Do Low Luminosity Stars Matter?

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Abstract. Historically, low luminosity stars have attracted very little attention, in part because they are difficult to see except with large telescopes, however, by neglecting to study them we are leaving out the vast majority of stars in the Universe. Low mass stars evolve very slowly, it takes them trillions of years to burn their hydrogen, after which, they just turn into a He white dwarf, without ever going through the red giant phase. This lack of observable evolution partly explains the lack of interest in them. The search for the "missing mass" in the galactic plane turned things around and during the 60s and 70s the search for large M/L objects placed M-dwarfs and cool WDs among objects of astrophysical interest. New fields of astronomical research, like BDs and exoplanets appeared as spin-offs from efforts to find the "missing mass". The search for halo white dwarfs, believed to be responsible for the observed microlensing events, is pursued by several groups. The progress in these last few years has been tremendous, here I present highlights some of the great successes in the field and point to some of the still unsolved issues.

Keywords. stars, white dwarfs, low mass, brown dwarfs, luminosity function

1. Introduction

Which stars are considered "low-luminosity" stars, is a definition that evolves with time, as more powerful telescopes and detectors explore new frontiers into the "dim universe". Here, I will discuss stars with a visual luminosity $L \leqslant 0.01 \ L_\odot$, corresponding to an absolute visual magnitude $M_V \sim 10$.

Figure 1 (from (Monet *et al.* (1992))) presents the Hertzprung-Russell (HR) Diagram of nearby stars with distances determined from trigonometric parallaxes. All stars in figure 1 are low-luminosity stars, the band that extends from $M_V \sim 10$ and $V - I \sim 1.6$ down to $M_V \sim 20$ and $V - I > 4$, are low mass hydrogen burning red dwarfs, that define the lower Main Sequence (MS) and cool sub-dwarfs (slightly to the left of the MS). The end of this sequence is defined by brown-dwarfs (BD) extending all the way to planet mass objects, which lie beyond this diagram. To the left of the MS in figure 1 is the white dwarf's (WD) cooling sequence.

Historically, low luminosity stars have received very little attention, in part because they are not only faint but also very stable. MS low mass stars burn their nuclear fuel at a very slow rate, therefore, they look the same for many Hubble times. Actually they have not had time to evolve like more massive stars do, the universe is not old enough for that.

On the other hand, WDs slowly evolve by cooling down, but in this case, it is only recently that we have begun to appreciate and understand the physics behind their evolution and its relevance to astrophysics in general.

Low luminosity stars constitute more than 80% of all stars in the universe, consisting of a variety of objects, like M-dwarfs, brown-dwarfs, white dwarfs, each with something to contribute to the advance of astronomical knowledge.
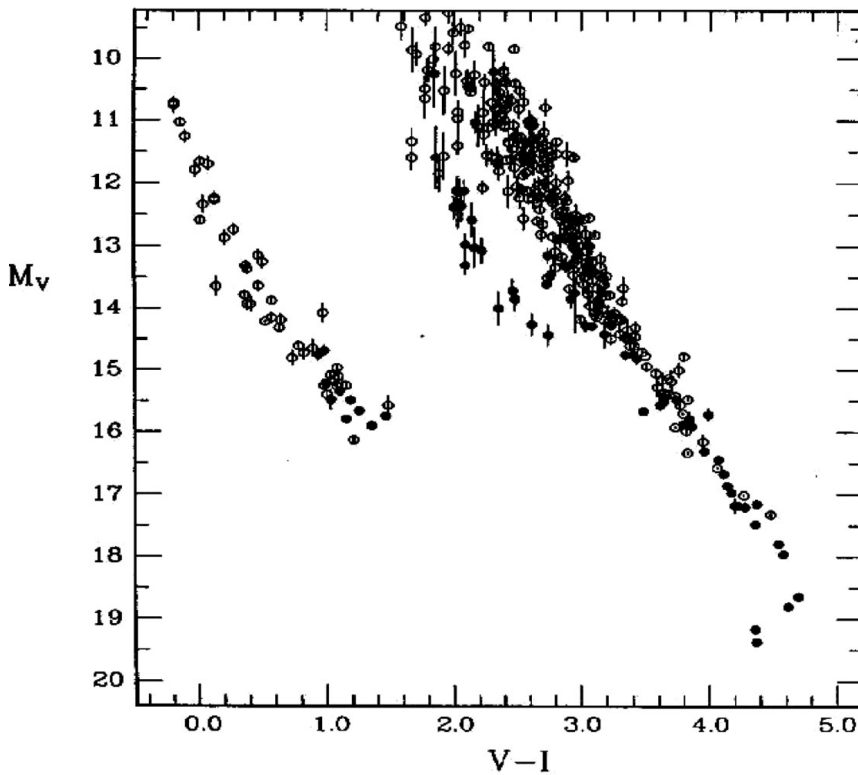
Figure 1. Hertzprung-Russell diagram of nearby stars with distances determined from trigonometric parallaxes, showing the lower main sequence and the white dwarf's cooling sequence. From (Monet *et al.* (1992)).

2. Missing Mass Problem

One of the first bursts of interest on the study of low-luminosity stars came from the so called "missing mass problem" in the galactic disk. Analyzing the motions of stars in the direction perpendicular to the galactic plane the astronomer, Jan Oort (Oort (1965)) found that the observed motions were produced by a gravitational force that required a local mass density of $\rho_0 \sim 0.15\ M_\odot\ pc^{-3}$. At that time, the contribution to the local density from stars was $\rho_{stars} = 0.06\ M_\odot\ pc^{-3}$, and from gas and dust $\rho_{g+d} = 0.03\ M_\odot\ pc^{-3}$, therefore the total mass in the galactic disk that could be accounted for was not enough to explain the stellar motions studied by Oort (Oort (1965); Reid & Hawley (2005)).

During the 60s and 70s the "missing mass problem" attracted a lot of attention towards the search for low luminosity stars. Suddenly M dwarfs became "objects of interest", due to their well known large mass to light ratios ($M/L > 10$). This prompted several efforts to determine the stellar luminosity function (LF) aimed at having a better defined faint end, where M-dwarfs make their contribution. With the LF, and knowing the relation between mass and luminosity, for stars of different masses, one can obtain the stellar mass function (MF). The stellar mass density can then be derived by integrating the MF.

In the 70s an intense debate took place regarding the LF determined by different authors (Sanduleak (1965); Gliese (1972); Schmidt (1974); Luyten (1968); Luyten (1974); Jones (1973); Faber *et al.* (1976); Weistrop (1972); Weistrop (1976)). In order to estimate

stellar luminosities (needed for the LF) of M-dwarfs, included in the different samples, it was necessary to know their distances, which were derived using spectroscopic and photometric parallaxes.

For a while, the LF determined by Weistrop (1972), Sanduleak (1965) and Gliese (1972), among other authors, implied a large density of M-dwarfs, enough to account for all Oort's missing mass. On the other hand, Luyten (Luyten (1968)) and previously van Rhijn (van Rhijn (1936)), had obtained a stellar LF indicating a local mass density of M-dwarfs that was a factor 5 to 10 lower.

The issue was discussed and settled during the IAU General Assembly of 1976. The conclusion was that the LFs that implied high densities of M-dwarfs were wrong. Discrepancies originated in the distance's determinations. Inaccurate photometry and spectral classifications, systematically under estimated distances, placing stars closer to us, thus occupying a smaller volume and implying a much larger density of stars.

The problem with the conflicting LFs was solved but we were left with the missing mass problem yet unsolved.

In spite of the progress in observational tools available to astronomy that follow that meeting in 1976, for more than two decades, Oort's missing mass was still not found.

More recent estimates (Chabrier (2001); Chabrier (2002); Robin (2001)), indicate that the local mass density considering the contribution by disk and halo (local) stars, brown dwarfs and that of gas and dust, amounts to: $\rho_{stars+bd+g+d} = 0.075 - 0.095 \ M_\odot \ pc^{-3}$.

On the other hand, the contribution by disk white dwarfs and neutron stars (Harris *et al.* (2006); Ruiz & Bergeron (2001); Holberg *et al.* (2002); Perna *et al.* (2006)) to the local density of matter is estimated to be : $\rho_{wd+ns} \sim 3.6 \times 10^{-3} \ M_\odot \ pc^{-3}$.

Adding up the contribution of all relevant low luminosity objects, mentioned above, plus that of gas and dust the total observed local mass density is : $\rho_{total} = 0.079 - 0.099 M_\odot pc^{-3}$. Therefore, decades after the meeting at the 1976 General Assembly and much effort from many groups, the missing mass had not been found.

The answer to this puzzle came from a very different approach (Creze *et al.* (1998); Bienayme (1999); Bienayme *et al.* (1999)), it came from a new analysis of stellar motions perpendicular to the galactic plane, this time using a very well defined sample of stars with distances obtained from Hipparcos Catalogs (ESA (1992); ESA (1997)). The remarkable result of these investigations was that the local dynamical density (needed to explain the observed stellar motions) was only $\rho_0 = 0.076 \pm 0.015 \ M_\odot \ pc^{-3}$, a value well below that found by Oort (Oort (1965)).

The present situation is that there is no missing mass in the local galactic disk, leaving no room for any disk dark matter component (Bienayme *et al.* (1999)). The problem was solved and this time apparently for good.

3. Renewed Interest in Low-luminosity Stars

In spite of the fact that efforts to find the missing mass among low-luminosity stars failed to do so, they were crucial to open up other lines of research on low luminosity stellar objects.

Microlensing experiments like MACHO (Alcock *et al.* (1997); Alcock *et al.* (2000)), EROS (Afonso *et al.* (2000); Lasserre *et al.* (2000)) and OGLE (Udalski *et al.* (1998)), found that the events detected towards the galactic bulge and the LMC were consistent with the lensing objects being small (in size) stars, with a mass of $\sim 0.6 M_\odot$, a very good match to a WD star. These faint objects could account for about 20 % to 30 % of the dark matter in the galactic halo, in this case the prime candidates are faint Halo WDs.
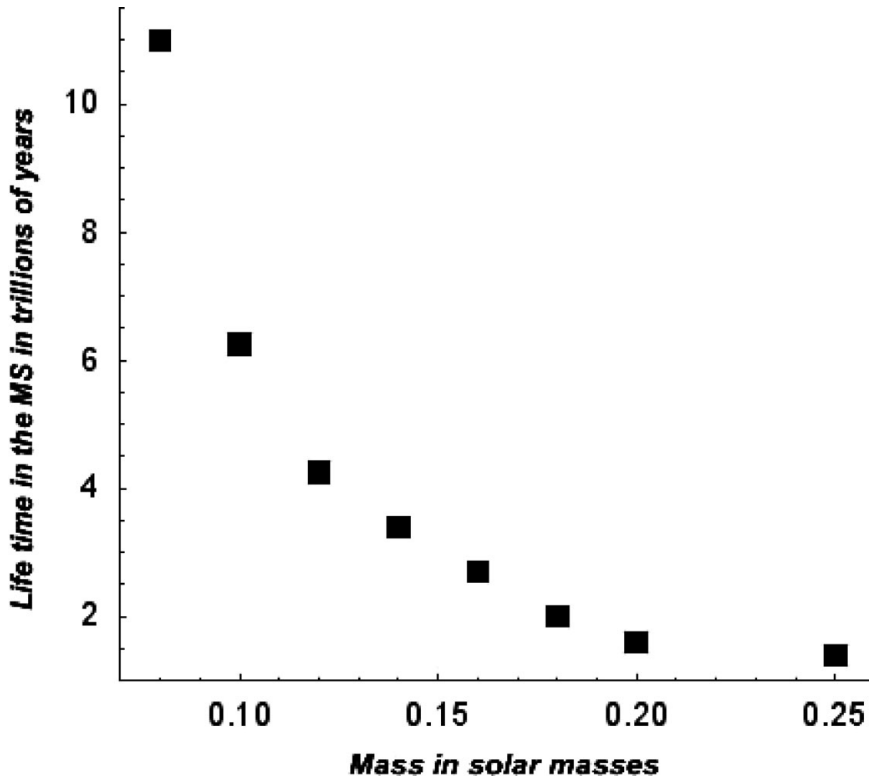
Figure 2. The evolution of a low mass star proceeds at a very slow rate, in time scales of trillions of years, (Laughlin *et al.* (1997)).

The field of brown dwarf's (BD) research and exoplanets were also spin-offs from the search for missing mass. The first BDs were identified in 1997 (Ruiz *et al.* (1997); Kirkpatrick *et al.* (1997)), and the first exoplanets in 1995 (Mayor & Queloz (1995)). Today, thanks to wide-deep surveys (like 2MASS, UKIDSS, SDSS, CFHTLS, DENIS, etc.) hundreds of BSs and exoplanets have been found in the solar neighborhood and in nearby stellar clusters.

Another source of interest in low mass stars research came from theoretical modeling of their evolution, interiors and atmospheres (Bergeron *et al.* (1995); Chabrier *et al.* (2000); Allard *et al.* (1997); Burrows *et al.* (1997); Marley *et al.* (2002); Baraffe *et al.* (1998)). Models today are quite mature, they rapidly evolve as new observations and the required physics become available. Every time a new type of object has been found models were almost ready to reveal their physical characteristics.

4. M-dwarfs

M-dwarfs are the lowest mass stars that populate the main sequence (see figure 1), they have masses between $0.5 M_\odot$ to $0.08 M_\odot$. Below $\sim 0.08 M_\odot$ the star cannot sustain stable hydrogen (H) nuclear burning in their core, in which case they are called brown dwarfs. Temperatures of low mass M-dwarfs range from $T_{eff} \sim 3600 K$ and $T_{eff} \sim 2400 K$, and their visual luminosities from $L \sim 0.01 L_\odot$ and $L \sim 10^{-5} L_\odot$.

The evolution of a low mass star not only proceeds at a very slow rate, in time scales of trillions of years, see figure 2 (taken from (Laughlin *et al.* (1997))), but it is somewhat different from that of more massive stars. A star with a mass $M < 0.2 M_\odot$ remains fully

convective over most of its life, mixing its helium (He) core with the surface H in a very efficient way. As a result almost all the H in an M-dwarf star is converted to He. The total amount of H burned by a $0.2M_\odot$ star is similar to that burned by a star like the Sun, in which only matter located in the central core participates in the nuclear process that converts H in He.

The end of an M-dwarf life, after more than 70 Hubble times, comes when the star runs out of H, they will not proceed to burn He as higher mass stars do. It will become a He white dwarf without ever going through the red giant phase (Laughlin *et al.* (1997); Chabrier & Baraffe (2000)).

Many Hubble times from now, when most stars will be dead, cold and invisible (white dwarfs, neutron stars or lack holes), these low mass stars will still be shining, and for a brief period of a few Gyrs, will have a surface temperature similar to that of the present day Sun. Maybe that would be the last chance for life in the Universe, as Laughlin *et al.* (1997) point out.

5. Brown Dwarfs

Below $\sim 0.08M_\odot$ stars cannot sustain stable hydrogen nuclear burning, they only have a brief initial period of deuterium (D) fusion (Chabrier & Baraffe (2000)). Later, they evolve cooling down supported by the pressure of their electron degenerate interiors. In this case the object is called a "brown dwarf" (BD) (Tarter (1974)).

After the first discovery of a handful of BDs, today thanks to large IR surveys, many hundreds of them are known. At the same time mature models (Chabrier *et al.* (2000); Burrows *et al.* (1997); Burrows *et al.* (2001)), are assigning physical meanings to their observed spectral characteristics (Geballe *et al.* (2002)).

As soon as the number of BDs known became large enough, they were classified according to their spectral features, which, thanks to the existence of reasonably good models were interpreted in terms of their physical parameters like temperature, metallicity, gravity etc.

The predominating features in the visual-IR spectra of M-dwarfs are TiO, CaOH, VO, H_2O, CO bands. On the other hand, L-dwarf spectra show the presence of dust clouds in their atmospheres, features of hydrides like FeH, CrH, MgH, CaH, and alkali metals like K, Na, Cs. Their effective temperatures range (spectral type L0 to L9.5) from $T_{eff} \sim 2400\ K$ and $T_{eff} \sim 1400\ K$.

Temperatures of T-dwarfs range from $T_{eff} \sim 1400\ K$ down to $T_{eff} \sim 600\ K$. In T-dwarfs the dust has completely precipitated to the bottom of the atmosphere, the most visible spectral features are CH_4, H_2O, NaI and KI.

The letter "Y" was reserved for yet a possible "new" spectral type, in case BDs with temperatures below 600 K were found, they were also expected to show the presence of NH_3 in their atmospheres (bad choice of letter, try to tell when somebody is talking about a "white dwarf" or a "Y dwarf"). It was a good idea though, because recently several Y-dwarfs have been found (Leggett *et al.* (2009); Burningham *et al.* (2008); Delorme *et al.* (2009)), with masses from 5 to 50 Jupiter masses, $T_{eff} \sim 550K$ and signs of NH_3 in their spectra. Y-dwarfs definitively enter the realm of exoplanets. This is even more clear in figure 3 (from (Burningham *et al.* (2008))), here the dark line spectrum is that of Jupiter, those bellow correspond to different Y-dwarfs, it is clear that the overall spectral shape of Y-dwarfs and Jupiter is remarkably similar.

The issue of whether low mass BDs and giant planets are the same thing is subject to some debate, although, the prevailing scenario suggests that they are not. BDs are believed to form the same way stars do, that is by the collapse of a dense core in a giant
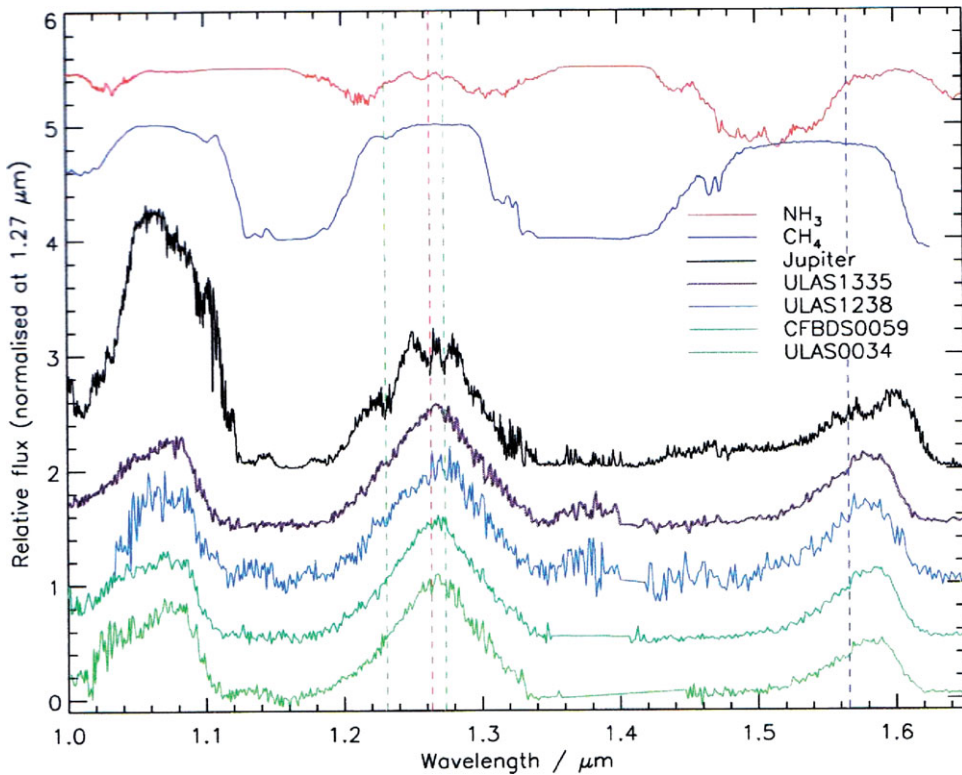
Figure 3. The close resemblance of the overall spectrum of the planet Jupiter (in solid black) and that of four Y-dwarfs, is clear from this figure taken from (Burningham *et al.* (2008)).

molecular cloud, therefore, its metallicity should reflect that of the parent cloud. On the other hand planets form from a debris disk around a star, the debris should have a higher metal content than the progenitor molecular cloud. This fact is actually observed in the solar system where Jupiter and Saturn have higher metallicities than the Sun. Other differences, consequence of their different origins are expected, like a large difference in their atmospheric pressures.

One other similarity between BDs and giant planets comes from the relation between their mass and radius. As can be seen in figure 4 (from (Chabrier *et al.* (2009))), for low mass M-dwarfs the radius is proportional to the mass while, for BDs and giant planets, radius seems to be rather insensitive to the mass, with all of them having a radius close to that of the planet Jupiter. The fits to the data in figure 4 correspond to models with different age and metallicity combinations (Chabrier *et al.* (2009)).

The difference between the mass-radius relation for stars and that for BDs and giant planets arise from the mechanisms supporting these objects against gravity. In the case of stars, this is the ideal-gas pressure, while for BDs and giant planets is the pressure from partially degenerate electrons.

6. Stellar Luminosity and Mass Functions

As a result of the search for "missing mass", a significant advance in the determination of the local stellar Luminosity and Mass Functions took place (Bochanski *et al.* (2009); Reid & Gizis (1997); Cruz *et al.* (2007)), thanks to large surveys with well defined distance
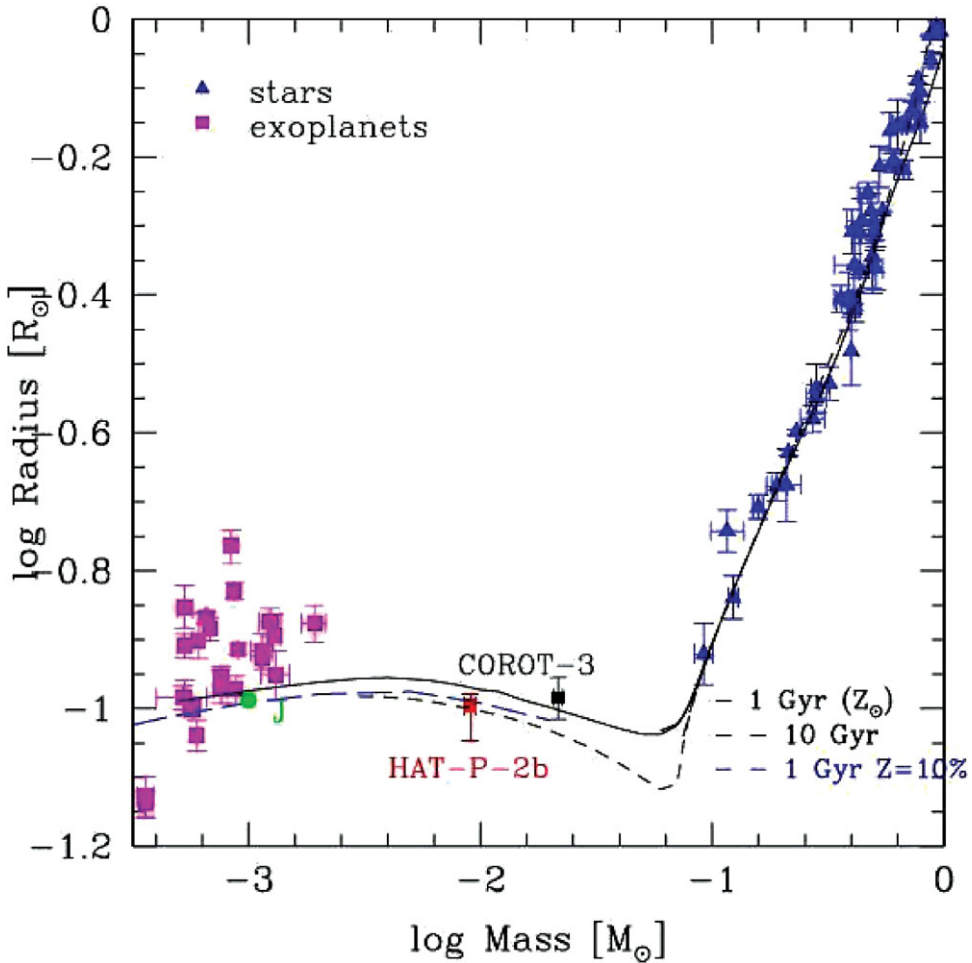
Figure 4. Mass-Radius relation for low mass stars, BDs and giant planets. The planet Jupiter is indicated with a solid dot and the letter J. Figure taken from (Chabrier *et al.* (2009)).

limits. Figure 5 (from (Cruz *et al.* (2009))), presents the local stellar LF determined by three different groups based on surveys that cover different volumes (8 pc with Hipparcos, 20 pc with 2MASS (for BDs) and 2000 pc with SDSS). Given the difference in samples, the LFs derived by these studies match pretty well, showing a decline below spectral type $\sim$ M4. The secondary peak shown in the BD's region of the LF, seems to be real (Cruz *et al.* (2007)), although this awaits confirmation from a larger volume sample of BDs.

The mass function (MF) for stars with masses $0.1 M_\odot < M < 0.8 M_\odot$ is shown in figure 6 (from (Bochanski *et al.* (2009))). Compared with previous determinations (Kroupa (2002); Miller & Scalo (1979)), the MF determined by Bochanski *et al.* (2009) presents a decline in the contribution of stars with masses below $0.27 M_\odot$, thus discarding the old idea that there could be huge numbers of low mass stars making an important contribution to the local baryonic dark matter.

6.1. *Subdwarfs Stars and BDs.*

So far we have discussed nearby disk stars, with ages of the order of a few Gyrs. However, in the solar vicinity there is also an older population of faint cool subdwarfs and BDs.
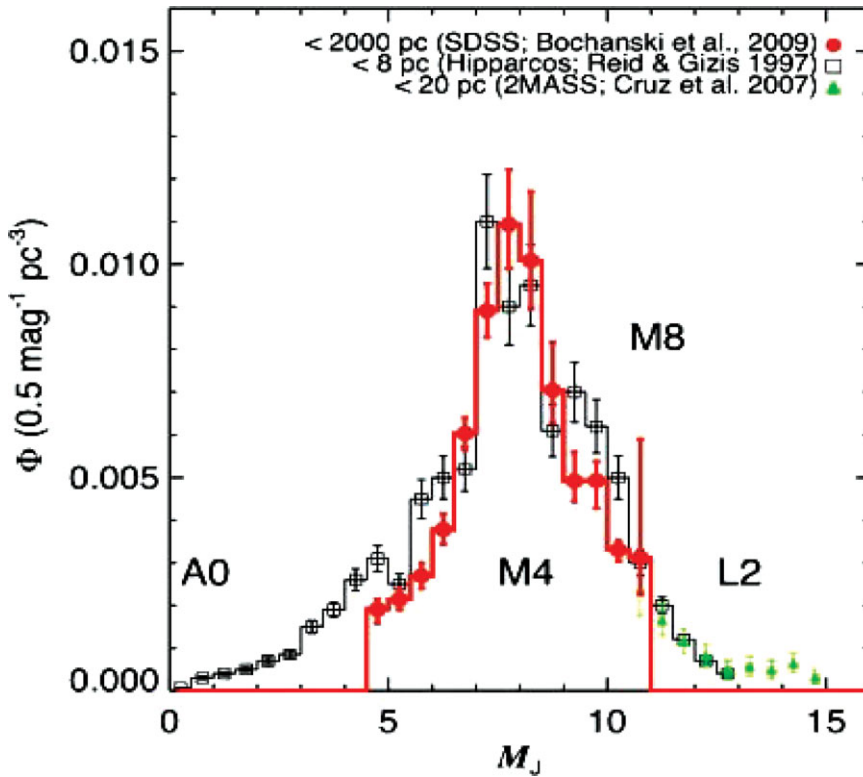
**Figure 5.** Stellar Luminosity Function. From (Cruz *et al.* (2009)).

Their local number density much lower than that of disk dwarfs (~ 200 disk dwarfs for each subdwarf (Gizis & Reid (1999))), and with bluer (hotter) colors, compared to a disk dwarf of the same mass, due to their lower metal opacity (Sandage & Eggen (1959)), make these cool subdwarfs hard to find. Until recently, no more than about 100 low mass cool subdwarfs were known (Gizis *et al.* (1997); Rojo & Ruiz (2003); Lepine *et al.* (2007)).

This situation has changed thanks to large area deep-surveys. For example, Lépine *et al.* (2009) discovered numerous local extreme-subdwarfs (esd) and ultra-subdwarfs (usd) from SDSS photometry (Lepine (2009)), using the color-color diagram (r-i) as a function of (g-r) (SLOAN filters), in which dwarfs of different metallicities clearly separate from each other. Subdwarfs (sd) have metallicities [Fe/H] ~ -1.2, while esd metallicity is [Fe/H] ~ -2.0 and that of usd is [Fe/H] < -2.0.

Accurate metallicities for low-mass, cool stars are difficult to obtain, at least in the optical region where absorption bands are saturated (Rojas-Ayala & Lloyd (2009); Lepine *et al.* (2007)), therefore this classification of sd, esd and usd is quite useful (and the best there is for now) when studying the older low-mass population.

Figure 7 (from (Lepine *et al.* (2007))), presents the differences in spectral features between dwarfs, subdwarfs and extreme-subdwarfs. The displayed wavelength range includes TiO bands and a CaH band. Low metallicity atmospheres, with less metals available, tend to produce hydrides (like CaH) instead of oxides (like TiO) which require two metals. In figure 7, the strength of the TiO band is maximum in solar metallicity dwarf stars (M-dwarf) and disappears towards esd type stars, while CaH does the opposite.
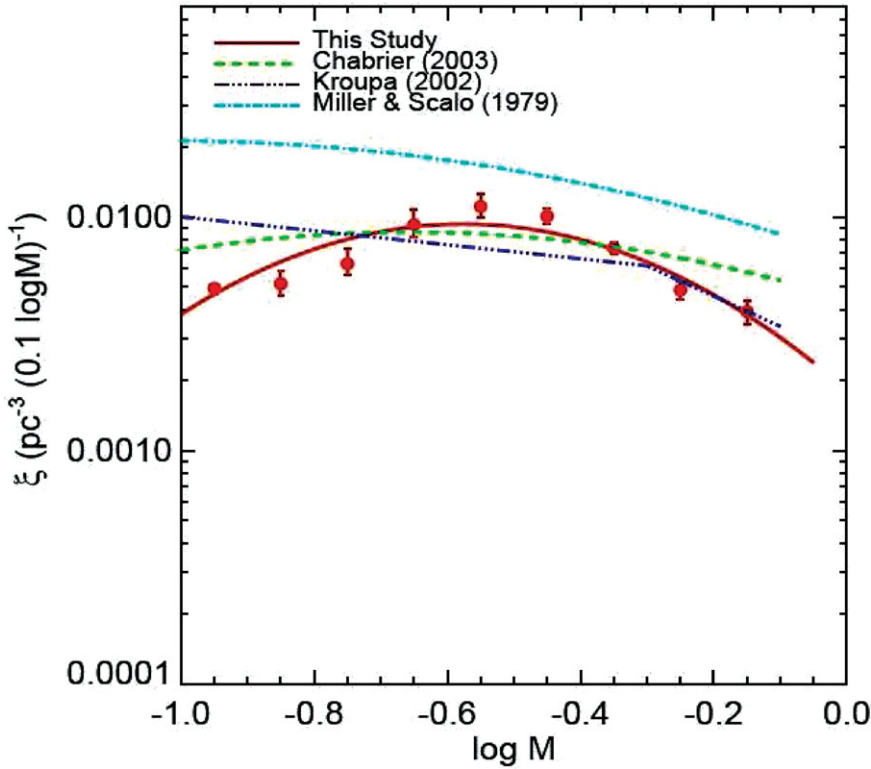
Figure 6. Stellar Mass Function. The fit is a log-normal distribution with a characteristic mass of $0.27 \pm 0.01 M_\odot$. Figure taken from (Bochanski *et al.* (2009)).

One of the latest additions to the subdwarf family has been the discovery of a few low metallicity BDs. IR surveys have revealed the existence of several L and T subdwarfs (Lepine & Scholz (2008); Burgasser *et al.* (2009); Burgasser *et al.* (2003); Cushing *et al.* (2009); Reiners & Basri (2006); Delorme *et al.* (2009)).

The field of low-mass stars, BDs and giant planets is rapidly advancing taking advantage of wide-deep surveys. We should expect much better constrained LFs, particularly at its faint end. The issue regarding differences between giant planets and BDs should be better understood, and models will evolve to be able to explain details regarding the physics of BDs (and giant planets), like for example, the relation between age-rotation-activity that in BDs seems to be different from that of stars. We are yet to find the oldest subdwarfs with no metals (they should be there).

6.2. *Cool White Dwarfs*

White Dwarfs (WD) are the solid remains of stars with main sequence masses below $\sim 8\ M_{odot}$. The typical WD mass is $\sim 0.6\ M_{odot}$ with an upper mass limit of $\sim 1.4\ M_{odot}$ and a radius of $\sim 0.01\ R_{odot}$. WDs are supported against gravity by a fully degenerate interior, in this case the radius is inversely proportional to the mass. More massive WDs are smaller and thus less luminous, than lower mass WDs.

WDs evolve by cooling therefore, in principle, if we could find the coolest WD and could determine its age (main sequence age + cooling age), then one could directly measure the age of that particular stellar system. The potential of WDs as "cosmic clocks" had long been recognized (Schmidt (1959); Winget *et al.* (1987); Wood (1992)). The disk
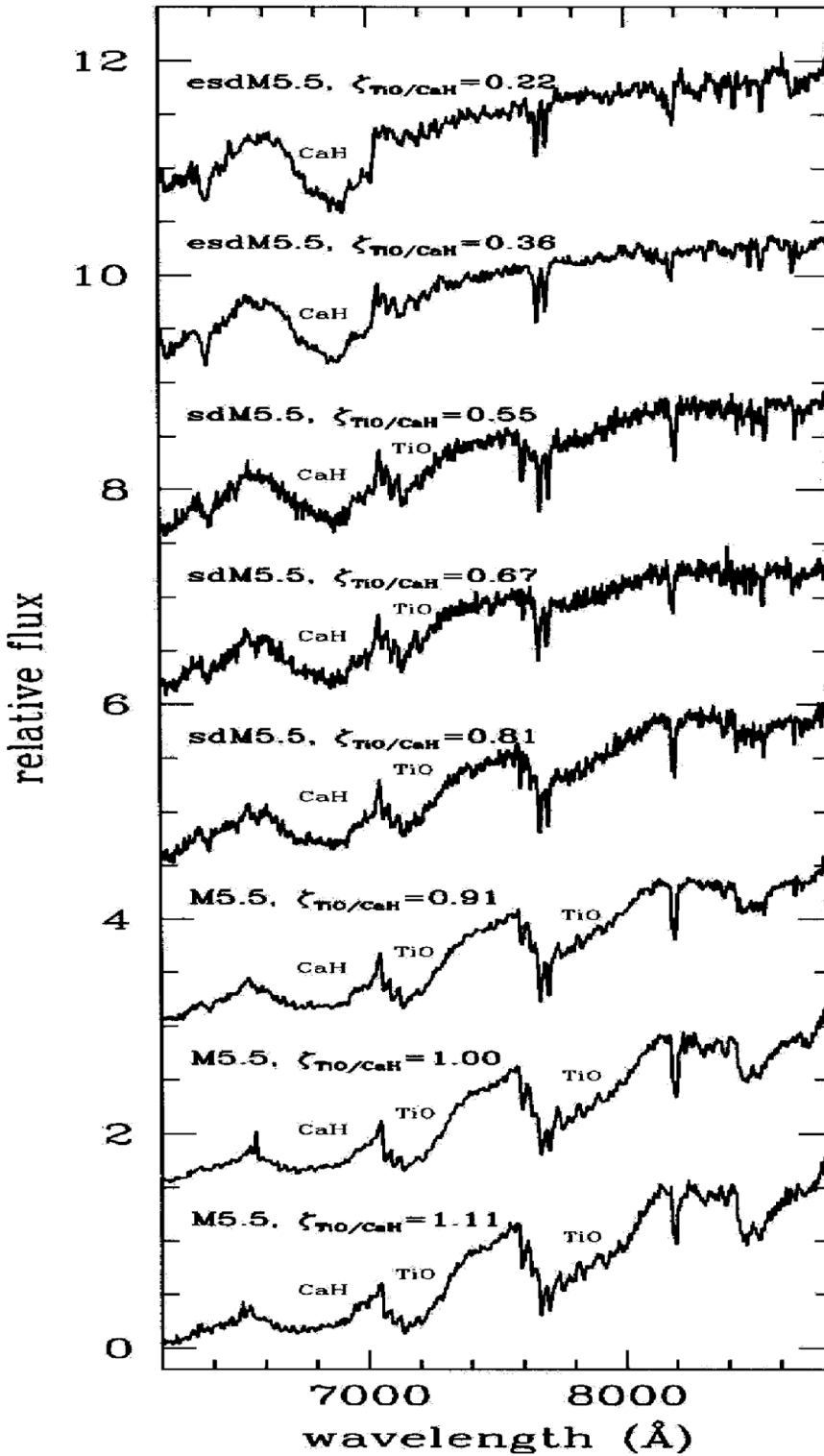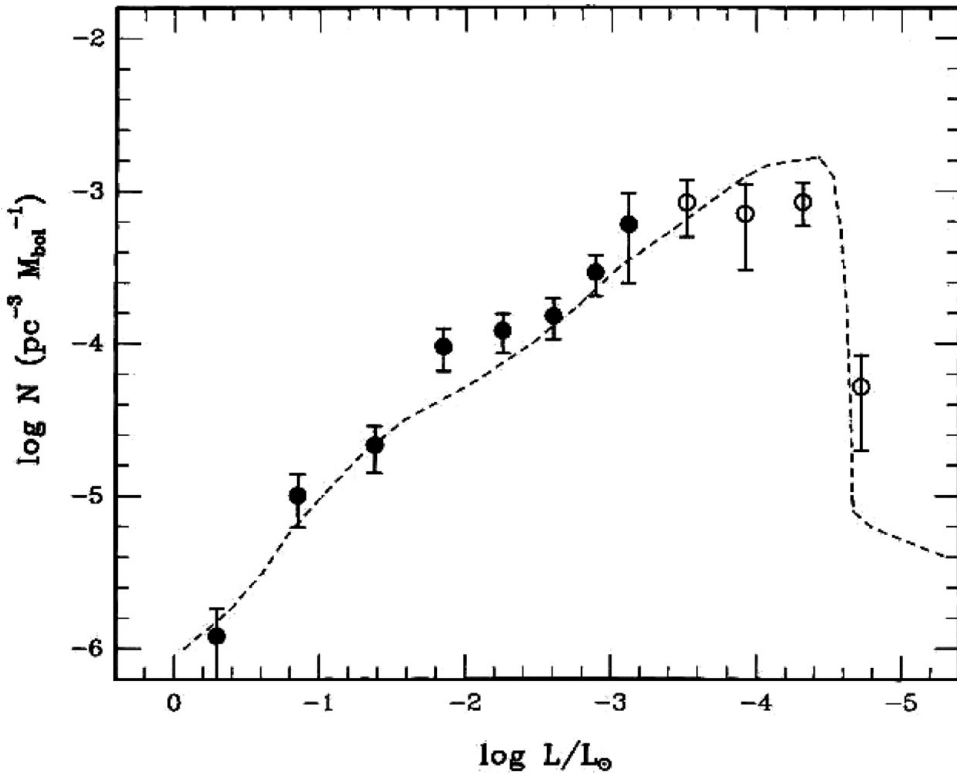
Figure 7. Stellar features in the spectra of disk dwarfs, subdwarfs and extreme-subdwarfs. Figure taken from (Lepine *et al.* (2007)).

Figure 8. White Dwarf Luminosity Function (model fit by Winget *et al.* (1987)). Figure taken from (Liebert *et al.* (1988)).

WD' luminosity function in figure 8 (from (Liebert *et al.* (1988))) shows a rise towards lower luminosities (L), which is expected given that WDs evolve by cooling and the timescales strongly increase at lower temperatures, therefore the LF has a maximum at low luminosities ($L \sim 10^{-4} L_{\odot}$). Beyond the maximum, the LF drops abruptly, this has been interpreted as due to the finite age of the galactic disk (Winget *et al.* (1987)). The first cooling models by Winget *et al.* (1987) derived an age of 9.3 Gyr for the galactic disk (later this value was modified by improved models).

For a while this very optimistic view regarding the use of WDs as cosmic clocks prevailed (Fontaine *et al.* (2001)).

The WD LF also contains information about the star forming History of a system (Noh & Scalo (1990); Isern *et al.* (1998); Rowell *et al.* (2009); Hernanz *et al.* (1994)), bumps and inflections reveal changes in the star formation process.

Today, the optimistic view is out, the realization that a "very cool WD is not necessarily old" did it. The age of a WD strongly depends on several parameters, like mass, core composition, and atmospheric composition (Fontaine & Brassard (2005)). Most WDs have a dense C/O core of degenerate matter with a stratified atmosphere of pure H, pure He or a mixed H-He composition. In some cases traces of metals (C, Ca) are also present.

Core composition is important, for instance, early models with pure C cores (Fontaine *et al.* (2001)), cool down slowly due to an increased heat capacity, suggesting older ages than those obtained assuming a mixed C/O core, while Ne/O cores (massive WDs) and He cores (low mass WDs) cool down at different rates. Therefore in order to obtain the age of a WD, its core composition needs to be known.

Atmospheric composition is also important, a pure He atmosphere is more transparent and cools down faster than a H atmosphere. A mixed atmosphere will be more complicated, will depend on the H/He ratio. Therefore, the atmosphere composition also needs to be known in order to determine the age of a WD.

Another relation that is important to calculate the age of a WD, is the relation between the initial to final mass, that is the mass of the star in the main sequence (MS) that is the progenitor of a given mass WD. This information is needed because the age of a WD is the sum of its age in the MS plus its cooling age. For very massive WDs the MS age can be neglected compared with its cooling age, the opposite is the case for low mass WDs, however for the great majority of WDs both ages are relevant. Recent work in the determination of the semi-empirical initial to final mass function shows that it depends on metallicity and more importantly there is a large scatter which is real and reflects the fact that stars loose mass during the AGB phase, in a process that seems to be stocastic in nature. That is to say, stars with the same mass in the MS can produce a WDs with a wide range of masses (Catalan (2008); Salaris *et al.* (2009)).

Work towards a better understanding of WDs and its evolution is under way, these problems that arose regarding WD's ages will be dealt with once some missing physics becomes available in order to improve the models.

One outstanding problem that still remains unsolved is the little success of various groups in finding WDs belonging to the galactic halo (Oppenheimer (2001); Lodieu *et al.* (2009)). The search, in this case, was motivated by the results of the microlensing experiments (MACHO (Alcock *et al.* (1997); Alcock *et al.* (2000)), EROS (Afonso *et al.* (2000); Lasserre *et al.* (2000)) and OGLE (Udalski *et al.* (1998)), that suggested that up to 30% of the Halo baryonic dark matter could be in the form of WDs. So far, the observed density of matter in halo WDs has only an upper limit of $\rho_{halo\ wd} < 4 \times 10^{-5}\ M_\odot\ pc^{-3}$ (Harris *et al.* (2006)). Where are the halo WDs ? Are they much fainter than we think ? these are important questions that still need to be answered.

7. Conclusions

Low luminosity stars, almost by chance, have become "hot topics" in modern astronomy, and new fields of research have been born, like BDs and exoplanet research and the halo baryonic dark matter issue (suggested by the microlensing experiments).

Dim stars are illuminating a range of important topics in astronomy. For example, low mass stars with their long lives have remained un-evolved since their birth, they constitute ideal objects to study the Initial Mass Function in different environments. WD's LF can reveal the history of star formation. Baryonic dark matter in the Halo and Disk, exoplanet formation mechanism, age of stellar system, these are among the many astrophysical areas that low luminosity star's research is making an important contribution to.

In summary, to answer the question in the title of this presentation: **yes, low luminosity stars do matter !**

Acknowledgements

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