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The Habitable Zones of White Dwarfs

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Resumo. Com este trabalho buscamos determinar os parâmetros físicos e as zonas habitáveis de uma amostra de estrelas do “Villanova Catalog of White Dwarfs”. Para alcançar tal resultado, estimamos as distâncias de uma amostra de 900 estrelas, para as quais dados de fotometria V, $(B - V)$, y, e $(b - y)$ estão disponíveis. As distâncias estimadas revelam-se corretas até 25%, baseado numa comparação entre estrelas da amostra que possuem distâncias determinadas por paralaxes. Os parâmetros físicos são então obtidos através da interpolação das aproximações das magnitudes absolutas e das cores numa grade de modelos. As zonas habitáveis são calculadas com os parâmetros físicos considerando-se a aproximação de uma atmosfera de camada única que emite como corpo negro. Investigamos as relações entre as características das zonas habitáveis com as propriedades das anãs brancas. As características calculadas para as zonas habitáveis mostram que elas podem ter tamanhos de até 40 AU. Planetas ou sistemas que sobrevivam à evolução da estrela e sejam capazes de abrigar vida podem, em princípio, ser detectados com tecnologia em desenvolvimento.

Abstract. In this work we determine physical parameters and the habitable zones of a sample of stars from the Villanova Catalog of White Dwarfs. To accomplish this we estimate distances for a sample of 900 stars for which V, $(B - V)$, y and $(b - y)$ photometry data is available. The distance estimates are shown to be good to 25% based on a comparison of stars from the sample that have good parallaxes. The physical parameters are then obtained through interpolation of the estimated absolute magnitudes and colors on a model grid. The habitable zones are calculated with the physical parameters considering the approximation of a single layer atmosphere that emits as a black-body. We investigate the relations of habitable zone characteristics to white dwarf properties. The calculated habitable zone characteristics show that they can have sizes of up to 40 AU. Planets or systems capable of harboring life that survived the evolution of the star could in principle be detected with upcoming technology.

Keywords. White Dwarfs – Planets – Habitable Zone

1. Introduction

The interest in the search for life in other planets and star systems has existed for a long time and has gained momentum in recent years due to improved detection techniques as well as instrumentation. One of the most important concepts related to the feasibility of life in other systems, at least in the forms that we currently know of, is the Habitable Zone. The term Habitable Zone, used to define the region around a star that could have life-supporting planets, was first used by Huang (1959). The exact way to define this region varies between authors, but the presence of liquid water seems to be the more relevant criteria since all known organisms require water in this state for some part of their life cycle. This of course carries the assumption that alien life-forms will be carbon based as the life we find on Earth. However, it has been know for a long time that organisms can survive in very extreme conditions on earth. Numerous works deal with the biological details of these extremophiles and the possible environments in which they can thrive. It is not the objective of this paper to discuss those details. We wish only to emphasize that these extremophiles should serve as a reminder that life can thrive in rather extreme conditions very different from the conditions we normally call “habitable”.

The search for planets outside our system has revealed many candidate objects in various stellar systems. Most of these planets are giants and this detection bias is mainly due to the techniques used to search for them. Future space missions, such as Terrestrial Planet Finder (Beichman, Woolf & Lindensmith 1999) that will be looking for the smaller, Earth-like planets, will certainly change this. However, we should not neglect the potential for life harboring systems around giant planets, like their moons. As far as habitability is concerned, essentially all that is need is liquid water and energy, and a moon of a giant planet suitably located can have the right conditions for this to happen.

Stars with masses lower than $8M_\odot$ comprise the majority of objects in the Galaxy, and will eventually evolve into electron-degenerate white dwarfs (WDs), making them the most common end product of stellar evolution. The large number of objects improve the probability of finding a planet (or moon) located in a region where liquid water can be found. Some groups have looked at WDs in the search for planets, finding none so far (Farihi et al. 2005; Mullally et al. 2006; Zinnecker et al. 2006). A planet has been found in a multiple star system including a WD (Mugrauer & Neuhäuser 2005).

Perhaps one of the main reasons for this lack of detections is the requirement that a planet survive the evolution of the star, as it passes the AGB phase. Until recently very little was know in this regard and general thought was that the intense mass loss, winds and UV radiation coming from the star as it exposed its core would destroy any nearby planet, especialy gaseous ones (Penz et al. 2008). In a recent paper, Villaver & Livio (2007) have worked out the details of the survival of Jupiter like planets as the stars go through the AGB phase. It is during the thermal-pulsing AGB phase that a planet's orbit will be most influenced, since during this phase the star loses most of its mass and reaches its maximum radius. In their work they show that planets with masses smaller than one Jupiter mass do not survive the Planetary Nebula phase if located at orbital distances smaller than 3 to 5 AU, and that planets more massive than two Jupiter masses around low mass (1 $M_\odot$ on the Main Sequence) stars survive the Planetary Nebula stage down to orbital distances of 3 AU. For the detailed discussion of planet survival and the many implications we refer the reader to their work.

With the chances of survival of a planet now better understood, we investigate the habitable zones of WDs. We use model distance determinations to obtain physical parameters of a sample of WDs drawn from the Villanova Catalog of White Dwarfs (McCook & Sion (1999) 2008 version), based on the most up to date models of Bergeron and collaborators. The luminosity obtained is used to calculate the habitable Zone (HZ). We then explore the relationship of WD parameters and HZ size and position and discuss the results.

2. Distance Determinations

In the *Villanova Catalog*, distances come from many sources and therefore are not uniformly determined. For the WDs with parallaxes, we adopted those distances with $\pi/\sigma_\pi > 3$ as correct. To avoid introducing unknown biases, we re-estimated the distances for WDs that did not have parallaxes.

The procedure used to estimate distances consists of interpolating observed colors in existing model grids. This technique was first used in Monteiro et al. (2006) to estimate ages for binary systems containing a WD. We use the curves defined by the parameters M_V,$(B-V)$,$(b-y)$, $\log g$, WD mass and composition. To estimate the distance we used the Bergeron, Wesemael & Beauchamp (1995) grid of models, assuming 1) $\mathrm{Mass}_{\mathrm{WD}} = 0.56 M_\odot$ and 2) DA or non-DA models (based on the catalog spectral classification) for the WDs in the sample. The narrow distribution of mass values shown for WDs (see Kleinman et al. (2004) for details), justifies this assumption. Assuming a fixed mass should also be better than assuming a fixed $\log g$ because the latter increases during their evolution of the WD along the cooling tracks. The assumption of constant $\log g$ introduces a T_{eff} dependent bias.

With the assumed mass we calculate a value for $\log g$ using $(B-V)$ or $(b-y)$ and interpolating on the model grid. This value in turn gives M_V which is then used to calculate a revised value for $\log g$, also through interpolation in the model grids. This procedure is then iterated until convergence is reached. The final value for M_V is then used to obtain the distance estimate. The procedure converges in 36 iterations to the chosen 1% accuracy level.

We determined the error in the distance estimates obtained with this procedure,comparing the model estimated distances to distances determined from parallax measurements that were available. Fig. 1 shows the comparison of parallax distances and model-estimated distances as well as M_V. The average error between the estimated distance and the parallax distance and model estimated M_V and M_V determined using the parallax distance for this set of objects is 25% and 4% respectively. We adopt this as the general accuracy for this method.

3. The Habitable Zone

The surface temperature of a planet is perhaps the most important quantity that determines the possibility of the existence of life. To determine the surface temperature we make some simplifying assumptions: i) the star radiates as a black-body; ii) the planet's temperature is constant over its surface and does not vary in time. The second assumption is basically an equilibrium condition allowing us to equate the absorbed energy (mainly from the star) to the emitted energy (mainly infrared). If this was not the case the planet's temperature would change in time and more complex models would be required. We assume that this temperature stays relatively constant over timescales that allow the development of life. The assumption of a constant temperature value over the surface is also reasonable for planets that have a circulating atmosphere (such as Earth for example). The planet's equilibrium surface temperature is then easily calculated using the Stefan-Boltzmann equation and accounting for the reflection of radiation due to the Albedo:

$$T_P = T_*(1-a)^{1/4}\sqrt{\frac{R_*}{2D}} \tag{1}$$

where T_P is the surface temperature of the planet, T_* the stellar effective temperature, R_* the stellar radius, a the planet's albedo and D it's distance to the star.

Eq. 1 does not take into account the complex nature of the atmosphere of the planet and especially the greenhouse effect due to the presence of water vapor. The error due to this simplification can be illustrated if we apply Eq. 1 to Earth taking the average albedo to be $a = 0.3$. Using this value we get $T_P = 255$ K or -19 °C, considerably lower than observed on average. We can improve our approximation adopting a single one dimensional layer atmosphere, transparent to visible wavelengths and opaque to infrared radiation emitted by the planet. At the top of this atmosphere the temperature will be given by Eq. 1. Since we assume that the temperature of this layer has to remain constant, the energy radiated into this layer by the planet minus the energy radiated out of the layer, must give a temperature equal to the one given by Eq. 1, ie. at the top of the atmosphere. Using Eq. 1 and assuming that the layer emits as a black-body we can express the surface temperature as:

$$T_S = 2^{1/4} T_P \tag{2}$$

Again,using Earth as an example and now applying Eq. 2 we get $T_P = 303$ K or 30 °C, much closer to the observed average.

To obtain the HZ as defined in Sec. 1 we use Eq. 2 and the temperature interval for which water is found in the liquid state. In normal conditions this would be the usual 273 K - 373 K interval, however, it has been suggested by Kasting & Catling (2003), using 1D climate modeling, that the outer limit can be extended for some atmospheric conditions. The author suggests that on the solar system the outer bound to the HZ can be anywhere from 1.37 AU to 2.4 AU. Using the value of 273 K and Eq. 2 we get $D = 1.23$ AU, reasonably close to the value obtained by Kasting & Catling (2003). If we take the authors value of 2.4 AU for the outer limit we get a temperature of $T_S = 196$ K. Using these two values for the temperature interval and model estimated physical parameters obtained for the WDs

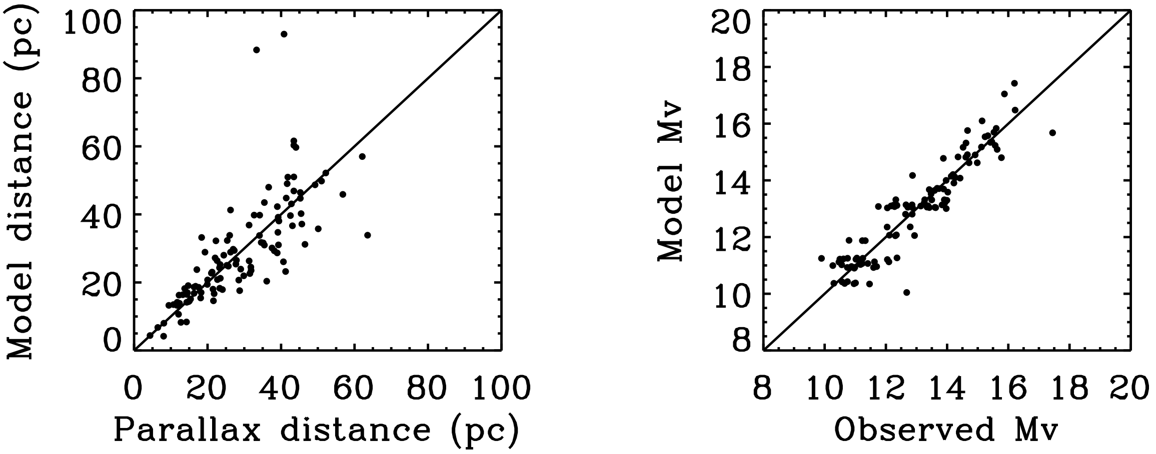

Figure 1. Comparison of model estimated distances and parallax distances as well as model estimated M_V and M_V determined using the parallax distance for WDs in the sample used in the present work. The graphs on the right show the error distributions for the estimates.

in Sec. 2, we determine the regions where liquid water can exist.

In Fig. 2 (upper-left), we show the variation of HZ inner and outer radius for the temperature limits discussed previously as a function of the WD luminosities. The figure shows that the HZ can reach as far as 40 AU for the higher luminosities. In Fig. 2 (upper-right) we also plot the relation of HZ outer radius and WD masses, showing that the majority of WDs have HZ sizes between 1.0×10^{-2} and 1 AU with little correlation of these parameters. In Fig. 2 (lower-left and right) we plot the variation of HZ outer radius with cooling age and effective temperature respectively, where we see the clear dependence of the HZ outer radius to the amount of energy irradiated by the WD as it evolves. As expected the youngest, therefore hotter WDs are the ones with the larger HZ outer radius. In fact we see only a small percentage of objects with HZ sizes greater than 1 AU.

4. Conclusions

Liquid water is a key ingredient for the development of life as we know it, and knowing where we can find it in a stellar system is the first step to narrowing down the places to search for habitable planets and life. In this work we estimated distances to WD stars from the Villanova Catalog based on the most up to date models calculated by Bergeron and collaborators. The distances were shown to be well determined when compared with WDs of known parallax with an estimated error of 25%. With these distance estimates we also obtained the physical parameters for these stars interpolating in the model grid. With the luminosity determined in this manner we then calculated the HZ as discussed in Sec. 3.

Our results show that HZs in WDs can have considerably large range of inner radius and sizes going as far as 40 AU in some cases. However, only a small percentage of the WDs in this sample have HZs sizes greater than 1 AU, considering the optimistic case with $T_S = 196$ K as suggested by Kasting and Catling (2003).

The presence of a large HZ does not imply the existence of life of course. This is even a more sensitive issue with WDs, being the end stages of an intermediate mass star's evolution. The chances of finding life forms in a planet in those regions is likely to be small when we consider that the star will have passed through the red giant and planetary nebula phase. If somehow the planet survives this and retains some kind of atmosphere capable of blocking the bulk of the UV radiation coming from the star, perhaps some form of life could survive or even emerge.

Villaver & Livio (2007) has shown that the conditions in planetary systems with a intermediate mass star going through the AGB phase will be much harsher when compared to Earth at the present moment, especially considering the strong UV radiation coming from the remnant WD. Especially in the case of gas giants, hydrogen and lighter materials will escape and those planets may even evaporate completely. However, the author also shows that there are suitable conditions in which the planets may survive. With respect to the atmosphere, it may be possible that some part of it could survive, given that Earth-like atmospheres are composed mostly of heavier elements such as oxygen and nitrogen. The rates of evaporation of the molecules formed from these elements will be much smaller than that of hydrogen and perhaps, given the right conditions, may lead to the survival of some form of atmosphere. However, precise models should be used to show if this is indeed the case. In any case, given our results for this sample of WDs and the planet survival conditions discussed by Villaver & Livio (2007), it seems very unlikely that we should find an earth-like planet with life-forms, given the small HZ outer radius of most WDs.

The likelihood of life developing and thriving in such extreme conditions is small. However, we should remember that even in our planet we encounter many extremophile organisms, such as Archean bacteria and others, that have been shown to survive from the freezing cold of the arctics to the scalding hot environments on tectonic fissures at the bottom of the oceans, and perhaps similar organisms could exist in the harsh HZs around white dwarfs.

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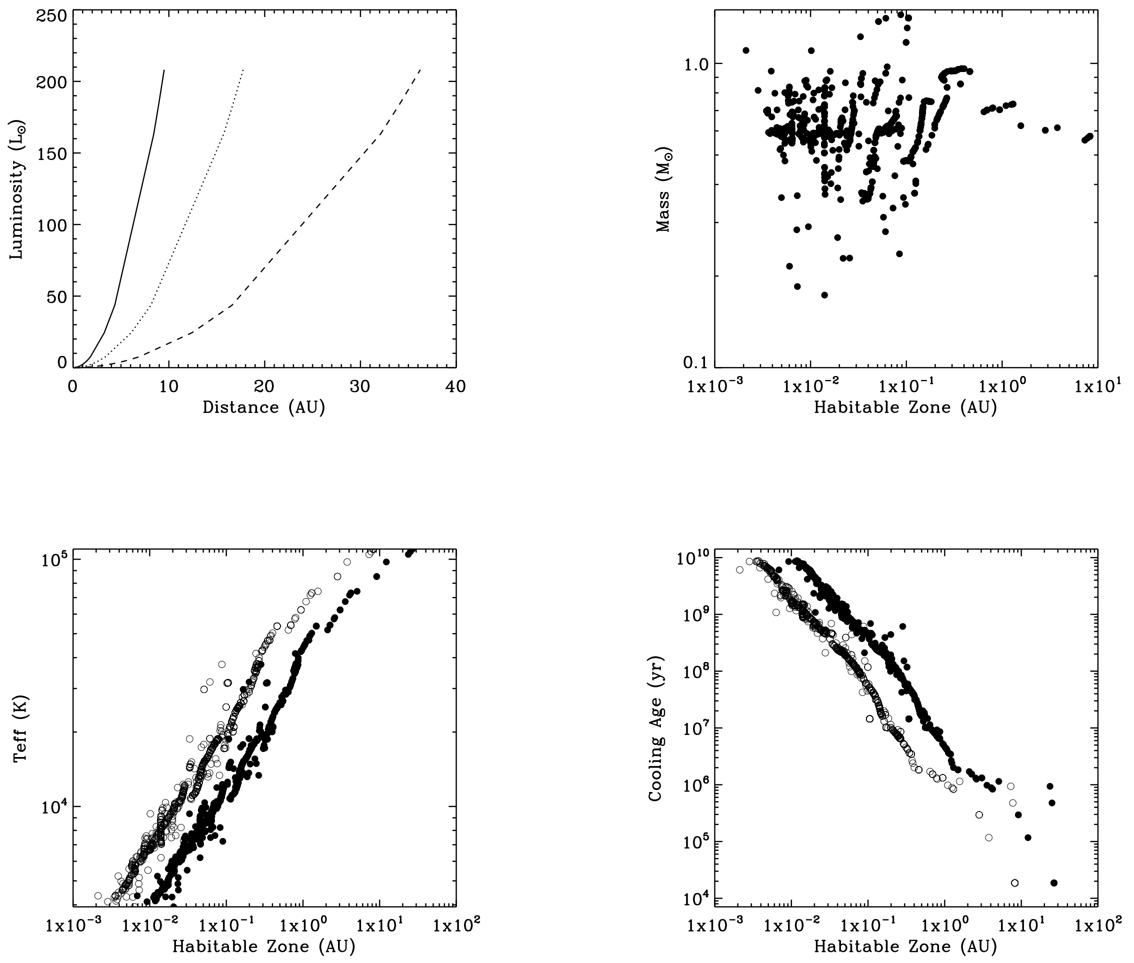

Figure 2. (Upper-Left) - Boundaries for the area around a star where liquid water can be found. The solid line indicates the interior boundary where $T_S = 373$ K, the dotted line where $T_S = 273$ K and the dashed line where $T_S = 196$ K as discussed in Sec. 3. (Upper-Right) - The relation of Mass and outer radius of the HZ as determined for the WDs in our sample and assuming $T_S = 196$ K. (Lower-Left) - The relation of temperature and outer radius of the HZ as determined for the WDs in our sample, adopting $T_S = 273$ K (open circles) and $T_S = 196$ K (closed circles). (lower-Right) - The relation of cooling age and outer radius of the HZ as determined for the WDs in our sample, adopting $T_S = 273$ K (open circles) and $T_S = 196$ K (closed circles).

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