher than solar. For HD 191408, it shows common proper motion with an M-dwarf; Endl *et al.* (2002) have found no radial velocity variation compatible with stellar or substellar companions. It has low HK flux, but its Hα flux higher than solar suggests an age of less than 1 Gyr, which is corroborated by detection of infrared excess compatible with a Vega-like disk (Laureijs *et al*., 2002). It is probably a young star. For HD 192310, it has low L_x and flux in the He I D3 line lower than solar (Saar *et al*., 1997). For HD 219134, it has low L_x and very low HK flux.

[b]HK refers to the chromospheric Ca II H & K line flux (see sources in text); Hα refers to the chromospheric flux data from Lyra and Porto de Mello (2005).

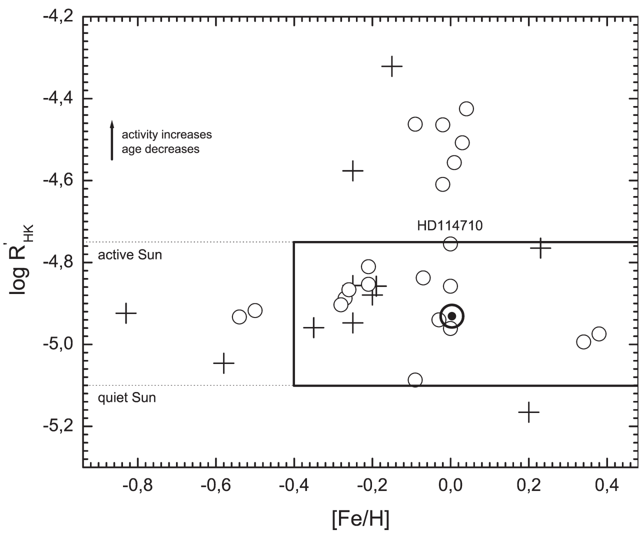
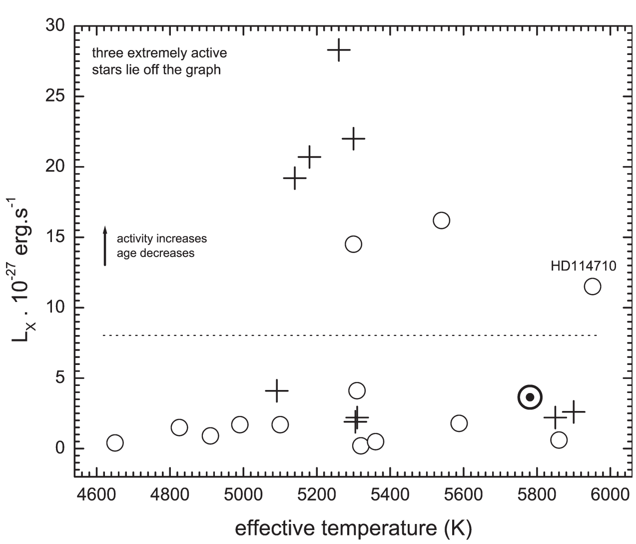


FIG. 2. The chromospheric absolute flux in the Ca II HK lines and stellar metallicity of the stars and the Sun. The horizontal dotted lines approximately bracket the range of the active and quiet Sun (Baliunas *et al.*, 1995). Stars are seen to divide themselves into active (log $R'_{HK} > -4.75$) and inactive (log $R'_{HK} < -4.75$) (Henry *et al.*, 1996). Old, magnetically quiet stars are found inside the black box; its horizontal limits bracket our cut in metallicity, [Fe/H] < -0.50, and the maximum metallicity found in our selected sample, [Fe/H] $\sim+0.4$. The star HD 114710 straddles the limit between active and inactive objects, but other data strongly point it to be a young star (see Fig. 3 and text). Crosses are binary or multiple stars.

with values of the atmospheric parameters T_{eff} and [Fe/H] spanning a fairly wide interval (Figs. 2 and 3). The relevant data for our discussion of the 33 solar-type stars selected by the (*B-V*)–M_V box are given in Table 1. It is noteworthy and lamentable that many of the spectroscopic analyses that provide the atmospheric parameters used in the present work leave much to be desired: some are still based on old, low signal-to-noise photographic plates, which suffer from random errors; some are not differential with respect to the Sun, and suffer from systematic effects; some determine their T_{eff} values using only one criterion, often ill-defined photometric calibrations that do not take into account the metallicity influence on the colors; and others are based on too few iron lines for a reliable estimation of [Fe/H]. It is clearly desirable to improve upon this situation, given the modern instrumental capabilities that can be trained upon such nearby and bright stars.

The task of weeding out unsuitable stars begins by eliminating binary and multiple systems from the sample. It is still controversial as to whether binaries should be given lower priority as abodes of complex life. Planetary stability around binary stars is possible in definite configurations around the system's center of mass and each of the components, given that the planet's orbital radius is sufficiently larger than the binary separation (external case, planet around center of mass), or *vice versa* (internal case, planet orbiting one of the components) (Pendleton and Black, 1993; Holmann and Wiegert, 1999; Quintana *et al.*, 2002). On the observational side, we further note

FIG. 3. The x-ray luminosities and stellar effective temperatures of the stars and the Sun. Again, stars divide themselves into active, L_X (10^{27}) > 10 erg/s, and inactive, below this limit. HD 114710 is seen to have a high x-ray flux. Also, its high lithium abundance and fast rotation reveal its youth (see text). The limit for inactive stars is then drawn at L_X (10^{27}) ~8 erg/s. Stars are seen to range from F-G (5,200 K < T_{eff} < 5900 K) to K-type (T_{eff} < 5,100 K) stars, and the latter make up the majority of the sample. Crosses are binary or multiple stars.



that Terrestrial Planet Finder mission requirements dictate a minimum acceptable binary separation of 10 arcsec to avoid overwhelming the planetary signal by shot noise from the secondary star (Lawson *et al*., 2004). Thus, single stars are to be preferred.

It is clear that many planetary dynamical instabilities exist in binary or multiple systems that are absent from single stars. In the case of binaries in eccentric orbits, excitation of resonances may lead to strong instabilities and highly eccentric planetary orbits, which endanger climate stability. It is a well-founded expectation, after all, that the formation and evolution of protoplanetary disks, and the planetesimal condensation processes, are probably different in a binary system as compared with those of an isolated star, which leaves at least some room to assume that binary systems are an unwanted complication. The probability of planetesimal condensation is constrained by the inclination between the accretion disk and the binary orbital plane: for large inclination angles the stability of planetary orbits is dramatically reduced (Quintana *et al*., 2002). We further note that the very few cases of planetary systems loosely similar to our own, among the 150 plus discovered, that have giant planets orbiting at >3 AU in approximately circular orbits were found around single stars.

A few binary or multiple systems, however, are sufficiently interesting in that they fulfill all adequate properties except multiplicity. These systems warrant a full dynamical analysis, and we will discuss these cases in a forthcoming paper. For our present purpose, we assume that general constitutions similar to that of the Sun's planetary system have a higher probabiblity of assembling in single stars. We found that 13 stars—39% of the full sample—are known astrometric and/or spectroscopic binaries, or multiple systems, and we disregard them; they are marked with crosses in Figs. 2 and 3.

The next step concerns the stellar metal abundance. Very metal poor stars, which we take here as those with approximately [Fe/H]<−0.5, are probably unable to build up a sufficiently massive telluric planet (Lineweaver, 2001). No giant planet has been found so far around a solar-type star with [Fe/H] less than approximately −0.6, and the detection rate of planetary companion falls off very sharply for stars less metal rich than the Sun (Santos *et al*., 2004; Fischer and Valenti, 2005), particularly for giant planets in orbits with periods of a few years. Constraints for the build-up of rocky planets are presumably even more severe. Therefore four stars—12% of the full sample—are set apart (Fig. 2).

Next we eliminated the very young, chromospherically active stars from our sample. These are not necessarily inadequate to living organisms, but judging from the example of the Earth, several Gyr must pass before a biosphere with complex life allows an O_2-rich atmosphere to develop. Recent estimates suggest that a major increase in the oxygen content of the Earth occurred when it was ~3 Gyr old (Blair Hedges *et al*., 2004), an event spurred by the advent of cell plastids and followed by the evolution of complex eukaryotes.

Furthermore, very young stars have their planets, if any, in the so-called heavy bombardment period, in which planets are routinely subjected to giant meteoroid and/or comet impacts up to the 100 km mark. Even very simple life forms might find it difficult to survive on planetary surfaces until the end of this phase, a few hundred Myr after the planetary system condensation. We thus concentrate our analysis in stars with at least a few Gyr of age.

In Figs. 2 and 3 we show, respectively, the Ca II HK chromospheric activity indicator against stellar metallicity and the x-ray luminosity against T_{eff}. Data on the absolute chromospheric flux on the Ca II HK lines come from Duncan *et al*. (1991), Baliunas *et al*. (1995), and Henry *et al*. (1996); their $<S>$ indices on the system of the Mount Wilson Observatory were converted to absolute fluxes according to the formula of Noyes *et al*. (1984). The x-ray luminosities come from Hünsch *et al*. (1998, 1999) and Schmitt and Liefke (2004). For some of the stars, data on the absolute flux in the Hα line are also available (Lyra and Porto de Mello, 2005). Chromospheric activity is a very steep function of age; the x-ray emission of young stars, in particular, quickly softens after 0.5 Gyr (Güdel *et al*., 1997), a fact of possible consequence to the evolution of the early planetary atmospheres. Young stars rapidly lose angular momentum by a magnetized wind after ~1 Gyr or so, and stars older than ~2 Gyr tend to pile up in low activity levels (Lyra and Porto de Mello, 2005). In this fashion, 10 stars are eliminated, a rather high fraction of 30% of the full sample. After the elimination of the multiple systems, metal-poor, and near-ZAMS stars, there remain 13 candidates: seven are K-type, five are G-type, and one is F-type.

ADDITIONAL CRITERIA: GALACTIC ORBITS AND ISOCHRONAL AGES AND MASSES

The next issue concerns the stellar orbits in the Galaxy. In Fig. 4, we plot the mean galactocentric radius (R_m) of the stellar galactic orbits with their orbital eccentricities (Woolley *et al*., 1970). These orbital eccentricities are not directly defined as in the two-body problem, as the actual orbits are open, but are defined as $e = (R_a - R_p)/(R_a + R_p)$, with R_a and R_p being the maximum (apogalacticum) and minimum (perigalacticum) distances, respectively, from the galactic center. The mean orbital distance is simply defined as $R_m = (R_a + R_p)/2$. The values of Woolley *et al*. (1970) were calculated with a rather simple model of the galactic potential and based on old pre-*Hipparcos* parallaxes. For these very nearby stars, however, the new parallaxes differ very little from those used by Woolley *et al*. (1970). Moreover, the mean distances R_m and orbital eccentricities calculated by Woolley *et al*. (1970) differ from those of Edvardsson *et al*. (1993), which were obtained from a more up-to-date code for the galactic potential, by ~0.4 kpc in R_m and ~0.04 in eccentricity, on average, for six stars in common. These differences have little bearing on our conclusions.

We have also calculated the *UVW* components of the stellar space velocities (Johnson and Soderblom, 1987) relative to the Sun from parallaxes and proper motions from *Hipparcos*, and we calculated radial velocities from the *SIMBAD* database. The components are plotted in Figs. 5 and 6, in the usual notation: *U*, *V*, and *W* are positive in the direction of the galactic center, galactic rotation, and north galactic pole, respectively. In these graphs, the 1σ and 2σ ellipsoids of the dispersions of the velocity components, with respect to the Sun and for stars with [Fe/H] > -0.4 in the Edvardsson *et al*. (1993) sample of thin disk stars, as calculated by Turnbull and Tarter (2003a), are also shown. The kinematic parameters are given for all 33 stars plus the Sun in Table 2. It can be seen that the range of the kinematic parameters is considerable.

In Fig. 4, the well-known "wedge" effect is apparent: stars with galactocentric distances far from the Sun's display systematically high eccentricity orbits. This is a necessary condition for them to be observed at all in the solar neighborhood. It is striking, as shown in Fig. 4, that the Sun possesses a very small orbital eccentricity, $e = 0.06$, which, along with its mean R_m near the co-rotation radius, makes for a near circular, stable orbit, and a small number of spiral arm passages. A large fraction of the local stars have orbital eccentricities higher than solar, which makes them but temporary dwellers of the solar vicinity. Their space velocities eventually carry them either far away to the outskirts of the galactic disk, where they are overtaken by the spiral arm density wave, or deeper into the inner disk, where they themselves overtake the waves. Both situations subject them to more encounters with star-forming regions than the Sun. Albeit with large uncertainty, the number of spiral arm encounters that a star experiences in its life can be calculated, but no comprehensive analysis on this, for the nearby population of solar-type stars,

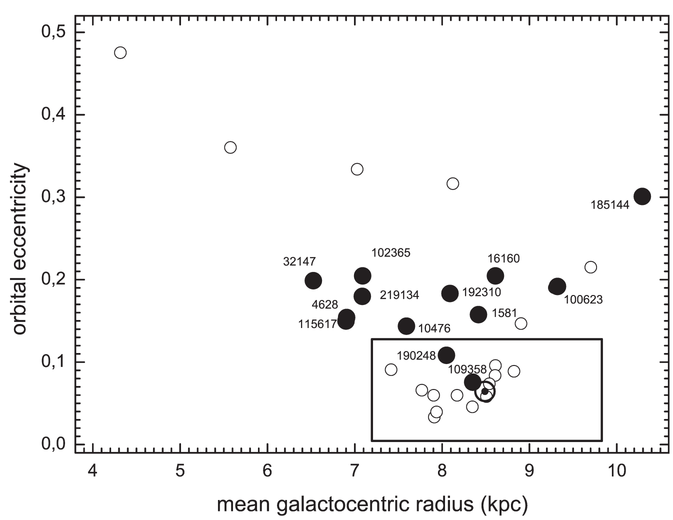


FIG. 4. The parameters of the stellar galactic orbits, the mean galactocentric distance R_m, and the orbital eccentricities. Each of the 13 stars that remained after eliminating the multiple systems, the metal-poor stars, and the near-ZAMS stars are labeled by HD number. The rectangular box merely depicts arbitrary limits for those stars for which a history of spiral arm passages similar to the Sun's is expected.

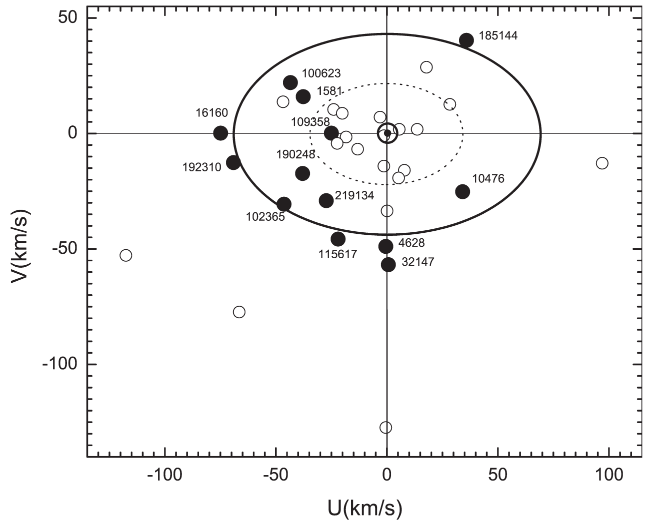


FIG. 5. The *U* and *V* velocity components of the full sample. The 1σ and 2σ velocity ellipsoids for thin disk stars with [Fe/H] > -0.4 in the sample of Edvardsson *et al*. (1993), as calculated by Turnbull and Tarter (2003a), are shown. Each of the 13 stars that remained after eliminating the multiple systems, the metal-poor stars, and the near-ZAMS stars are labeled by HD number.

has been published to the best of our knowledge, nor has a systematic, volume-limited, and up-to-date review of the mean galactocentric distances and orbital eccentricities of nearby stars. Nevertheless, quantitative discussions of the hazards of spiral arm crossing remain highly speculative to this date. Therefore, we are not expelling stars from our final best candidate list on the basis on the galactic orbit parameters. In Fig. 4, we merely show, inside the box, the three stars with orbital parameters truly similar to the Sun's, for which a similar history of passages through the galactic spiral arms could be reasonably expected. Another group of nine stars have orbital eccentricities within ~0.15–0.20, and their galactic orbits have probably allowed a larger number of spiral arm passages than the stars with eccentricities less than ~0.10. One star, HD 185144, has such a large orbital eccentricity as to have very probably experienced a totally different history of interaction with the spiral arms than that of the Sun.

In Figs. 5 and 6, it is seen that few stars fall significantly outside the 2σ ellipsoids either in the *UV*-plane or the *VW*-plane. The *UV*-plane is the most relevant to our discussion, since the *U* and *V* velocities determine the orbital eccentricity and mean galactocentric distance in the plane of the galactic disk. Thus, they determine the number of spiral arm passages undergone. The *W* component actually determines the amount of time the stars spend vertically away from the galactic disk, as well as the maximum distance reached above the disk. Larger values of this component may merely mean that, unfavorable *U* and *V* com-

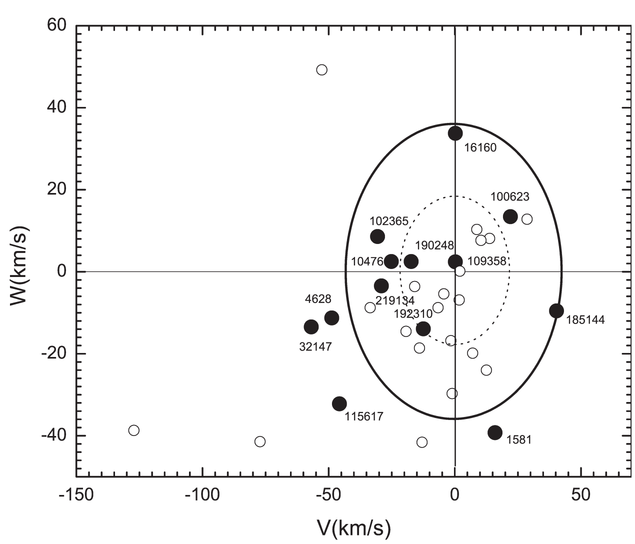


FIG. 6. The *V* and *W* velocity components of the full sample. The 1σ and 2σ velocity ellipsoids for thin disk stars with [Fe/H] > -0.4 in the sample of Edvardsson *et al*. (1993), as calculated by Turnbull and Tarter (2003a), are shown. Each of the 13 stars that remained after eliminating the multiple systems, the metal-poor stars, and the near-ZAMS stars are labeled by HD number.

Table 2. Space Motion Components, with Respect to the Sun, and Galactic Orbit Parameters for the 33 Solar-Type Stars Within 10 pc of the Sun That Are Candidates for Astrobiologically Interesting Stars

	km/s				
HD	*U*	*V*	*W*	*Eccentricity*	R_m *(kpc)*
Sun	0	0	0	0.06	8.5
1581	−38	+16	−39	0.16	8.4
4614	−18	−2	−17	0.06	8.2
4628	0	−49	−11	0.15	6.9
6582	−1	−127	−39	0.48	4.3
10360	−1	−14	−19	0.03	7.9
10476	+34	−25	+3	0.14	7.6
10700	+18	+29	+13	0.22	9.7
10780	−13	−7	−9	0.04	7.9
16160	−75	0	+34	0.20	8.6
20630	−22	−4	−5	0.05	8.4
20794	−67	−77	−41	0.36	5.6
22049	−3	+7	−20	0.09	8.8
26965	+97	−13	−42	0.32	8.1
32147	+1	−57	−13	0.20	6.5
39587	+14	+2	−7	0.10	8.6
100623	−43	+22	+13	0.19	9.3
101501	+8	−16	−4	0.06	7.9
102365	−46	−31	+9	0.21	8.4
109358	−25	0	+2	0.08	8.4
114710	−47	+14	+8	0.15	8.9
115617	−22	−46	−32	0.15	6.9
128620	−24	+10	+8	0.08	8.6
128621	−20	+9	+10	0.08	8.6
131156	+6	+2	0	0.07	8.5
149661	−1	−1	−30	0.06	8.5
155885	0	−34	−9	0.09	7.4
156274	+28	+13	−24	0.19	9.3
165341	+5	−19	−15	0.07	7.8
185144	+36	+40	−10	0.30	10.3
190248	−38	−17	+3	0.11	8.1
191408	−118	−53	+49	0.33	7.0
192310	−69	−13	−14	0.18	8.1
219134	−27	−29	−3	0.18	7.1

The Sun is included as the first entry. Columns 2–4 give the velocity components (in km/s), respectively, positive in the direction of the galactic center, the galactic rotation, and the galactic north pole. Proper motions and distances were taken from the *Hipparcos* catalogue; radial velocities are from the *SIMBAD* database. Columns 5 and 6 give, respectively, the orbital eccentricity and the mean galactocentric distance, taken as the mean of the apogalactic and perigalactic distance (Woolley *et al.*, 1970), normalized to a solar galactocentric distance of 8.5 kpc.

ponents notwithstanding, the star will tend to experience fewer passages inside the disk and fewer encounters with spiral arms. In the *UV*-plane, the outliers are HD 4628, 16160, 32147, 102365, 115617, and 185144, though none of them significantly. As will be seen below, all of these are interesting candidates after consideration of all criteria. In the *VW*-plane, HD 1581, 4628, 32147, and 115617 are outliers. Three stars—HD 4628, 32147, and 115617—have all component velocities rather distinct from the Sun's. Only a few stars, as shown in Figs. 5 and 6, possess velocity components within 1σ of the solar ones or nearly so: HD 10476, 109358, and 190248. The last two also very closely share the galactic orbits of the Sun, as shown in Fig. 4.

The criteria applied above excluded from our final sample any star with an age of 1–2 Gyr. For older stars, age determination from chromospheric activity is uncertain (Pace and Pasquini, 2004; Lyra and Porto de Mello, 2005), and thus one must resort to isochronal fitting when attempting to constrain ages. It is known that chromospheric activity indicators are very sensitive to age for the first ~2 Gyr of a star's life (Güdel *et al*., 1997; Pace and Pasquini, 2004; Lyra and Porto de Mello, 2005; Ribas *et al*., 2005), but lose considerably this sensitivity as stars age, so that beyond the solar age, ~4.6 Gyr, virtually no age-discrimination ability remains. At this point, for stars older than the solar age, theoretical isochrones possess good age discrimination, provided that the stellar T_{eff} and metallicity are known with sufficient accuracy and the stars are not too close to the ZAMS. Therefore, we now examine each star in detail in the theoretical HR diagrams of Kim *et al*. (2002) and Yi *et al*. (2003) to assess their masses and isochronal ages. Each diagram has been calculated, using routines provided by the authors, for a set of stellar masses ranging from 0.6 to 1.3 solar masses, which correspond to a given metallicity. Taking into account, conservatively, the uncertainty of the T_{eff} values and metallicities of our sample due to the heterogeneity of sources and the errors inherent to spectroscopic analyses, we have grouped the candidate stars in intervals of ±0.1 dex around a value [Fe/H] chosen such that each star is evaluated in the HR diagram that corresponds to a metallicity very similar to its own. For the six stars with more than three spectroscopic determinations of T_{eff} and [Fe/H], we determined the standard deviations around the mean of these quantities considering all published values as, respectively, 70 K and 0.08 dex. The results are shown in Figs. 7–14, where we adopt 100 K and 0.1 dex, rather conservatively, as an estimate of the respective uncertainties in T_{eff} and [Fe/H], respectively.

We note that the results of the HR diagram analysis are weakly dependent on the T_{eff} and

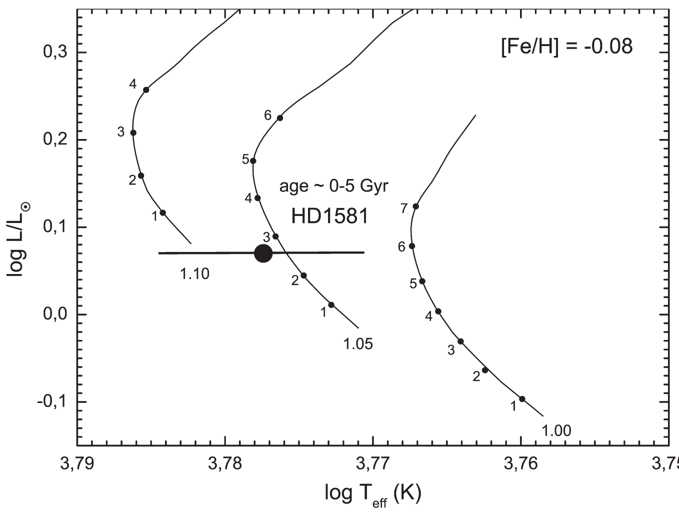


FIG. 7. The star HD 1581 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track; the full dots alongside the tracks give the ages in Gyr; the luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_\odot$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown.

[Fe/H] errors as long as the goal remains at identifying stars that are older than a few Gyr; better age discrimination would require much more accurate T_{eff} values. Some allowance also has to be made for uncertainties in the models, even though the Sun's state of evolution is well reproduced for the correct age (Fig. 12).

The CHZ positions essentially depend only on the stellar luminosity, known to better than 2% in all cases studied here; effects on these positions of varying the stellar T_{eff} values are second order (Kasting *et al.*, 1993). The uncertainty in determining the CHZ locations thus come almost exclusively from the planetary climate theory. Stellar ages inferred from HR diagrams do depend rather heavily on T_{eff} but are also constrained by the chromospheric activity indicators. The conservative allowance of 100 K we made for the T_{eff} errors, even though affecting the age estimates, does not change any of the conclusions presented.

It is worth noting that five stars in Table 1 were finally rejected solely because of their very young age. These stars in principle are good candidates to look for young Earth-like planets in their CHZs, even though it is not reasonable to expect that biological activity has altered planetary atmospheres to the point of allowing the detection of biomarkers. These stars were not subjected to the isochronal age analysis described in the next section. They could be considered as targets of secondary interest; they are HD 10780, 20630, 22049, 101501, 114710, and 149661. Included is the famous nearby star Epsilon Indi, already known to possess a planetary companion (Hatzes *et al.*, 2000).

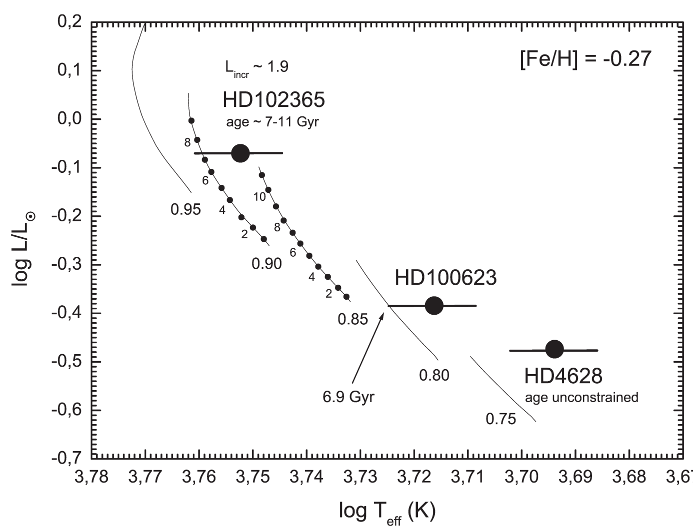


FIG. 8. The stars HD 4628, 100623, and 102365 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The full dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_\odot$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

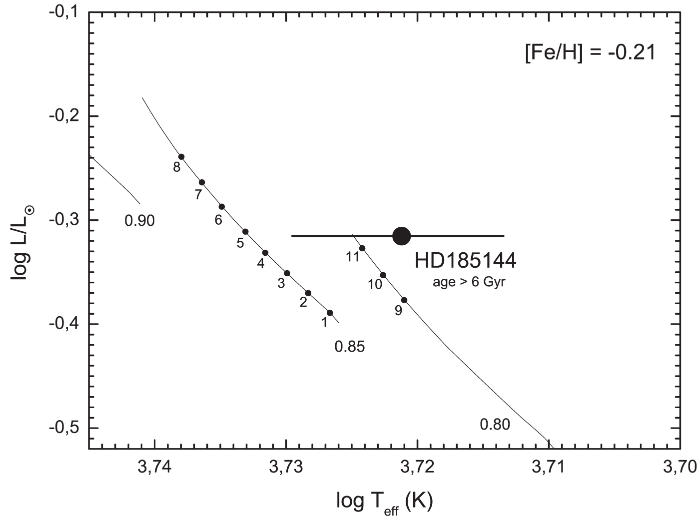


FIG. 9. The star HD 185144 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The full dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_\odot$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

DISCUSSION

The 13 stars that survived all our criteria differ somewhat in mass, age, metallicity, and orbital properties. A qualitative assessment of these is given in Table 3, where stars are rated according to their similarity with the solar parameters. According to the models of Kasting *et al.* (1993), there are definite luminosity limits for the succesful operation of the planetary climatic feedback mechanisms. These limits are given as three cases. In the so-called "pessimistic" scenario, the feedback is considered to fail: at the "hot" end, with the onset of ocean evaporation, which begins at a luminosity of $L/L_\odot \sim 1.10$; at the "cool" end, with the formation of CO_2 clouds, which begin at $L/L_\odot \sim 0.53$. In a somewhat less stringent view, failure happens at the "hot" end only with the runaway greenhouse by which water loss happens in a short time scale as compared with geologic time. This corresponds to $L/L_\odot \sim 1.41$. At the "cool" end, the planet cannot be further warmed when the maximum greenhouse limit is reached, at which time the partial pressure of CO_2 is so high that clouds form and increase the planetary albedo, at a luminosity of $L/L_\odot \sim 0.36$. A very optimistic possibility discussed by Kasting *et al*. (1993) is the case where Venus is considered to have had a water ocean for as long as a few Gyr, and Mars is considered to have been sufficiently warm in its early evolution to have large standing bodies of water. The corresponding luminosity limits, respectively, would be $L/L_\odot \sim 1.76$ and $L/L_\odot \sim 0.32$ in this case. Considerable

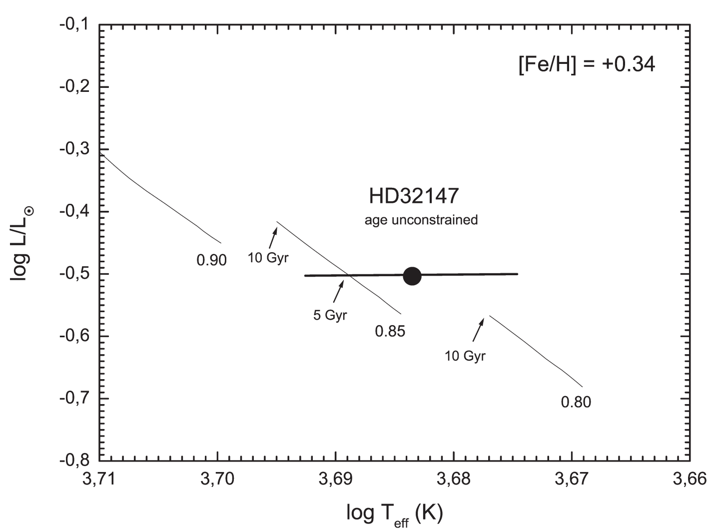


FIG. 10. The star HD 32147 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The full dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_\odot$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

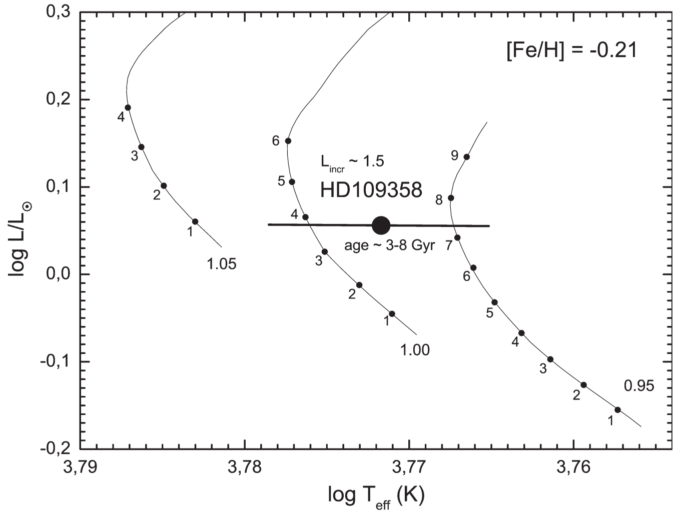


FIG. 11. The star HD 109358 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The full dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_{\odot}$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

uncertainty still affects the luminosity values for each of the above cases.

For the present discussion, the important issue is that there is a maximum luminosity increase a star may undergo and, therefore, a maximum age, once a planet is initially placed in the most favorable configuration for its maximum stay at the CHZ (its outer limit) before the climatic feedback stops working. This maximum luminosity increase for the "pessimistic" case, the one we shall adopt here, would thus be L_{incr} ~2, being slightly mass dependent; it is L_{incr} ~4 for the less rigid case. These limits also suffer from appreciable variation due to planetary properties. Franck *et al*. (2003) found that planets with larger ocean-to-land ratios might be more robust to the external forcing of the stellar radiation, having extended habitability life spans.

In Figs. 7–14, an evaluation of the evolutionary state and age of the stars can be made whenever the data allow a good match with theory. Metallicity is a key quantity. Its accurate determination enables a correct choice of the set of evolutionary diagrams to be used in the determination of the stellar mass and age. The T_{eff} more directly affects the mass and age determinations. Metallicity also has an important bearing on the evolutionary time scale. At the same mass, metal-poor stars have less opacity and, therefore, have their radiative energy blanketed farther away from the core. This makes them more luminous and their rate of evolution faster, and it takes them less time to grow too luminous for a given CHZ location. The difference is not inconsiderate. For a solar mass star and evolutionary times comparable to the solar age, the time required to reach a given

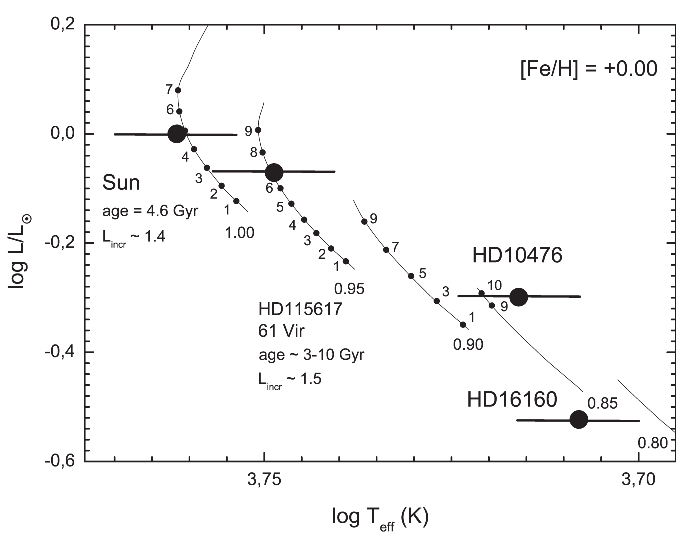


FIG. 12. The stars HD 115617, HD 10476, and HD 16160, along with the Sun, plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The full dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_{\odot}$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

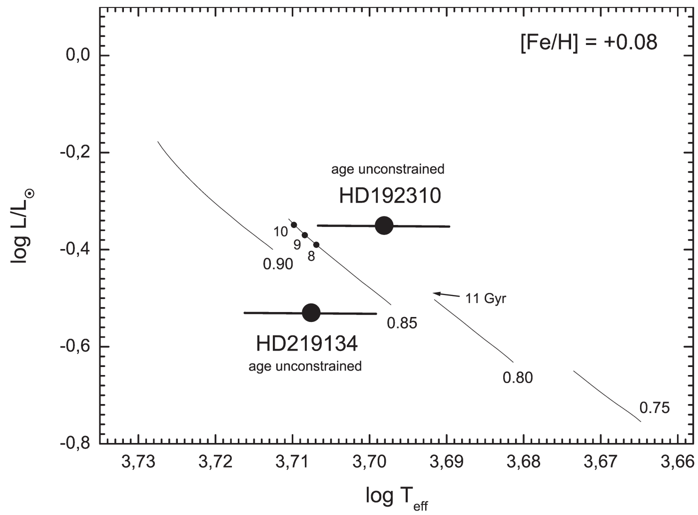


FIG. 13. The stars HD 192310 and HD 219134 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The full dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_{\odot}$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

increase in luminosity is ~20% less for a star with half the solar metal content. The corresponding time is ~30% longer for a star with double the solar metal content. This evolutionary time scale can therefore be more than 50% longer for a metal-rich star, as compared with a metal-poor star, for the same mass, a situation that affects considerably the lifetime of planets within the stellar CHZs.

Candidate star systems with astrobiological potential

Figure 7 shows HD 1581 to be a very good candidate, since its mass and metallicity are close to solar. Its position in the HR diagram might be compatible with a near-ZAMS status, judging by the T_{eff} error bar, but the chromospheric activity data consistently point toward an age greater than 3 Gyr. HD 1581 could be compatible with the solar age for a slightly lower mass. The data, therefore, place HD 1581 as very probably slightly more massive and slightly younger than the Sun, and it has probably also suffered less evolutionary change.

In Fig. 8, three candidates with [Fe/H] = −0.27 are plotted. HD 102365 turns out to be an interesting candidate, being slightly less massive than the Sun, but considerably older. Its age can be confidently determined as larger than ~7 Gyr. HD 102365 has suffered a luminosity increase, since the ZAMS phase, L_{incr} ~1.9, approaches the limits for the "pessimistic" case, and this, along with an appreciably lower metallicity, would suggest a not so high priority. HD 100623 is not very well fitted by the theoretical tracks, but it is

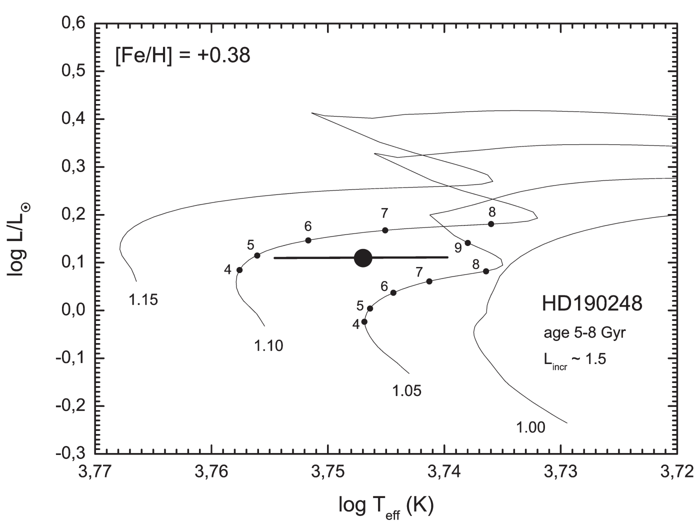


FIG. 14. The star HD 190248 plotted in the theoretical HR diagram. Each evolutionary mass is labeled by its mass, along each track. The solid dots alongside the tracks give the ages in Gyr. The luminosity increase L_{incr} undergone by the star since the ZAMS is given, when relevant. The error bars correspond to an uncertainty of 100 K in T_{eff}. In luminosity, the average uncertainty is in 0.01 in log $L/L_{\odot}$, and thus the error bars in luminosity are comparable to, or smaller than, the stellar dot size shown. The evolutionary tracks have been truncated at 10 Gyr whenever relevant.

TABLE 3. THE 13 FINAL CANDIDATES FOR ASTROBIOLOGICALLY INTERESTING STARS

HD	Hipparcos	*Gliese*	*Name*	*Mass*	*Age*	*[Fe/H]*	*Eccentricity*	*Rating*
1581	1559	17	ζ Tuc	~	~	~	>	***
4628	3765	33	—	<	?	<	>	—
10476	7981	68	107 Psc	<	>	<	>	—
16160	12114	115	—	<	?	~	>	*
32147	23311	183	—	<	?	>	>	—
100623	56452	432	—	<	?	<	>	—
102365	57443	442	—	<	>	<	>	—
109358	61317	475	β CVn	~	~	<	~	***
115617	64924	506	61 Vir	~	~	~	>	***
185144	96100	764	σ Dra	<	>	<	>	—
190248	99240	780	δ Pav	>	~	>	~	**
192310	99825	782	—	<	>	~	>	*
219134	114622	892	—	<	?	~	>	*

For ease of reference, the Gliese (Gliese and Jahreiss, 1979) numbers are also given for the stars, besides their *Hipparcos* numbers and names. The stars are ranked by comparing their mass, metallicity, age, and galactic orbit eccentricity with the solar values. For each parameter similar to the corresponding solar one, we give, qualitatively, in the respective column the symbol "~," and one asterisk is added to the final column, which ranks the stars according to the number of parameters similar to the solar ones. For parameters larger and smaller than solar, the symbols ">" and "<" are given, respectively. For poorly constrained parameters, "?" is given in the corresponding column.

barely compatible with a mass of 0.80 $M_\odot$ and an age ~7 Gyr. HD 4628 is not fitted at all by the models, lying well above the tracks for any reasonable age. Its age cannot be constrained. Lebreton *et al*. (1999) have discussed the incompatibility of theoretical models and the stellar positions in the HR diagram for moderately metal-poor stars, [Fe/H] < -0.45. These stars are displaced toward lower $T_{\rm eff}$ values than the models predict, exactly the effect seen in Fig. 8. Lebreton *et al*. (1999) have attributed this discrepancy to deviations from local thermodynamic equilibrium (LTE) and the sedimentation of helium and heavy metals toward the stellar interiors in time scales approaching 10 Gyr. In their analysis, this effect is enhanced for the lower mass stars. Taking into account the combined effect of non-LTE corrections and the diffusion of metals improves considerably the agreement between theory and observations. Another possible source of the inability of the models of Kim *et al*. (2002) and Yi *et al*. (2003) to reproduce the low mass, low metallicity stars is the inherent difficulty in determining the $T_{\rm eff}$ of these objects. The differential technique is normally applied in the spectroscopic analyses of solar-type stars, and the greater the difference between the stellar and solar $T_{\rm eff}$, the higher the possibility of systematic errors that have a direct bearing on the [Fe/H] determination. Thus, the results for the K stars must be regarded as less reliable. In the present case, HD 100623 could be considered as marginally compatible with an age higher than the Sun, while HD 4628 is unconstrained in age and has a probable mass close to the lower limit for a planet to remain tidally unlocked inside the CHZ.

In Fig. 9, we consider the slightly metal-poor star HD 185144, which is reasonably compatible with an age greater than ~8 Gyr and a mass of 0.80 $M_\odot$. Assigning lower masses to it, however, would lead to unreasonable ages greater than that of the galactic disk, ~8–10 Gyr (del Peloso *et al*., 2005b). In Fig. 10, HD 32147 is seen to be another case of a K-dwarf with totally unconstrained age. Its $T_{\rm eff}$ error bar allows any age value from the ZAMS to the age of the Galaxy, while its mass lies probably in the 0.80–0.85 $M_\odot$ range. HD 32147 has a rather high metallicity of [Fe/H] = +0.34, and non-LTE effects are not a reasonable explanation for the discrepancy (Lebreton *et al*., 1999). A very old age and metal diffusion could be the culprits here.

Figures 11 and 12 present two excellent candidates: HD 109358 and HD 115617. HD 109358 is slightly metal poor, its mass is strictly within the solar range, and its age is well constrained in the 3–8 Gyr range. Its luminosity has increased since the ZAMS phase to $L_{\rm incr}$ ~1.5, similar to the Sun, $L_{\rm incr}$ (Sun) ~1.4. HD 115617 is plotted along with the Sun, HD 10476, and HD 16160 in a diagram that corresponds to the solar metallicity. Its age range lies within the 3–11 Gyr interval, and it is compatible with a mass slightly lower than that of the Sun, an age fairly similar, though with a good degree of uncertainty. HD 10476 is essentially unconstrained in age, but could be compatible with ~6 Gyr, with its mass slightly larger than 0.85 $M_\odot$. If HD 10476 is indeed an old star, heavy element diffusion could explain its discrepant position in the HR diagram. HD16160 lies below the ZAMS, but its T_{eff} error bar places it within compatibility with a mass in the 0.80–0.85 $M_\odot$ range, even though its age cannot be constrained in the diagram. This solution would place it at the ZAMS, and we note that its chromospheric activity indicators in the literature are inconsistent (Table 1). Some suggest low activity and old age, while others suggest the opposite, which leaves the status of this object uncertain.

Figure 13 presents two low mass candidates: HD 192310 and HD 219134. HD 192310 is barely compatible, at the hot end of its T_{eff} uncertainty, with a mass of ~0.85 $M_\odot$ and a very old age. Lower masses are untenable since they would lead to unreasonably old ages. HD 192310's discrepant position in the HR diagram could again be explained by metal diffusion and old age. HD 219134 lies below the ZAMS but could be reconciled with a mass of ~0.80 $M_\odot$ if its T_{eff} was cooler by ~150 K. Yet even then it would be placed at the ZAMS, and all chromospheric activity data discredit this option. HD 219134 is less active than HD192310, which is already an inactive star.

The last candidate, HD 190248, is shown in Fig. 14. It is the nearest of the 13 final candidates and a super-metal rich star (del Peloso *et al.*, 2005a). HD 190248 is more luminous than the Sun and certainly an evolved star in the process of becoming a subgiant and close to the turn-off point. HD 190248's age is well constrained, in the 5–8 Gyr interval, by its position in the locus of the evolutionary tracks where they are parallel to the T_{eff} axis, even though HD 190248 is close to the region in the HR diagram where the isochrones overlap and an unambigous age determination becomes difficult. Its luminosity has increased ~50% since zero age, which is similar to that of the Sun. It is a fair example of slow stellar evolution due to a high metallicity. At its derived mass of 1.08 $M_\odot$, a solar metallicity star aged 8 Gyr would already be a subgiant, with a luminosity 2.5 times greater than solar. High metallicity stars more massive than the Sun may thus become interesting astrobiological targets, owing to their slow evolution along with their wide CHZs due to high luminosity. HD 190248 is certainly more massive and cooler than the Sun, and a rather interesting object. Its high metallicity probably lies at the high tail of the thin disk distribution (Castro *et al.*, 1997; Bodaghee *et al.*, 2003). HD 190248's old age, coupled with its high metallicity, implies that it is a fairly non-typical object for its epoch of formation and galactic orbit, which closely matches that of the Sun (Fig. 4). Turnbull and Tarter (2003b) have considered it the nearest interesting SETI target. Santos *et al*. (2004) found that, at the metallicity of HD 190248, 30% of nearby stars possess at least one giant planet, most of them in close-in orbits, yet none has been reported so far for HD 190248. To date, not one of our 13 final candidates have had any detection of planetary companions.

We consider the optimum candidates to be those stars with mass and metallicity close to the solar ones, and of an age compatible with our working hypothesis that a minimum of ~3 Gyr must have elapsed before a putative habitable planet can develop an atmospheric O_2 content high enough to be remotely detected. The last criterion is a stellar orbit reasonably similar to that of the Sun. In Table 3, we qualitatively rank the stars as candidates by comparing their mass, age, metallicity, and galactic orbit with those of the Sun, giving one asterisk in the final column for each parameter similar to the solar one.

A few candidate stars have undergone a greater increase in luminosity since the ZAMS phase than the Sun and are on their way to becoming a subgiant. Present subgiants may have been pleasant hosts to planets suitable to complex life during their stay in the main sequence, but as they evolve, the planet is hard put to remain inside the CHZ. The Earth will eventually be rendered uninhabitable by the increased solar luminosity; at a luminosity of $L/L_\odot$ ~1.1, water loss begins. In Fig. 12, it can be seen that the models of Kim *et al*. (2002) and Yi *et al*. (2003) place this event approximately 1 Gyr in the future. However, Franck *et al*. (1999, 2000a) have modeled the evolution of the CO_2 content in the Earth's atmosphere, coupled with the variation of continental area, the weathering rate, and the bioproductivity of the biosphere (biomass per area per time), under the influence of the external forcing of the Sun's luminosity evolution for geostatic and geodynamic planetary models. They concluded that the lowering of the CO_2 partial pressure necessary to counter the forcing of the increasing solar radiation will render photosynthesis impossible between 0.6 to 2.0 Gyr from now, with the results being relatively insensitive either to the adopted model of continental area evolution or to the stellar mass involved. It seems possible that such issues ultimately govern a planet's stay inside the CHZ. Therefore, stars close to the maximum luminosity increase adopted by us for the "pessimistic" case, ~2, are less promising candidates. Moreover, the conclusions of Franck *et al*. (2003), on the importance of land/ocean coverage for long-term habitability, imply that planets with larger ocean coverage are more robust and are habitable for longer periods. It remains uncertain, however, whether these worlds provide useful biomarkers distinguishable from natural abiotic processes, at least for an ocean coverage approaching 100% (Léger *et al*., 2004). It is interesting to note that, if rocky planets with higher ocean/land ratios have indeed extended habitability time scales, there might be an optimum metallicity interval to produce these worlds. The probability of the formation of "ocean planets" that are totally covered by water and, therefore, unable to close the silicate–carbonate cycle is probably tied to the stellar host's metallicity in the sense that a larger fraction of volatiles can be more easily assembled in more massive planets. It is reasonable to suppose that the total volatile mass scales with planetary mass and therefore with R^3, with R being the planetary radius. The planetary surface scales with R^2, and it seems possible to conclude that the volatile fraction per surface area, which might be roughly taken as equivalent to the ocean coverage, other variables being equal, scales with R and, therefore, with planetary mass. High metallicity stars then could facilitate forming planets slightly more massive than Earth, and therefore more robust to failure of the carbonate–silicate cycle, but too high a metallicity might imply a higher probability of forming overmassive terrestrial planets and, thus, a greater difficulty in forming truly Earth-like planets with plate tectonics interacting both with a water surface and with land biota.

A possible drawback to six of the final 13 candidates (Table 3) is their moderately low metallicity, ~50–60% solar, which may carry a lower probability of formation of telluric planets, though recent results imply a constant frequency of giant planets in stars within the range of metallicity from solar to one-fourth solar (Santos *et al*., 2004). Such lower metallicity might also imply, for hypothetical telluric planets, a higher abundance ratio of Mg-Si to Fe [according to known trends in galactic chemical evolution (Edvardsson *et al*., 1993)], a different mantle–core ratio, different liquid metallic core convection properties (and consequently a different magnetic field), and a different content of radiogenic isotopes (Gonzalez *et al*., 2001), all of which presumably have a bearing on the habitability of telluric planets.

CONCLUSIONS

After all criteria are considered, we have 13 good candidates for nearby "biostars," a fraction of roughly 40% of the nearby solar-type stars, 7% of all stars within 10 pc (excluding a possible incompleteness for the latest M-dwarfs). Three of these candidates—HD 1581 (ζ Tucanae), HD 109358 (β Comae Berenicis), and HD 115617 (61 Virginis)—rank especially high in that they have properties reasonably similar to the Sun's with regard to mass, age, metallicity, and evolutionary status. If we relax somewhat the orbital eccentricity criterion and allow for the fact that HD 1581 and 115617 have orbital eccentricities e ~0.15, these two candidates would also rank well in all criteria. We suggest that these objects should be high-priority targets in SETI surveys and future space interferometric missions designed to detect life by way of the ozone atmospheric infrared biosignature of telluric planets.

The basic astrophysical information on nearby solar-type stars is fairly complete, though in many cases still inaccurate or of low quality. Moreover, important details are still lacking. Chromospheric activity indicators provide a broader picture that constrain stellar ages. However, it is well known that different chromospheric flux diagnostics may lead to different conclusions. For example, it has been suggested that the Sun is less active and shows a longer cycle (Hall and Lockwood, 2000) than its almost perfect twin HD 146233 (Porto de Mello and da Silva, 1997) as judged by its Ca II HK flux. However, when evaluated by its Hα flux, the Sun does not seem to be an exceptional star (Lyra and Porto de Mello, 2005). Isochronal ages for moderately evolved stars may be well constrained in theoretical HR diagrams, if metallicities and effective temperatures are known with high accuracy. These call for detailed, high-quality homogeneous spectral analyses. It would also be very interesting to study the abundances of elements other than Fe in the photospheres of the "biostars."

We fully anticipate that the astrobiological suitability criteria here discussed will have to be revised as our knowledge deepens. Important present themes of research include more detailed models of the planetary climate stability and a possible relaxation of the exclusion of late-K stars as inadequate, as well as a clearer assessment of the importance of stellar metallicity for the formation of planets. Also, an analysis of the effective biological dangers of galactic orbits that subject stars to frequent crossings of spiral arms would be of great interest.

An observational program to extend the present analysis to greater distances from the Sun and determine homogeneously, with high-quality data, T_{eff} values, chemical composition, chromospheric activity level, evolutionary status, mass, and the age of the astrobiologically interesting stars of the solar neighborhood is under currently way.

ACKNOWLEDGMENTS

G.F.P.M. acknowledges financial support by FAPESP/Projeto Temático (grant 00/06769-4), CNPq/Conteúdos Digitais (grant 552331/01-5), the CNPq/MEGALIT/Institutos do Milênio program, and a FAPERJ (grant APQ1/26/170.687/2004). E.F.d.P. thanks FAPERJ for a postdoctorate grant (E-26/150.567/2003) and the CNPq for a DTI grant (382814/2004-5). L.G. thanks CNPq/Brazil for a PIBIC grant. This research has made use of the *SIMBAD* database, operated at the Centre de Données Stellaires, Strasbourg, France. We thank the two anonymous referees for comments and criticism that considerably improved the final version of this paper.

ABBREVIATIONS

CHZ, continuously habitable zone; Gyr, billion years ago; HR diagram, Hertzprung-Russell diagram; Myr, million years ago; LTE, local thermodynamic equilibrium; pc, parsecs; SETI, search for extraterrestrial intelligence; ZAMS, zero age main sequence.

REFERENCES

Abia, C., Rebolo, R., Beckman, J.E., and Crivellari, L. (1988) Abundances of light metals and Ni in a sample of disc stars. *Astron. Astrophys*. 206, 100–107.

Abt, H. and Levy, S.G. (1976) Multiplicity among solar-type stars. *Astrophys. J. Suppl. Ser*. 30, 273–306.

Adelman, S. (2001) Hipparcos photometry: the least variable stars. *Astron. Astrophys*. 367, 296–297.

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V. (1980) Extraterrestrial cause for the Cretaceous Tertiary extinction. *Science* 208, 1095.

Balázs, B. (2000) SETI and the galactic belt of intelligent life. In *ASP Conference Series 213, Bioastronomy '99: A New Era in Bioastronomy*, edited by G.A. Lemarchand and K.J. Meech, Astronomy Society of the Pacific, San Francisco, pp. 441–444.

Baliunas, S.L., Donahue, S.A., Soon, W.H., Horne, J.H., Frazer, J., Woodard-Eklund, L., Bradford, M., Rao, L.M., Wilson, O.C., Zhang, Q., Bennet, W., Briggs, J., Carroll, S.M., Duncan, D.K., Figueroa, D., Lanning, H.H., Misch, A., Mueller, J., Noyes, R.W., Poppe, D., Porter, A.C., Robinson, C.R., Russell, J.A., Shelton, J.C., Soyumer, T., Vaughan, A.H., and Whitney, J.H. (1995) Chromospheric variations in main sequence stars II. *Astrophys. J*. 438, 269–287.

Batten, A.H., Fletcher, J.M., and MacCarthy, D.G. (1989) *Publications of the Dominion Astrophysical Observatory, Vol. XVII: Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems*, Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, BC.

Becker, L., Poreda, R.J., Basu, A.R., Pope, K.O., Harrison, T.M., Nicholson, C., and Iasky, R. (2004) Bedout: a possible end-Permian impact crater offshore of Northwestern Australia. *Science* 304, 1469–1475.

Benton, M.J. and Twitchett, R.J. (2003) How to kill (almost) all life: the end-Permian extinction event. *Trends Ecol. Evol*. 18, 358–365.

Blair, D.G., Norris, R.P., Troup, E.R., Twardy, R., Wellington, K.J., Williams, A.J., Wright, A.E., and Zadnik, M.G. (1992) A narrow band search for extraterrestrial inteligence (SETI) using the interstellar contact channel hypothesis. *Monthly Notices R. Astron. Soc*. 257, 105–109.

Blair Hedges, S., Blair, J.E., Venturi, M.L., and Shoe, J.L. (2004) A molecular timescale of eukaryote evolution and the rise of complex multicellular life. *BMC Evol. Biol*. 4, 2–10.

Bodaghee, A., Santos, N.C., Israelian, G., and Mayor, M. (2003) Chemical abundances of planet-host stars: results for alpha and Fe-group elements. *Astron. Astrophys*. 404, 715–727.

Castro, S., Michael Rich, M., Grenon, M., Barbuy, B., and McCarthy, J.K. (1997) High-resolution abundance analysis of very metal rich stars in the solar neighborhood. *Astron. J*. 114, 376–387.

Castro, S., Porto de Mello, G.F., and da Silva, L. (1999) Copper and barium abundances in the Ursa Major Moving Group. *Monthly Notices R. Astron. Soc*. 305, 693–700.

Catling, D.C., Glein, C.R., Zahnle, K.J., and McKay, C.P. (2005) Why O_2 is required by complex life on habitable planets and the concept of planetary "oxygenation time." *Astrobiology* 3, 415–438.

Cayrel de Strobel, G. and Bentolila, C. (1989) In search of real solar twins II. *Astron. Astrophys*. 211, 324–340.

Cayrel de Strobel, G., Perrin, M.-N., Cayrel, R., and Lebreton, Y. (1989) A thorough spectroscopic study of the very nearby triple system: 36 Ophiuchi. *Astron. Astrophys*. 225, 369–380.

Cayrel de Strobel, G., Soubiran, C., and Ralite, N. (2001) Catalogue of [Fe/H] determinations for FGK stars: 2001 edition. *Astron. Astrophys*. 373, 159–163.

Chmielewksi, Y., Friel, E., Cayrel de Strobel, G., and Bentolila, C. (1992) The 1992 detailed analysis of Alpha Centaruri A and B. *Astron. Astrophys*. 263, 219–231.

Clegg, R.E.S., Lambert, D.L., and Tomkin, J. (1981) Carbon, nitrogen and oxygen abundances in main-sequence stars. II. 20 F and G stars. *Astrophys. J*. 250, 262–275.

Clube, S.V.M. and Napier, W.M. (1982) Spiral arms, comets and terrestrial catastrophism. *Q. J. R. Astron. Soc*. 23, 45–66.

Cunha, K., Smith, V.V., and Lambert, D.L. (1995) Chemical evolution of the Orion association. III. The lithium abundance of F and G stars. *Astrophys. J*. 452, 634–651.

Cutispoto, G., Pastori, L., Pasquini, L., de Medeiros, J. R., Tagliaferri, G., and Andersen, J. (2002) Fast-rotating nearby solar-type stars I. Spectral classification, $v \sin i$, Li abundances and X-ray luminosities. *Astron. Astrophys*. 384, 491–503.

del Peloso, E.F., da Silva, L., and Porto de Mello, G.F. (2005a) The age of the galactic thin disk from Th/Eu nucleocosmochronology. I. Determination of [Th/Eu] abundance ratios. *Astron. Astrophys*. 434, 275–300.

del Peloso, E.F., da Silva, L., Porto de Mello, G.F., and Arany-Prado, L.I. (2005b) The age of the galactic thin disk from Th/Eu nucleocosmochronology. III. Extended sample. *Astron. Astrophys*. 440, 1153–1159.

des Marais, D.J., Harwit, M.O., Jucks, K.W., Kasting, J.F., Lin, D.N.C., Lunine, J.I., Schneider, J., Seager, S., Traub, W.A., and Woolf, N.J. (2002) Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrobiology* 2, 153–181.

Dole, S.H. (1964) *Habitable Planets for Man*, Blaisdell, New York.

Drake, J.J. and Smith, G. (1993) The fundamental parameters of the chromospherically active K2 dwarf Epsilon Eridani. *Astrophys. J*. 412, 797–809.

Duncan, D.K., Vaughan, A.H., Wilson, O.C., Preston, G.W., Frazer, J., Lanning, H., Misch, A., Mueller, J., Soyumer, D., Woodard, L., Baliunas, S.L., Noyes, R.W., Hartmann, L.W., Porter, A., Zwaan, C., Middelkoop, F., Rutten, R.G.M., and Mihalas, D. (1991) Ca II H and K measurements made at Mount Wilson Observatory 1966–1983. *Astrophys. J. Suppl*. 76, 383–430.

Duquennoy, A. and Mayor, M. (1991) Multiplicity among solar type stars in the solar neighborhood. II. Distribution of the orbital elements in an unbiased sample. *Astron. Astrophys*. 248, 485–524.

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., and Tomkin, J. (1993) The chemical evolution of the galactic disk. I. Analysis and results. *Astron. Astrophys*. 275, 101–152.

Endl, M., Kürster, M., Els, S., Hatzes, A.P., Cochran, W.D., Dennerl, K., and Döbereiner, S. (2002) The planet search program at the ESO Coude Echelle spectrometer. III. The complete Long Camera survey results. *Astron. Astrophys*. 392, 671–690.

European Space Agency (1997) *The Hipparcos Catalogue, Special Publication 120*, ESA Publications Division, Noordwijk, The Netherlands.

Fernandes, J., Lebreton, Y., Baglin, A., and Morel, P. (1998) Fundamental stellar parameters for nearby visual binary stars: η Cas, ξ Boo, 70 Oph and 85 Peg. *Astron. Astrophys*. 338, 455–464.

Fischer, D.A. and Valenti, J. (2005) The planet-metallicity correlation. *Astrophys. J*. 622, 1102–1117.

Flynn, C. and Morell, O. (1997) Metallicities and kinematics of G and K stars. *Monthly Notices R. Astron. Soc*. 286, 617–625.

Franck, S., Kossacki, K., and Bounama, C. (1999) Modelling the global carbon cycle for the past and future evolution of the Earth system. *Chem. Geol*. 159, 305–317.

Franck, S., von Bloh, W., and Bounama, C. (2000a) Determination of habitable zones in extrasolar planetary systems: where are Gaia's sisters? *J. Geophys. Res*. 105, 1651–1658.

Franck, S., Block, A., von Bloh, W., Bounama, C., Schellnhuber, H.-J., and Svirezhev, Y. (2000b) Habitable zone for Earth-like planets in the solar system. *Planet. Space Sci*. 48, 1099–1105.

Franck, S., Cuntz, M., von Bloh, W., and Bounama, C. (2003) The habitable zone of Earth-mass planets around 47 UMa: results for land and water worlds. *Int. J. Astrobiol*. 2, 35–39.

François, P. (1986) Chemical evolution of the Galaxy: a comparison of the abundances of light metals in disk and halo stars. *Astron. Astrophys*. 160, 264–276.

Fuhrmann, K. (1998) Nearby stars of the Galactic disk and halo. *Astron. Astrophys*. 338, 161–183.

Gehrels, N., Laird, C.M., Jackman, C.H., Cannizzo, J.K., Mattson, B.J., and Chen, W. (2003) Ozone depletion from nearby supernovae. *Astrophys. J*. 585, 1169–1176.

Gliese, W. and Jahreiss, H. (1979) Nearby star data published 1969–1978. *Astron. Astrophys. Suppl*. 38, 423–448.

Gonzalez, G., Brownlee, D., and Ward, P. (2001) The galactic habitable zone: galactic chemical evolution. *Icarus* 152, 185–200.

Gratton, R.G., Carreta, E., and Castelli, F. (1996) Abundances of light elements in metal-poor stars. I. Atmospheric parameters and a new T_{eff} scale. *Astron. Astrophys*. 314, 191–203.

Griessmeier, J.M., Stadelmann, A., Motschmann, U., Belisheva, N.K., Lammer, H., and Biernat, H.K. (2005) Cosmic ray impact on extra-solar Earth-like planets in close-in habitable zones. *Astrobiology* 5, 587–603.

Güdel, M., Guinan, E., and Skinner, S.L. (1997) The X-ray Sun in time: a study of the long term evolution of coronae of solar-type stars. *Astrophys. J*. 483, 947–960.

Hall, J.C. and Lockwood, G.W. (2000) Evidence of a pronounced activity cycle in the solar twin 18 Scorpii. *Astrophys. J.* 545, L43–L45.

Hartkopf, W.I. and McAlister, H.A. (1984) Binary stars unresolved by speckle interferometry. III. *Publ. Astron. Soc. Pacific* 96, 105–116.

Hatzes, A., Cochran, W., McArthur, B., Baliunas, S., Walker, G., Campbell, B., Irwin, A., Yang, S., Kürster, M., Endl, M., Els, S., Butler, P., and Marcy, G. (2000) Evidence for a long-period planet orbiting Epsilon Eridani. *Astrophys. J.* 544, L145–L148.

Heiter, U. and Luck, R.E. (2003) Abundance analysis of planetary host stars. I. Differential iron abundances. *Astron. J.* 126, 2015–2036.

Henry, T.J., Soderblom, D., Baliunas, S., Davis, R., Donahue, R., Latham, D., Stefanik, R., Torres, G., Duquennoy, A., Mayor, M., Andersen, J., Nordstrom, B., and Olsen, E. (1995) The current state of target selection for NASA's High Resolution Microwave Survey. In *ASP Conference Series 74, Progress in the Search for Extraterrestrial Life, 1993 Bioastronomy Symposium*, edited by G.S. Shostak, Astronomy Society of the Pacific, San Francisco, pp. 207–217.

Henry, T.J., Soderblom, D.R., Donahue, R.A., and Baliunas, S.L. (1996) A survey of Ca II H and K chromospheric emission in southern solar-type stars. *Astron. J.* 111, 439–464.

Holman, M.J. and Wiegert, P.A. (1999) Long term stability of planets in binary systems. *Astron. J.* 117, 621–628.

Huang, S.S. (1959) Occurrence of life in the universe. *Sci. Am.* 47, 397–402.

Hünsch, M.M., Schmitt, J.H.M.M., and Voges, W. (1998) The ROSAT All-Sky Survey Catalogue of optically bright main-sequence dwarfs and subgiant stars. *Astron. Astrophys. Suppl.* 132, 155–171.

Hünsch, M.M., Schmitt, J.H.M.M., Sterzik, M.F., and Voges, W. (1999) The ROSAT All-Sky Survey Catalogue of nearby stars. *Astron. Astrophys. Suppl.* 135, 319–338.

Irwin, A.W., Yang, S., and Walker, G.A.H. (1992) A precise radial-velocity determination of the orbit of chi1 Orionis. *Publ. Astron. Soc. Pacific* 104, 101–105.

Johnson, D.R.H. and Soderblom, D.R. (1987) Calculating galactic space velocities and their uncertainties, with an application to the Ursa Major group. *Astron. J.* 93, 864–867.

Joshi, M.M., Haberle, R.M., and Reynolds, T.R. (1997) Simulations of the atmospheres of synchronously rotating terrestrial planets orbiting M dwarfs: conditions for atmospheric collapse and the implications for habitability. *Icarus* 129, 450–467.

Kasting, J.F. (1996) Planetary atmosphere evolution: do other habitable planets exist and can we detect them? *Astrophys. Space Sci.* 241, 3–24.

Kasting, J.F. and Catling, D. (2003) Evolution of a habitable planet. *Annu. Rev. Astron. Astrophys.* 41, 429–463.

Kasting, J.F., Whittet, D., and Reynolds, R. (1993) Habitable zones around main sequence stars. *Icarus* 101, 108–128.

Kim, Y.C., Demarque, P., Yi, S.K., and Alexander, D.R. (2002) The Y^2 isochrones for alpha-element enhanced mixtures. *Astrophys. J. Suppl.* 143, 499–511.

Lammer, H., Kulikov, Y.N., Penz, T., Leitner, M., Biernat, H.K., and Erkaev, N.V. (2005) Stellar-planetary relations: atmospheric stability as a prerequisite for planetary habitability. *Celestial Mech. Dynam. Astron.* 92, 273–285.

Laureijs, R.J., Jourdain de Muizon, M., Leech, K., Siebenmorgen, R., Dominik, C., Habing, H.J., Trams, N., and Kessler, M.F. (2002) A 25 micron search for Vega-like disks around main-sequence stars with ISO. *Astron. Astrophys.* 387, 285–293.

Lawson, P.R., Unwin, S.C., and Beichman, C.A. (2004) *Precursor Science for the Terrestrial Planet Finder*, JPL publication 04-014, Jet Propulsion Laboratory, Pasadena, CA. Available online at: http://planetquest.jpl.nasa.gov/documents/RdMp273.pdf.

Lebreton, Y., Perrin, M.-N., Cayrel, R., Baglin, A., and Fernandes, J. (1999) The Hipparcos HR diagram of nearby stars in the metallicity range: $-1{:}0 < [Fe/H] < 0{:}3$. A new constraint on the theory of stellar interiors and model atmospheres. *Astron. Astrophys.* 350, 587–597.

Léger, A., Selsis, F., Sotin, C., Guillot, T., Despois, D., Mawet, D., Ollivier, M., Labèque, A., Valette, C., Brachet, F., Chazelas, B., and Lammer, H. (2004) A new family of planets? "Ocean-Planets." *Icarus* 169, 499–504.

Leitch, E.M. and Vasisht, G. (1998) Mass extincitions and the Sun's encounters with spiral arms. *New Astron.* 3, 51–56.

Lépine, J.R.D., Mishurov, Y.N., and Dedikov, S.Y. (2001) A new model for the spiral structure of the Galaxy: superposition of 2- and 4-armed patterns. *Astrophys. J.* 546, 234–247.

Lépine, J.R.D., Acharova, I.A., and Mishurov, Y.N. (2003) Co-rotation, stellar wandering, and fine structure of the Galactic abundance pattern. *Astrophys. J.* 589, 210–216.

Lineweaver, C.H. (2001) An estimate of the age distribution of terrestrial planets in the Universe: quantifying metallicity as a selection effect. *Icarus* 151, 307–313.

Lyra, W. and Porto de Mello, G.F. (2005) Fine structure of the chromospheric activity in solar type stars: the Hα line. *Astron. Astrophys.* 431, 329–338.

Mallik, S.V. (1998) Chomospheric activity in cool stars and the lithium abundance. *Astron. Astrophys.* 338, 623–636.

Mason, B.D., Wycoff, G.L., Hartkopf, W.I., Douglass, G.G., and Worley, C.E. (2002) The 2001 US Naval Observatory Double Star CD-ROM. I. The Washington Double Star Catalog. *Astron. J.* 122, 3466–3471.

McAlister, H.A. (1978) Binary stars unresolved by speckel interferometry. *Publ. Astron. Soc. Pacific* 90, 288–296.

McElroy, M.B. (1972) Mars: an evolving atmosphere. *Science* 175, 443–445.

Morbey, C.L. and Griffin, R.F. (1987) On the reality of certain spectroscopic orbits. *Astrophys. J.* 317, 343–352.

Noyes, R.W., Hartmann, L.W., Baliunas, S.L., Duncan, D.K., and Vaughan, A.H. (1984) Rotation, convection and magnetic activity in lower main-sequence stars. *Astrophys. J.* 279, 763–777.

Pace, G. and Pasquini, L. (2004) The age-activity-rotation relationship in solar-type stars. *Astron. Astrophys.* 426, 1021–1034.

Pasquini, L. (1992) The Ca II K line in solar type stars. *Astron. Astrophys.* 266, 347–359.

Pendleton, Y.J. and Black, D.C. (1993) Further studies on criteria for the onset of dynamical instability in general three-body systems. *Astron. J*. 88, 1415–1419.

Perrin, M-.N., Cayrel de Strobel, G., and Cayrel, R. (1975) Colors and ionization equilibria in K dwarfs. *Astron. Astrophys*. 39, 97–106.

Perrin, M-.N., Cayrel de Strobel, G., and Dennefeld, M. (1988) High S/N detailed spectral analysis of four G and K dwarfs within 10 parsecs of the Sun. *Astron. Astrophys*. 191, 237–247.

Porto de Mello, G.F. (1996) The abundance pattern of solar-type stars in the solar neighborhood [Ph.D. thesis], Observatório Nacional, Rio de Janeiro, Brazil.

Porto de Mello, G.F. and da Silva, L. (1997) HR6060: the closest ever solar twin? *Astrophys. J*. 482, L89–L92.

Pourbaix, D., Neuforge-Verheecke, C., and Noels, A. (1999) Revised masses of α Centauri. *Astron. Astrophys*. 344, 172–176.

Quintana, E.V., Lissauer, J.J., Chambers, J.E., and Duncan, M.J. (2002) Terrestrial planet formation in the α Centauri system. *Astrophys. J*. 576, 982–996.

Ribas, I., Guinan, E.F., Güdel, M., and Audard, M. (2005) Evolution of the solar activity over time and effects on planetary atmospheres. I. High energy irradiances (1–1700 Å). *Astrophys. J*. 622, 680–694.

Rocha-Pinto, H.J. and Maciel, W.J. (1996) The metallicity distribution of G dwarfs in the solar neighbourhood. *Monthly Notices R. Astron. Soc*. 279, 447–458.

Ruck, M.J. and Smith, G. (1995) A fine analysis of iron and calcium lines in the spectrum of the chromospherically active G8 dwarf Xi Bootis A. *Astron. Astrophys*. 304, 449–460.

Russell, J.L. and Gatewood, G.D. (1984) The parallax and astrometric orbit of Mu Cassiopeiae. *Publ. Astron. Soc. Pacific* 96, 429–431.

Saar, S.H., Huovelin, J., Osten, R.A., and Shcherbakov, A.G. (1997) He I D3 absorption and its relation to rotation and activity in G and K dwarfs. *Astron. Astrophys*. 326, 741–750.

Santos, N.C., Israelian, G., and Mayor, M. (2001) The metal-rich nature of stars with planets. *Astron. Astrophys*. 373, 1019–1031.

Santos, N.C., Israelian, G., Mayor, M., Rebolo, R., and Udry, S. (2003) Statistical properties of exoplanets. II. Metallicity, orbital parameters, and space velocities. *Astron. Astrophys*. 398, 363–376.

Santos, N.C., Israelian, G., and Mayor, M. (2004) Spectroscopic [Fe/H] for 98 extra-solar planet-host stars: exploring the probability of planet formation. *Astron. Astrophys*. 415, 1153–1166.

Saxner, M. and Hammarbäck, G. (1985) An empirical temperature calibration for F dwarfs. *Astron. Astrophys*. 151, 372–390.

Schmitt, J.H.M.M. and Liefke, C. (2004) NEXXUS: a comprehensive ROSAT survey of coronal X-ray emission among nearby solar-type stars. *Astron. Astrophys*. 417, 651–665.

Segura, A., Krelove, K., Kasting, J.F., Sommerlatt, D., Meadows, V., Crisp, D., Cohen, M., and Mlawer, E. (2003) Ozone concentrations and ultraviolet fluxes on Earth-like planets around other stars. *Astrobiology* 3, 689–708.

Strassmeier, K.G., Washuettl, A., Granzer, T., Scheck, M., and Weber, M. (2000) The Vienna-KPNO search for Doppler-imaging candidate stars. I. A catalog of stellar-activity indicators for 1058 late-type Hipparcos stars. *Astron. Astrophys*. 142, 275–311.

Tarter, J. (2001) The search for extraterrestrial intelligence (SETI). *Annu. Rev. Astron. Astrophys*. 39, 511–548.

Taylor, B.J. (2003) Statistical cataloging of archival data for luminosity class IV–V stars. II. The epoch 2001 [Fe/H] catalog. *Astron. Astrophys*. 398, 731–738.

Thorén, P. and Feltzing, S. (1998) Chemical abundances in cool metal rich disk dwarf stars. *Astron. Astrophys*. 363, 692–704.

Turnbull, M.C. and Tarter, J. (2003a) Target selection for SETI. I. A catalog of nearby habitable stellar systems. *Astrophys. J. Suppl*. 145, 181–198.

Turnbull, M. C., and Tarter, J. (2003b) Target selection for SETI. II. Tycho-2 dwarfs, old open clusters, and the nearest 100 stars. *Astrophys. J. Suppl*. 149, 423–436.

von Bloh, W., Bounama, C., and Franck, S. (2003) Cambrian explosion triggered by geosphere-biosphere feedbacks. *Geophys. Res. Lett*. 30, 1963–1967.

Ward, P.D. and Brownlee, D. (2000) *Rare Earth*, Copernicus Edition, Springer-Verlag, New York.

Warren, R.H., Jr. and Hoffleit, D. (1987) The Bright Star Catalogue, 5^{th} edition. *Br. Astron. Astrophys. Soc*. 19, 733.

Woolley, R., Epps, E.A., Penston, M.J., and Pocock, S.B. (1970) Catalogue of stars within 25 parsecs of the Sun. *R. Obs. Ann*. 5, 1–227.

Yi, S.K., Kim, Y.C., and Demarque, P. (2003) The Y^2 stellar evolutionary tracks. *Astrophys. J. Suppl*. 144, 259–261.

Zboril, M. and Byrne, P.B. (1998) Metallicity and photospheric abundances in field K and M dwarfs. *Monthly Notices R. Astron. Soc*. 299, 753–758.

Zhao, G. and Gehren, T. (2000) Non-LTE analysis of neutral magnesium in cool stars. *Astron. Astrophys*. 362, 1077–1082.

Address reprint requests to:
Dr. Gustavo Porto de Mello
Observatório do Valongo
Universidade Federal do Rio de Janeiro
Ladeira Pedro Antônio, 43
Rio de Janeiro, 20080-090, Brazil

E-mail: gustavo@ov.ufrj.br