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White dwarfs: Recent developments

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Summary. During the last decade white dwarfs have become important as tools in many areas beyond traditional stellar physics: from the age determination of the stars in the solar neighborhood to the dating of open clusters and the distance determination of globular clusters. They are primary candidates for the MACHO microlensing events, possibly for a stellar component of the dark halo, and for the supernova Ia progenitors. The recent developments in these areas are reviewed, but some highlights from more "mature" areas such as stellar parameters, mass distributions, magnetic, and pulsating white dwarfs are also summarized briefly.

Keywords. white dwarfs – Galaxy: halo – globular clusters: general – supernovae: general – open clusters and associations: general

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1. Introduction

White dwarfs (WDs) offer cosmic laboratories with physical conditions that cannot be achieved in terrestrial laboratories. Their very existence, the mass-radius relation, and the limiting Chandrasekhar mass are macroscopic demonstrations of the Pauli principle for fermions and the electron degeneracy following from it. The study of the structure and evolution of WDs thus tests our understanding of the equation of state under these extreme conditions. A fraction of about 3% of all white dwarfs show magnetic fields of up to 10^9 G in their atmospheres; this is much smaller than the fields in most neutron stars, but still much larger than any fields studied in our labs. This region is also a very difficult one to study theoretically, because Coulomb and magnetic fields in the atoms are of comparable strength and perturbation methods cannot be applied. Theoretical predictions of energy levels and transition probabilities have become available over the last 20 years and the observation of magnetic WDs is the only possibility to test them.

Conditions are even more extreme in neutron stars and black holes. The advantage in the case of WDs is that their surfaces can be observed directly and studied with the classical methods of spectroscopy and stellar atmosphere modeling, giving reliable data for effective temperatures, surface gravities, element abundances, and the parameters derived from these data as masses, radii, and ages. With these methods we have in the last decades accumulated a detailed understanding of the basic properties of white dwarfs and their evolution. This does not mean that there are no open questions; indeed some fairly fundamental facts like the reason for very different atmospheric compositions (spectral types) and likely changes from one to the other are not really understood. White dwarfs are therefore still a very lively field of research with an active community.

There is, however, clearly a growing interest in WDs beyond this community, which is related to the use of white dwarfs not so much as interesting objects of study but as a tool to study completely different aspects in other astrophysical areas. The observed spectra of WDs are in general quite simple and can be modeled theoretically with high accuracy and confidence to the level of approximately 1% or even better of the absolute flux. They are therefore primary candidates for the calibration of spectrographs on spacecrafts, and have been used successfully for that purpose on the International Ultraviolet Explorer (IUE), the Hubble Space Telescope (HST), the Extreme Ultraviolet Explorer (EUVE), the Far Ultraviolet Explorer (FUSE), and many others.

WDs are the end product of stellar evolution for 95 - 98% of all stars, with neutron stars and black holes sharing the small remaining fraction. The present population of WDs therefore contains information about the star formation rate throughout the history of our Galaxy. The relation between the mass of a WD and that of its progenitor star on the main sequence tells us the complete, integrated mass loss throughout the evolution. These are important data for an understanding of the mass budget of the Galaxy: how much mass is locked away forever in remnants and how much is given back to the interstellar medium and can be used again for star formation? Since we do not yet have a theory for the mass loss in all phases of stellar evolution, and since the observation is difficult especially in the latest phases where mass loss is strongest, this is currently the only method to get reliable data.

The oldest white dwarfs in the solar neighborhood belong to the oldest objects in the galactic disk. Since it is possible to estimate their ages from theoretical evolutionary calculations, this gives a lower limit for the beginning of star formation in the disk. If a population of halo WDs is found this will give an indication of the total age of our Galaxy. White dwarfs in open clusters and in globular clusters offer new and independent methods for age determinations, and also distance determinations, which are often strongly coupled using the traditional main sequence fitting methods.

There have been no general review papers on white dwarfs for a long time. Koester & Chanmugam (1990) present a fairly broad overview, but with the emphasis on the physics governing the structure, evolution, magnetic fields, atmospheric processes, and pulsations. Weidemann (1990) discusses the mass distribution of the WD population and its implications, and D'Antona & Mazzitelli (1990) review the evolution and theoretical luminosity functions, which are an important ingredient for galactic age determinations. Except for two very important recent reviews of magnetic white dwarfs (Wickramasinghe & Ferrario, 2000) and of the potential of white dwarf cosmochronology (Fontaine et al., 2001) I am not aware of any other reviews.

I have therefore decided to consider the last decade as the time frame for this review. Nearly all traditional areas of WD research have made significant progress during that time, triggered as in all areas of astrophysics by the advent of very large telescopes and powerful instruments and detectors, predominantly on HST and on the new 8m-class telescopes. I will briefly summarize the progress in the following sections. However, the main emphasis will be on completely new developments, which have only become possible, or which have obtained a new dimension of urgency in this last decade: the search for a halo population of white dwarfs, white dwarfs in globular and open clusters, and the search for supernova of type Ia progenitors.

For the reader interested in a more detailed account of the current work in all areas I recommend as a starting point the conference proceedings of the "European Workshops on White Dwarfs", which have been published in regular intervals since 1991 (Vauclair & Sion, 1991; Barstow, 1993; Koester & Werner, 1995; Isern et al., 1997a; Solheim & Meistas, 1999; Provencal et al., 2001).

2. A halo white dwarf population?

One of several longstanding "dark matter problems" is the fact that the dynamics – in particular the rotation curves – of our and most other spiral galaxies can only be explained by assuming an unobserved "dark" spheroidal halo. The exact numbers depend somewhat on the galactic models used, but the local density of this halo matter in the solar neighborhood must be approximately 0.01 $M_\odot \mathrm{pc}^{-3}$ (e.g. Bahcall & Soneira, 1980). Since the standard model for primordial nucleosynthesis of ^{2}H, ^{3}He, ^{4}He, and ^{6}Li requires a higher baryon density in the universe than is observed in the luminous matter, the least exotic candidates for some of the missing mass in the galactic halo have been some kind of stars or stellar remnants.

Massive stars with $M > 1\ M_\odot$ can be excluded immediately, because they would be detected easily and have not been found in sufficient numbers. That leaves the possibilities of low-mass red dwarfs, brown dwarfs, Jupiter–like objects (JLOs), as well as the stellar remnants black holes, neutron stars, and white dwarfs. Numerous papers have discussed the direct and indirect constraints for all candidates; it is impossible and not the intention of this review to give a complete account; we rather mention a few examples to indicate the kind of constraints that have to be considered.

The most direct evidence is that against low-mass red main sequence stars above the hydrogen-burning limit 0.08 $M_\odot$. Ground based observations of the luminosity function are limited to the disk in the solar neighborhood, since the discrimination between stars and faint galaxies becomes very difficult for faint magnitudes $V > 20$. Significant progress has been possible using the unique capabilities of the CCD cameras onboard HST, which pushed the limit to much fainter magnitudes. With star counts in various fields, combined with galactic models, Bahcall et al. (1994) concluded that red main sequence stars contribute less than 6% to the halo mass. Using somewhat less conservative assumptions with the same observational data, Graff & Freese (1996) find an upper limit of 1%, including even objects below the hydrogen-burning limit by a plausible extrapolation of the mass function and the remnants of the higher-mass stars. More recent observations and analyses of red dwarfs (e.g. Mera et al., 1996; Flynn et al., 1996; Freese et al., 1999; Gould et al., 1998; Zheng et al., 2001) essentially confirm these results, almost definitely ruling out all stellar–like objects except the remnants as major contributors to the halo mass. It should be noted, however, that the luminosity function below the H-burning limit is not known observationally and has to be extrapolated. All modern studies agree that the luminosity function does not continue to rise below 1 $M_\odot$ towards small masses, but shows a downturn somewhere between 0.2 and 1.0 $M_\odot$. It is *assumed* that this decline continues beyond the observational limit, whereas a significant contribution from brown dwarfs or JLOs would demand a steeply increasing mass function (Hegyi & Olive, 1986).

2.1. Stellar remnants: indirect constraints

Neutron stars and white dwarfs are known to exist, and the arguments for stellar black holes are very strong. Whether they exist in the halo in numbers large enough to make a significant contribution to the missing mass is still speculative. Direct observations – or the absence thereof – provide some constraints, but much of the discussion in the literature is dominated by the discussion of constraints related to the progenitors and the early evolution. These constraints include

i The formation of black holes or neutron stars necessarily involves supernova events. Looking back in time to early galaxies (redshifts up to ~ 3.5), where these massive stars are evolving now, this implies a certain luminosity and supernova rate.

ii The matter expelled during the evolution of the massive stars and in the supernova event is enriched with helium and heavy elements, e.g. Fe, which should at least partially be mixed with the gas in the disk.

iii More than half of all the mass of the progenitors is given back to the interstellar medium. If this gas is present in the halo, it should be hot (10^6K), and emit X-rays (Spitzer, 1956).

iv If the returned gas is somehow removed from the Galaxy, this again very likely requires many supernovae (galactic collisions and mergers may be another possibility).

v Stars of intermediate mass, which leave WD remnants, are also the major producers of C and N in the Galaxy.

vi The initial–mass function (IMF) for the progenitors should not produce too many low–mass stars, since these are not observed.

vii There are only very few main sequence halo stars with masses above 1 $M_\odot$.

viii The present mass to light ratio for the halo (as observed in nearby spiral galaxies) should be larger than 100 in the B-Band (e.g. Ryu et al., 1990).

ix Even the observation of TeV γ-rays from Mrk 421 and Mrk 501 can be used as a constraint. Progenitors in galaxies at cosmological distances would contribute to a diffuse IR background radiation, with a strong opacity for energetic γ-rays through pair creation (Graff et al., 1999).

Let us look at some of these studies and their conclusions in more detail. Ryu et al. (1990) put the emphasis on the constraints (ii), (iii), and (viii). They use a simple model to calculate the evolution of halo matter, luminosity, metallicity, and helium abundance. Their conclusions are:

- The IMF for the halo must be very different from that of the disk. It must be confined to the range of 2 to 8 $M_\odot$ to be compatible with the constraints from metal enrichment (massive stars) and luminosity of long-lived main sequence stars (low-mass end). Even then (with no metal formation in the halo) they have to assume that the star formation in the disk starts at the same time as in the halo, before the first halo stars die, in order to avoid a large overproduction of helium in the disk.
- Star formation in the halo is limited to the first $\sim$ 2 billion years.

These results firmly rule out a significant halo contribution from black holes and neutron stars as remnants of massive stars, and the emphasis has been strongly on the white dwarfs as the only viable candidate in all following studies. Almost all of these papers use the observed luminosity function (LF) of white dwarfs, which shows a cutoff at $\log L/L_\odot \sim -4.4$ and very few halo white dwarfs (see below) as one of the constraints.

Tamanaha et al. (1990) model the theoretical LF for disk and halo white dwarfs, following earlier work of Winget et al. (1987) and Iben & Laughlin (1989). The input ingredients are – as in all similar studies – the IMF of the progenitor stars, the relation between the initial mass on the main sequence and the final remnant mass (MIMF), the star formation rate (SFR) as a function of time, and the cooling times for white dwarfs as a function of mass. With this input the LF of white dwarfs can be calculated; the comparison with observed data requires in addition some transformation between theoretical and observational data like bolometric corrections (B.C.). They find that it is possible to explain all the required halo mass with white dwarfs, provided that the halo IMF is confined to the range 2 - 6 $M_\odot$, the star formation occurred in a very strong (800 times the constant SFR for the disk), but short (10^8 yr) burst. Such halos have to be at least 12 Gyr old for the WDs to have faded now beyond the observational limits. Even if these dim WDs contribute only 1% of the dark matter, a definite signature of these objects is predicted, which should be within the observable reach of current searches.

Adams & Laughlin (1996) derive a larger minimum age of 16 Gyr from the current WD LF constraints. In addition they use the galactic metallicity and the limits on infrared background light to argue that the mass fraction of the WD in the halo is most likely less than 25%, and that the halo IMF has to be strongly peaked around 2.3 $M_\odot$. An even larger age limit (18 Gyr) is obtained by Chabrier et al. (1996), using different cooling ages for the WDs and the additional constraint from the few halo WDs known; while Graff et al. (1998) bring the limit back to 12 Gyr for a 30% WD halo contribution in their most favorable calculation. As a typical example for these more recent studies using the LF constraints we show a figure from Chabrier (1999) (Fig. 1). The solid circles are the observational LF from Liebert et al. (1989), the squares are the halo WDs from the same paper. The solid lines are the LF for

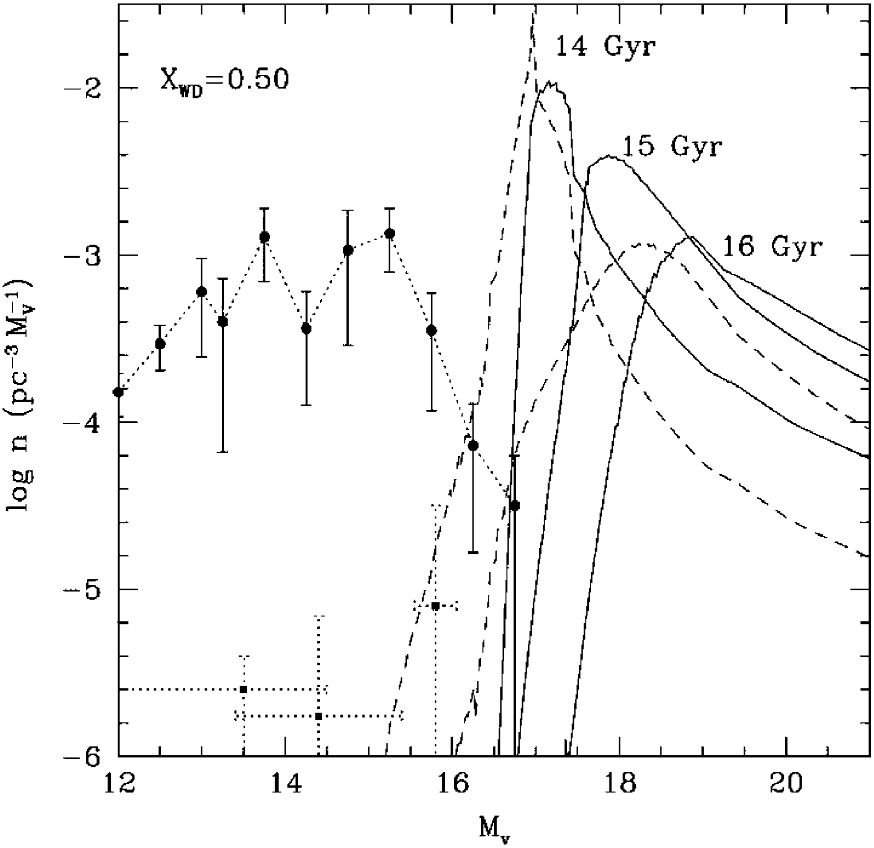

Fig. 1. White dwarf luminosity function. *Filled circles:* Liebert et al. (1989). *Squares:* halo WDs from the same paper. *Solid lines:* Theoretical halo WD LF for halo ages of 14, 15, 16 Gyr and a halo WD mass fraction of 50%. *Dashed lines:* halo WD LF for 14 and 16 Gyr, but with a different IMF. From Chabrier (1999)

halo WDs, assuming that they constitute 50% of the halo mass, for 3 different ages. The dashed lines are similar calculations with a different IMF and ages of 14 and 16 Gyr. From this figure, a halo age of $\sim$ 14 Gyr seems consistent with observations. The author cautions, however, that these calculations are extremely sensitive to input physics, which are still very little constrained (e.g. the IMF).

Charlot & Silk (1995), using population synthesis models and the constraints from deep galaxy surveys, constrain the WD contribution to $<$ 25%, because the bright early phases of these halos should be detectable in deep galaxy counts, especially in the near-infrared. Constraints from the C and N enrichment by intermediate mass stars are used by Gibson & Mould (1997) to demonstrate that the Population III precursor population of a large halo WD population would result in [C,N/O] ratios much larger than observed in present-day halo stars. Chemical constraints are also used by Fields et al. (2000); they find that a significant contribution of WDs to the dark halo is very unlikely.

Summarizing these and many other similar studies not mentioned here in detail, one must conclude that strong constraints limit the possible WD fraction in the halo dark mass. However, with the freedom in the choice of the parameters for IMF, age of the halo, and remaining uncertainties in the atmospheric properties, cooling ages, lower end of the LF, and space densities of the WD a significant contribution of the order of 30 %, or perhaps even 100 % cannot definitely be excluded. It thus becomes urgent to really search for these objects and possibly find them.

2.2. Microlensing experiments and MACHOs

A search for dark halo matter in the form of massive compact halo objects or MACHOs with the microlensing effect was suggested by Paczynski (1986) and realized during the nineties by several research groups, who reported the first discoveries in 1993: the MACHO, EROS, and OGLE collaborations (Aubourg et al., 1993; Alcock et al., 1993; Udalski et al., 1993).

These groups continuously survey several fields containing huge numbers of stars in the Magellanic Clouds or the Galactic Bulge for light variations. A massive, star-like dark object passing the line-of-sight between the observer and a star in the LMC will focus the light due to the relativistic deflection effect, which leads to an increase of the stellar magnitude with maximum amplifications typically of factors 2 – 5. The light curves are symmetric and independent of wavelength/passband, which can be used to distinguish these events – a very difficult work nevertheless – from variable stars in the LMC or supernova events in background galaxies. The duration of the amplification, of the order of some ten days, and the maximum amplification, depend on the mass of the intervening object, its distance, and its transverse velocity. The number of events obviously is related to the number and distribution of MACHOs in the halo, but the analysis is extremely difficult and involved.

Expanding on earlier results (Alcock et al., 1997), Alcock et al. (2000) present the analysis of 5.7 years of LMC observations of the MACHO collaboration. They report the detection of 13-17 microlensing events, whereas only 2-4 would be expected from lensing by known stellar populations. The range of numbers for the observations here reflects the use of different sets of criteria to distinguish between microlensing and other reasons for variability. Interpreted in the context of a Galactic dark matter halo, this means that the MACHO halo fraction is about 20%, with a 95% confidence interval of 8% - 50%. The average MACHO mass is 0.5 $M_\odot$, with a likely range of 0.15 - 0.9 $M_\odot$. The analysis of EROS observations towards the LMC, with the smaller statistics of only 3 detected events, is compatible with these numbers (Lasserre et al., 2000). As example we show in Fig. 2 the allowed ranges in MACHO mass and halo mass fraction for a typical halo model and two different sets of criteria (A or B) for the discrimination of mirocrolensing events. Two of the results also include a possible contribution to microlensing from a halo of the LMC (see Alcock et al. 2000 for details).

The absence of any events with crossing times shorter than 10 days essentially excludes all planet-like objects and brown dwarfs as candidates (Chabrier, 1999; Lasserre et al., 2000; Alcock et al., 2000), in agreement with the earlier studies of indirect constraints. The average mass is, on the other hand, exactly the expected mass of a white dwarf. Obviously these results provided new impetus to the search for these hypothetical objects.

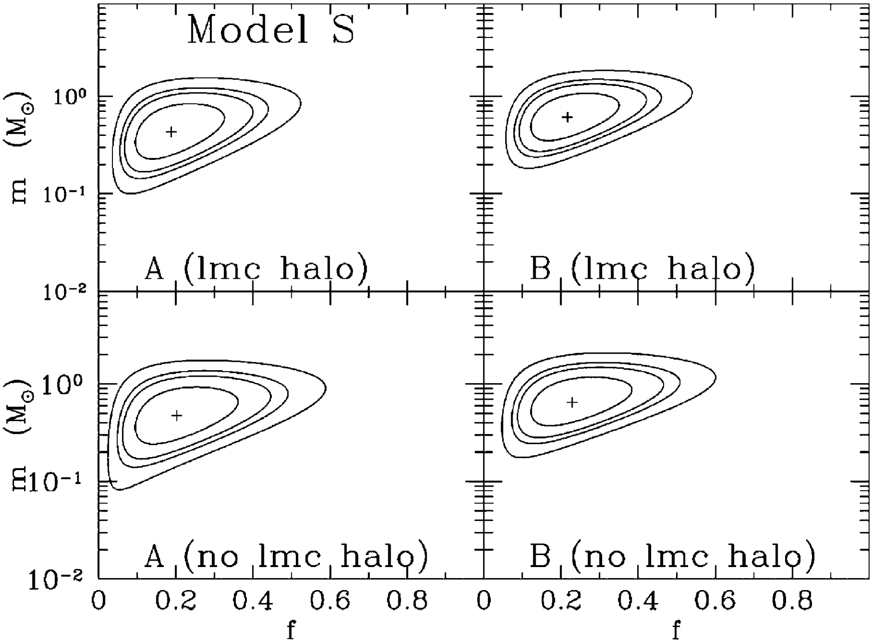

Fig. 2. Likelihood contours for MACHO mass m and halo fraction f for a typical halo model. The plus sign shows the maximum-likelihood estimate, and the contours enclose regions of 68%, 90%, 95%, and 99% probability. The panels are labeled according to which set of selection criteria (A or B) is used, and whether or not a LMC halo with MACHO fraction f is included. From Alcock et al. (2000)

2.3. Earlier evidence for halo white dwarfs

The standard reference for the observed luminosity function of white dwarfs has been for many years the work of Liebert et al. (1988, LDM). For the first time LDM proved conclusively that the disk white dwarf LM ends at $L/L_\odot = -4.4$ or $M_V = +16$, and that this is not an observational effect but rather certainly the signature of a finite age of the galactic disk $< 9 - 12$ Gyr. Liebert et al. (1989) use kinematical constraints to extract a first LF for halo white dwarfs from this sample, unfortunately based on only 6 objects.

The WD sample for these studies was drawn from the proper motion surveys by Luyten, predominantly the LHS survey (Luyten, 1979). The completeness of these surveys, especially for faint stars of large motion, has been the topic of a controversial discussion (Hanson, 1979; Dawson, 1986; Oswalt et al., 1996; Wood & Oswalt, 1998; Hambly et al., 1997; Flynn et al., 2001). Monet et al. (2000) have therefore readdressed the problem of completeness for the stars of larger proper motion, using some fields of the POSS II survey, where extra plates exist, spanning times of 1.5 to 10 years between epochs (the long times of 35 to 50 years between POSS I and POSS II epochs would make the detections of very larger proper motions extremely difficult!). The conclusion of this paper is that the Luyten proper motion catalogs are close to 90% completeness for large pm stars ($\mu > 0.''5$). The authors also did not find a single object with motion faster than the upper Luyten limit of $2.''5$. Although the total space density of white dwarfs (mostly belonging to the disk population) still has considerable uncertainty (see the recent discussion of results from different methods in Holberg et al. 2001), one consequence from this type of studies is unavoidable: if a substantial halo WD population exists, they must be fainter than M_V = 17 and cooler than $T_{\rm eff}$ = 4000 K. This regime of parameters for white dwarfs was theoretically almost unexplored until about 1998, which is quite understandable in view of the absence of any observations. The standard in stellar atmospheres and colors for cool white dwarfs of helium and hydrogen composition was a series of papers by Bergeron and collaborators (Bergeron et al., 1991, 1995b,c), but their models did not extend below 4000 K. Likewise, the long-time standard for cooling ages of white dwarfs was the work of Wood (1990, 1992, 1995), which used extrapolations to go to magnitudes slightly below the observational limits. More theoretical work in these fields was urgently needed.

The next major milestone on the observational front was the search for stellar objects in the Hubble Deep Field (HDF), and later in the southern equivalent HDF South (Williams et al., 1996, 2000), which had of course been observed mostly for extragalactic studies. Compared to ground-based studies the field of approximately 4 square arc minutes is very small; this is to a large extent – especially for studies of the halo composition – compensated by the larger distance sampled with a limiting magnitude of typically I = 27.5. Using halo models like those of Bahcall & Soneira (1980), Kawaler (1996) estimated the total halo mass sampled by the HDF as 1.05 – 7.8 $M_\odot$. White dwarfs could thus only be expected if they indeed constitute a significant fraction of the halo mass, and direct searches on the HDF seemed to confirm that. Flynn et al. (1996) found no white dwarfs down to a limit of V = 26.3 in the color range of $1.8 < V - I < 2.5$, a result confirmed by Mendez et al. (1996), although they found blue, stellar-like objects in the field.

2.4. Theoretical developments: atmospheres and cooling times

The story of the search for halo white dwarfs took a completely new turn, when Hansen (1998) drew the attention to the fact that WDs with hydrogen-rich atmospheres do not become ever redder when they cool down, but turn back to the blue region again below 4000 K. This happens for colors involving near infrared bandpasses like $V-I$, though not for $B-V$, which is typically used for hotter WDs. The $V-I$ color can even become as blue as -2 for a hydrogen atmosphere WD of 1500 K. Figure 3 shows this very clearly in the CMD using M_V vs. $V-I$, for two different formulations of the equation of state. The reason is a source of opacity, which had been known and incorporated in atmosphere codes since years (Saumon et al., 1994; Bergeron et al., 1995b), but never at such low effective temperatures and high surface gravities. The hydrogen molecule H_2 has no permanent electric dipole moment; however, in very dense environments a collision with e.g. another H_2 molecule or neutral He atom can induce a temporary dipole moment, which leads to extremely strong quasi-continuous "collision-induced absorption" or CIA (see Jørgensen et al., 2000; Zheng & Borysow, 1995; Borysow et al., 1997). Below $T_{\rm eff}\sim$ 3000 K this absorption dominates the spectral energy distribution: the strong suppression of the flux in the IR leads to a redistribution, with the maximum shifting to shorter wavelengths. This is the reason for the turn to the blue in $V-I$. One should note, however, that this absorption occurs only in atmospheres containing some hydrogen. A significant fraction of WDs at higher temperatures (10000 - 4000 K) has pure or almost pure helium atmospheres (Bergeron et al., 1997, 2001); they will continue to get redder as they cool. Atmosphere models

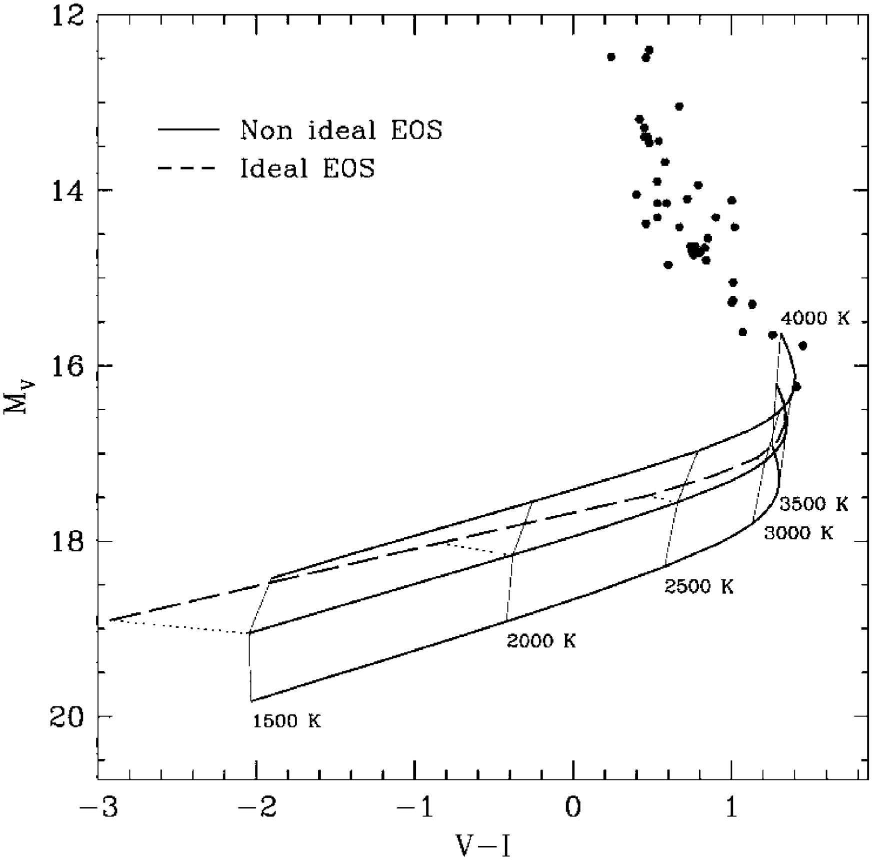

Fig. 3. Color-magnitude diagram for pure hydrogen white dwarf atmospheres. The dashed line shows the locus of models computed with an ideal EOS. The points are a subset from Bergeron et al. (1997) with hydrogen atmospheres and known parallaxes. From Saumon & Jacobson (1999)

for very cool WDs including this source of opacity have also been calculated by Saumon & Jacobson (1999); Chabrier et al. (2000); Jørgensen et al. (2000); Fontaine et al. (2001).

At the same time significant theoretical progress was achieved in the second area identified above (evolution of very cool WDs), again by Hansen (1999). He pointed out that at very low temperatures the convection zone extends throughout the whole nondegenerate region up to the high atmosphere. Without an intermediate radiative layer, the temperature structure throughout this whole zone depends strongly on the exact atmospheric conditions, and it is extremely important to use correct atmospheric models with detailed radiative transfer calculations as boundary conditions for the interior structure, as opposed to using e.g. grey atmosphere conditions. While this had been known before, the effects become dramatic only at the very low temperatures, which had not found much interest until recently. As a result of using these improved boundary conditions, Hansen found dramatic differences in the cooling times for hydrogen vs. helium atmosphere WDs. While a 0.6 $M_{\odot}$ hydrogen model (with a C/O core) still has a luminosity of $\log L/L_{\odot}$ = −4.5 at 10 Gyr, the corresponding model with helium atmosphere has already cooled down to $\log L/L_\odot = -6.0$ and will be unobservable at the age corresponding to the assumed halo ages. *The search area for halo white dwarfs is thus narrowed down to hydrogen-rich WD with blue colors* $V - I < 1.4$ *and* $M_V > 17 - 18$.

The interest in possible halo WD has stimulated several groups to extend evolutionary calculations into the interesting regime (Salaris et al., 1997; Benvenuto & Althaus, 1999; Montgomery et al., 1999; Salaris et al., 2000; Chabrier et al., 2000; Serenelli et al., 2001; Fontaine et al., 2001). Unfortunately, the results, e.g the cooling ages, do not always agree very well. This will hopefully improve in the near future, when all calculations use sophisticated boundary conditions, as well as the best available input physics for equation of state and opacities. However, there are also still unsolved or at least controversial physical and astrophysical problems, which may prove hard to solve. Among those we mention the equation of state, especially for mixed hydrogen/helium envelopes at extremely high pressures leading to pressure ionization. Another open question – studied extensively by the Barcelona group over the last decade (e.g. Garcia-Berro et al., 1988; Isern et al., 1997b, 1998; Salaris et al., 2000) – is the chemical fractionation, when a mixture of carbon and oxygen crystallizes. If the elements separate during freezing, oxygen may diffuse towards the center, releasing additional gravitational energy. The magnitude of this effect depends on the unknown fractions of oxygen and carbon and their distribution in the interior, and on the exact time or luminosity, when this energy is set free (if this occurs at higher luminosity, the increase in the ages is small, since the amount of additional energy is constant). To give an impression of the uncertainties that are still present in the latest generation of cooling ages: at $L/L_\odot = -6$ the age of a pure carbon interior model is 3.6 Gyr larger than that of a pure oxygen core (Fontaine et al., 2001), and the consideration of C/O separation for mixed compositions adds another 1 Gyr uncertainty (Salaris et al., 2000).

2.5. *The search is on*

With the new theoretical understanding, the blue point-sources in the HDF became viable candidates (Méndez & Minniti, 2000). Since the confusion problem with blue extragalactic sources is severe at faint magnitudes, the only safe criterion would be proper motion of the sources. Using HST images of the same field taken 2 years later, Ibata et al. (1999) claimed to have found a substantial proper motion for two objects (23 and 26 mas yr^{-1}), with 3 more objects possibly also moving. The colors of these objects agreed with the predictions of the new set of model atmospheres of Hansen (1998, 1999). The suggested numbers, however, would mean that several times more of these objects should have been detected in existing ground–based surveys, but none had been found (Flynn et al., 2001). Apparently a third epoch image has shown that neither of the objects has a homogenous motion and the proper motions were thus spurious detections (Richer 2001 in prep., as cited in Reid et al. 2001). However, in the meantime the exciting claim had given new impetus to ongoing and new proper motion surveys, since this is arguably the best method to find halo objects in the solar neighborhood.

The first new discovery was the detection of WD 0346+246 serendipitously in a search for brown dwarfs in the Pleiades cluster (Hambly et al., 1997). This object has a very high relative proper motion of $1.''3\ \mathrm{yr}^{-1}$; colors and spectroscopy obtained by Hambly et al. (1997) indicated that it might be one of the coolest WD known.

A parallax was subsequently measured (Hambly et al., 1999), with a corresponding distance of 28 ± 4 pc, and absolute magnitude of M_V = 16.8, the second-lowest luminosity at that time. The kinematic properties are consistent with membership of the Galactic halo.

Two more cool high proper motion WD were found by Ibata et al. (2000). F 351-50 has a proper motion of 2.″33 yr^{-1}, F 821-01 (a rediscovery of LHS 542 in the LHS catalog) has 1.″72 yr^{-1}. The distance of LHS 542 of 31 pc implies a high space motion and makes halo membership likely. LHS 3250, also a previously known WD, was discovered to be a very low-luminosity, and therefore cool and old WD, when the parallax became available (Harris et al., 1999). All these WD showed the blue V-I colors and the depression of the infrared flux likely due to the CIA absorption predicted by the new generation of models and demonstrated for the helium-rich LHS 1126 at slightly higher temperatures by Bergeron et al. (1994). A detailed investigation, with new photometric and spectroscopic observations, by Oppenheimer et al. (2001b) confirmed that the effective temperatures of WD 0346+246, F 351-50, and LHS 3250 are very likely below 4000 K. Even the latest models, however, where not able to reproduce the observations in detail, and especially LHS 3250 occupies a unique position in color-color and color-magnitude diagrams, which led Oppenheimer et al. (2001b) to the suggestion that it might be a very cool double degenerate. Bergeron (2001) has also warned against overinterpreting the current results, as long as the data cannot be fitted more convincingly by the models. For WD 0346+246 he obtains a solution with equal amounts of H and He in the atmosphere, instead of the very He-rich solution proposed by Oppenheimer et al. (2001b). While the effective temperature he obtains is very similar, the cooling age implied would be 11 Gyr instead of 8.7 for the helium-rich solution.

The confirmation of very unusual colors of extremely cool white dwarfs suggests the possibility of using photometry in the search as an alternative to proper motions. The largest such search currently underway, the Sloan Digital Sky Survey (York et al., 2000), is expected to be an efficient tool (Harris et al., 1999; Hansen, 2000), and has proven so already in the commissioning phase with the discovery of SDSSp J133739.40+000142.8 (Harris et al., 2001). The colors of this object are similar to those of LHS 3250, and the CIA depression in the infrared spectrum indicates an even lower temperature, although the models still fail to reproduce the energy distribution. The space velocity of this object, however, is low, making it very likely a member of the disk population.

2.6. Direct detection of Galactic halo dark matter?

Great excitement and an extremely lively debate was stirred up in 2001 with the claim by Oppenheimer et al. (2001a, OH01) to have found 38 halo white dwarfs, accounting for at least 2% of the halo dark matter.

This work was based on digitized photographic plates in two passbands (magnitudes B_J and $R59F$) approximately equivalent to the optical wavelengths 4500 and 5900 Å, obtained for the SuperCOSMOS Sky Survey (Hambly et al., 2001). The sky area, which could be used for the study, corresponds to roughly 10% of the sky at the South Galactic Cap, several times larger than the coverage of two other recent surveys (Ibata et al., 2000; Monet et al., 2000). A search for proper motions between 0.33 and 10 arcsec yr^{-1} down to a magnitude of $R59F$ = 19.8 allowed them to discover many objects at the faint end not in the Luyten samples, which are the primary candidates for their search for halo objects. The technique used is that of reduced proper motions, using $H_R = R59F + 5\log\mu + 5$ as an estimate of the absolute magnitude based on the apparent magnitude $R59F$ and the proper motion μ (Hertzsprung, 1922; Jones, 1972; Luyten, 1979; Knox et al., 1999; Flynn et al., 2001). 126 objects were selected from the H_R vs. $(B_J - R59F)$ diagram as being subluminous; this sample included 63 new faint high proper motion stars, as well as 63 previously cataloged objects, of which 29 had no published spectroscopic follow-up. 69 of these candidates were observed spectroscopically, which resulted in 38 new cool white dwarfs (the others are M dwarfs, M subdwarfs, and 15 hotter white dwarfs), a few of which might be even cooler than WD 0346+246, the one very cool WD with definitely established halo kinematics.

The interpretation of OH01 then centers on the question of the kinematical properties of this sample, which is not easy in the absence of trigonometric parallaxes and radial velocities. To estimate photometric distances they use a fit to the cool WD sample by Bergeron et al. (1997), supplemented by WD 0346+246, which gives a linear relation for the absolute magnitude as a function of color, $M_{B_J} = 12.73 + 2.58\,(B_J - R59F)$, with an estimated uncertainty for the distances of 20%. Proper motion and distance give the tangential velocity, which is converted to the usual Galactic velocity vector (U, V, W) by assuming $W = 0$. Using the $U - V$ diagram they finally select a sample of 38 WD (24 cool and 12 with Hα), which deviate more than 2σ from the central position of the old disk stars, which corresponds to tangential velocities larger than 94 km s^{-1}. Finally, using the $1/V_{max}$ technique and a typical value of 0.6 $M_\odot$ for the objects, they obtain a space density of $1.3\,10^{-4}$ $M_\odot$ pc^{-3}, or between 1 and 2% of the estimated dark matter mass of the halo. To put this into context, one could also state that the mass in halo white dwarfs is comparable to the entire disk of our Galaxy (Gibson & Flynn, 2001), or a factor of 10 above what would be expected from the halo density of subdwarfs and a standard IMF (“stellar halo” as opposed to dark halo).

Even before the publication of this paper it sparked a very animated debate, which is still raging on at the moment of this writing. The discussion is centered on three aspects of the claims: the kinematics of the sample and the interpretation as halo stars, the question whether this can really be the searched-for extremely old halo population, and what the real space density of these objects is. As the debate is still going on, we will only discuss a few arguments put forward in the case.

Gibson & Flynn (2001) criticize the application of the $1/V_{max}$ and V/V_{max} tests by OH01. Repeating a similar analysis, and examining some of the OH01 assumptions, they arrive at a mass density of about a factor of 2 smaller. They also give arguments that this population should have been detected in previous proper motion surveys, if the density is as high as obtained by OH01.

The halo membership – at least of the majority of the OH01 sample – is questioned by Reid et al. (2001). Using the same dataset and a variety of different arguments, they conclude that probably 75% of the sample belong to the high-velocity tail of a rotating disk population, most likely the thick disk. Only the remaining 25% are likely halo members, which is consistent with the expected number of white dwarfs in the Population II halo, thus eliminating the need for an additional contribution from hypothetical WD members of the dark halo.

Hansen (2001) basically agrees with the Reid et al. (2001) conclusion about the possible thick disk membership from the kinematic data. Moreover, he points out that the OH01 interpretation is inconsistent with the age distribution of the sample. The oldest white dwarf in the OH01 sample – even using the most conservative

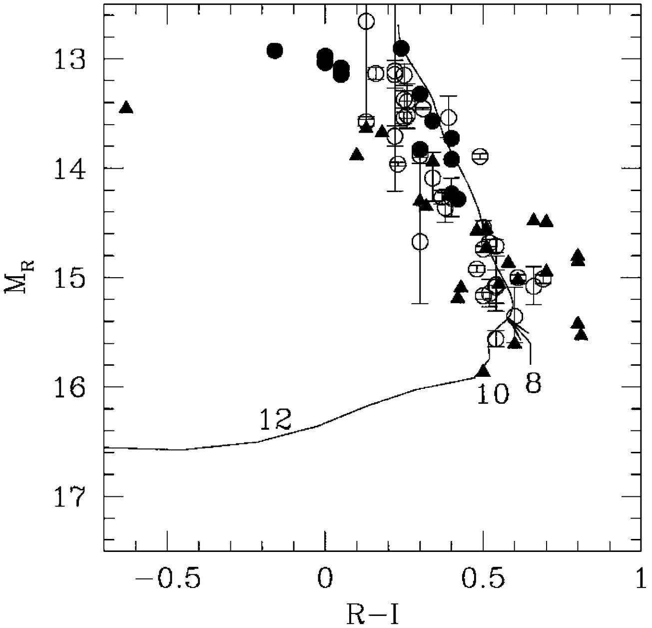

Fig. 4. OH01 sample of white dwarfs in the CMD (solid points, triangles are objects without Hα). Open points are the thin disk WD from the Bergeron et al. (2001) sample. The solid curve represents the slowest plausible cooling WD, with some ages in Gyr noted along the curve. From Hansen (2001)

assumptions – is not older than 10 Gyr, and most are considerably younger. This is very nicely demonstrated with the CMD in Fig. 4. The solid points are objects from the OH01 sample, the open points are thin disk white dwarfs from the Bergeron et al. (2001) sample; the solid line represents the slowest plausible cooling WD (0.5 $M_\odot$, hydrogen atmosphere), with some ages in Gyr noted along the curve. The age distribution of the OH01 sample is very similar to that of the thin disk cool WD. The OH01 white dwarfs are obviously not as old as would be expected for a thick disk and it is tempting to conclude that they originate from the thin disk. That, however, is hard to reconcile with the high velocities, which point to the thick disk (Reid et al., 2001).

2.7. Conclusions on halo white dwarfs

This question certainly has not been finally settled. Many indirect arguments severely constrain the possible contribution of very cool white dwarfs to the dark mass in the halo. The results of OH01 provide a very interesting sample of ultracool WD and will undoubtedly be studied intensely in the near future. At the moment it does not seem likely that this is indeed the new halo WD component as the authors claim. But even if they can prove their case, the fraction this would provide for the dark halo mass is less than 2%, significantly less than what is required by the MACHO results. The origin of the majority of the microlensing events is thus still unsolved.

3. White dwarfs in globular clusters

Globular clusters (GCs) are the oldest stellar systems for which reliable ages can be determined from a comparison of observations with calculations of stellar evolution. They constrain the age of the Galaxy and that of the universe, and therefore finally also the choice of cosmological parameters. The only method to reliably obtain absolute ages of GCs is to use the absolute magnitude of the main sequence turnoff. While other observable data as the horizontal branch morphology or the colors of the turnoff are also sensitive to age, they also depend on other parameters as assumed convective efficiency and mass loss history, which are not yet completely understood. The turnoff luminosity comes from the observed magnitudes of the turnoff main sequence stars, correction for reddening, and a comparison with some standard main sequence. An analysis of the method of age determination shows that the largest contribution to the error comes from the uncertainty of distances, and much of the work trying to improve the age estimates in recent years has therefore centered on the issue of distances. Since the position of the main sequence depends on the metallicity of the stars, the large sample of parallaxes for local metal-poor subdwarfs by HIPPARCOS has been a big progress, with a significant reduction of the GC age scale. However, due to the many difficulties involved, the distance and age scale of GCs are still a matter of debate and different authors obtain differences of up to 0.4 mag for the distance modulus and several Gyr differences in age even for the closest GCs (see e.g. Zoccali et al., 2001, for a discussion). It is therefore important to study alternative methods, which avoid some of the uncertainties inherent in the main sequence fitting technique.

One such method is the so-called white dwarf fitting technique, which tries to compare the WD cooling sequence in a GC with a local sample of WDs to determine the distance modulus independently. The advantage is that DA white dwarfs have very simple pure hydrogen atmospheres, independent of the metallicity of the parent cluster; their masses – the only parameter to determine the luminosity at fixed $T_{\rm eff}$ or color – are expected to fall into the narrow range of $0.51 - 0.55 M_\odot$ (Renzini et al., 1996; Renzini & Fusi Pecci, 1988). Because of the severe crowding in the cluster, and typical magnitudes $V > 23$, such a study became only feasible with HST, after the repair of the optical system. White dwarf sequences were identified in 47 Tuc by Paresce et al. (1995a); Ferraro et al. (2001); Zoccali et al. (2001), M 4 by Richer et al. (1995, 1997), in NGC 6397 by Paresce et al. (1995b); Cool et al. (1996); Taylor et al. (2001), in NGC 6752 by Renzini et al. (1996).

As an example of the use of this method we will consider the most recent work on 47 Tuc (Zoccali et al., 2001) in some detail. The observations were obtained with the WFPC2 camera onboard HST, using the UV to optical filters F336W, F439W, F555W, and F814W; for the details of the reductions and tests performed we refer the reader to the original paper. In the various CMDs which can be constructed (using only instrumental magnitudes corresponding to 1 s exposures without any transformations) a white dwarf cooling sequence can easily be identified (Fig. 5). From the narrowness of the sequence, especially in the diagrams including the m_{336} magnitude, and a comparison with the local WD sample, they conclude that these are only DA white dwarfs.

The local WD sample consists of 8 WDs, selected for having accurate parallaxes to better than 10% and a spectroscopically determined mass as close as possible to 0.53 $M_\odot$, the predicted mass for the GC white dwarfs. Two of these are DB (helium atmosphere) objects, which are not used in the final comparison. The local sample was observed with the HST in the same filters, with great care taken to work as

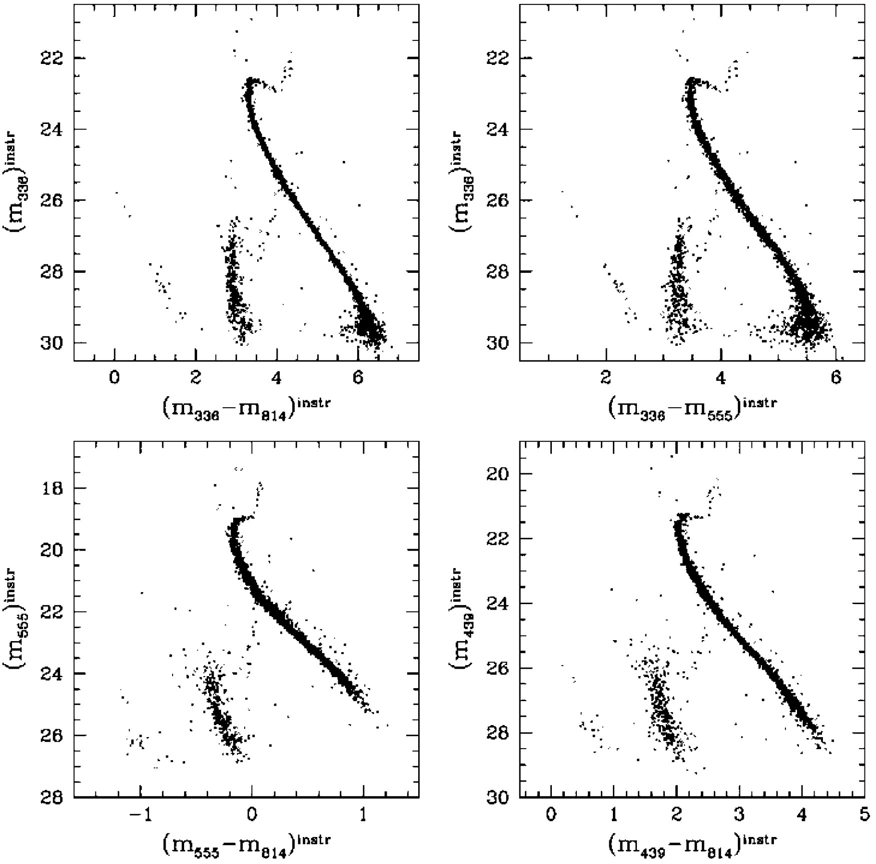

Fig. 5. Instrumental CMD of a field in the globular cluster 47 Tuc. Three main branches are clearly distinguishable: the cluster main sequence on the right, the SMC main sequence branch in the middle, and the cluster white dwarf sequence on the left. From Zoccali et al. (2001)

much as possible in a differential fashion to eliminate errors as much as feasible. Using the parallaxes, the local sample was transformed to absolute magnitudes and then corrected for small mass differences compared to the "standard" 0.53 $M_\odot$. This results in a very well defined fiducial WD cooling sequence for the standard mass with absolute magnitudes, which can then be used to determine the distance modulus by shifting the GC cooling sequence to fit onto the fiducial local sequence. The final true distance modulus the authors obtain is $(M-m)_0$ = 13.09 ± 0.14, which lies at the lower end of the range of 8 distance determinations over the last 15 years using a variety of methods. The distance is, however, significantly shorter than the values recently reported by Reid (1998) and Carretta et al. (2000) using the subdwarf method based on HIPPARCOS parallaxes. This discrepancy is currently not understood.

Salaris et al. (2001) study the possible sources of error in the WD fitting technique. They conclude that with great care in principle systematic errors as small as 0.10 mag could be reached. Besides uncertainty in the reddening the contamination of the cluster sequences by DB stars may introduce much larger errors, especially when using

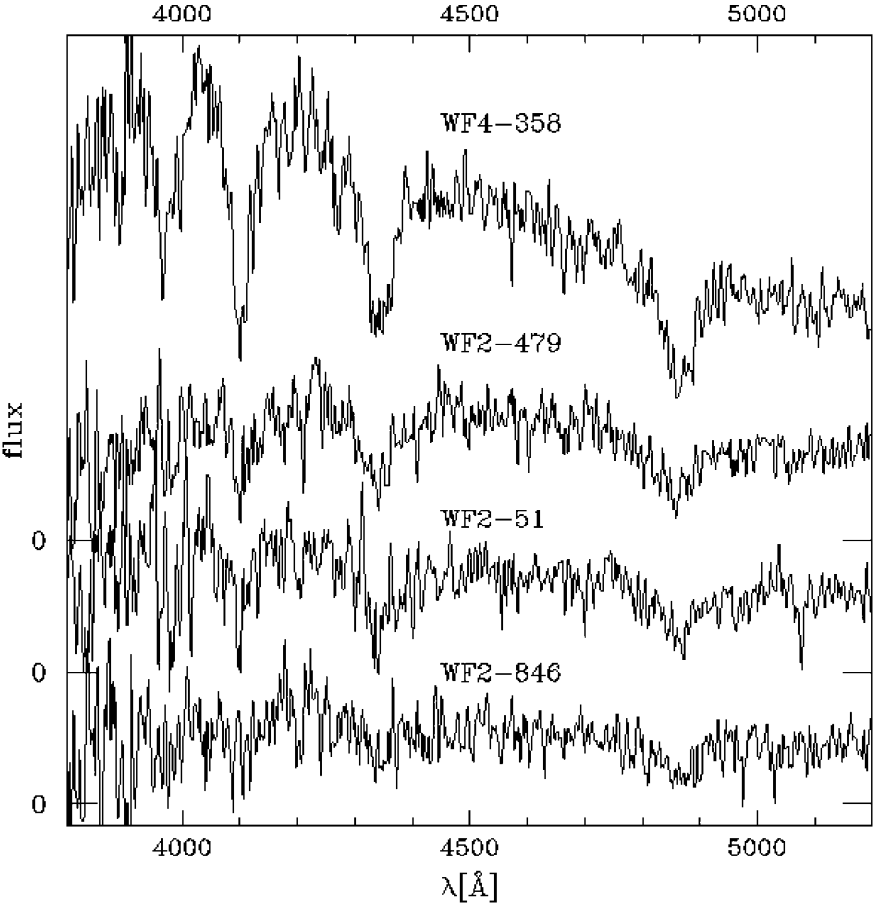

Fig. 6. VLT spectra of four DA white dwarfs in the clobular cluster NGC 6397. From Moehler et al. (2000)

magnitudes in the blue spectral region. DA and DB are very difficult to distinguish from photometry alone (Cool et al., 1996), and Richer et al. (1995) speculate that the brightest WD in M 4 might be a DB. A first spectroscopic study of one of the blue objects in NGC 6397 seemed to indicate a very low gravity and thus higher luminosity for a WD candidate (Edmonds et al., 1999). To dispel any doubts about the nature of the white dwarfs in the GCs, and to determine masses instead of assuming them, obviously a systematic spectroscopic study is necessary, which had to wait for the advent of the new generation of large telescopes.

The first attempt using the ESO/VLT was presented by Moehler et al. (2000). They selected objects brighter than $V \approx 25$ in NGC 6397 from the CMD in King et al. (1998), which were sufficiently isolated to be observable from the ground. The spectra obtained with the FORS1 spectrograph have a resolution of about 11.5 Å. Although the S/N ratio was understandably rather low, the broad Balmer lines are clearly visible in all 4 objects observed (Fig. 6). The spectra were fitted with a grid of DA model atmospheres to determine atmospheric parameters, but in the 3 stars with the lowest S/N the surface gravity could not be determined independently and was held fixed

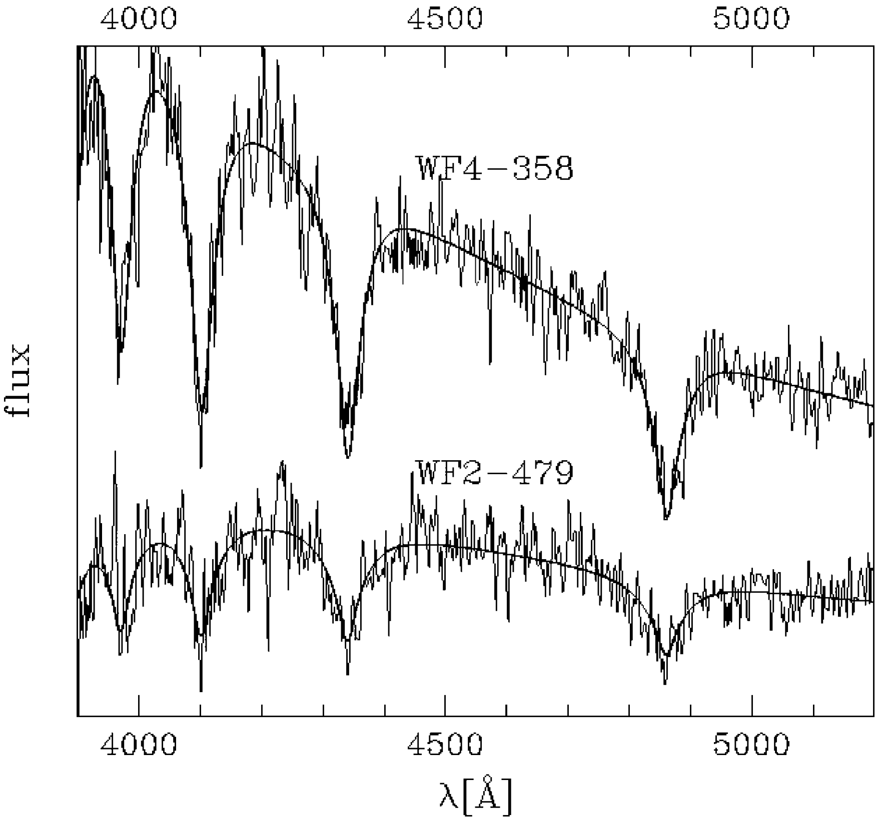

Fig. 7. The two brightest DA in NGC 6397, together with the best fitting models: WF4-358, $T_{\rm eff}$ = $18200K, \log g$ = 7.3 and WF2-479, $T_{\rm eff}$ = $11000K, \log g$ = 7.7. For WF2-479 the surface gravity ($\log g$) was held fixed. From Moehler et al. (2000)

at an assumed value. The best spectrum, for WF4-358, when allowing $\log g$ to vary, resulted in a rather low value of 7.30 ± 0.36, corresponding to a low-mass He-core white dwarf, although within the errors a low-mass C/O core cannot be excluded. The two best spectra with their model fits are shown in Fig. 7. The demonstration that indeed all these objects are hydrogen atmosphere DA represents a big progress. However, the next step now has to be to verify the assumption of a "standard mass" with more accurate determination of the surface gravity, which requires a better S/N – a very difficult project even with current 8m-class telescopes.

The current work on WD in GC concentrates on the distance scale as a prerequisite to determine ages from the cluster turnoff by comparison with evolutionary calculations. In principle the white dwarfs could also be used to determine ages directly, using the cooling theory of white dwarfs. Observationally this demands not only to reach the bottom of the WD cooling sequence at $V > 28$, but to prove that a lack of fainter WD is not caused by observational limits. These projects will very likely have to wait for the next generation of telescopes and instruments.

4. White dwarfs in open clusters

Similar problems exist for the method of age determination by isochrone fitting in open clusters: age, distance, and reddening determination are strongly coupled, and moreover, different theoretical groups calculating evolutionary tracks and isochrones often obtain widely discrepant results. It is then not surprising that age determinations for the same cluster in the literature can span a range of 25 – 50%. The method based on the lithium depletion edge seems yet to provide another age scale. An independent test of these methods is as badly needed as in the case of globular clusters, and for the nearer and younger clusters the use of the WD cooling sequence seems to be on the verge of feasibility. The idea of the method is very simple: find the faintest, coolest, and oldest WD in the cluster and then determine its cooling age. For clusters with ages of a few Gyr the white dwarfs are brighter than $M_V = 15$, and all the complications discussed in connection with very cool halo and GC WD – crystallization with phase separation, strong dependence of ages on atmospheric chemical composition, blue (IR) colors of the coolest WD – are not relevant. The physics and cooling of the white dwarfs in open clusters seems to be well understood; the observational demands are, however, still formidable.

4.1. Ages of open clusters

In M 67 for example, the coolest WDs for a cluster age of about 4 Gyr are expected at $V = 24 – 25$. Richer et al. (1998) reach below this limit with ground-based observations, using the Canada-French-Hawaii Telescope under excellent seeing conditions. They identify an area of higher density in the WD region of the CMD as the “pile-up” at the bottom of the WD sequence. Such a maximum in the luminosity function, with a steep decline towards fainter objects is expected from the slow-down of the cooling as measured versus $\log L$ (Brocato et al., 1999; Richer et al., 2000). The derived WD age is 4.3 Gyr, within the range of ages derived from main sequence isochrone fitting.

Currently the only instrument, which can go deeper without intractable confusion of stellar images with extragalactic background is HST. After a first attempt, which was not deep enough (von Hippel et al., 1995), von Hippel & Gilmore (2000) obtained a CMD for NGC 2420 down to $V = 27$. Their CMD, after removing all extended objects and image defects, is shown in Fig. 8. A white dwarf cooling sequence can be identified in this diagram, following the theoretical cooling track for a 0.7 $M_\odot$ WD. The bottom of the WD sequence is determined at about $V = 25.7$, which gives a cluster age of 2.0 ± 0.1 Gyr for the distance and reddening values preferred by the authors. Comparing this age with numerous determinations using stellar isochrone fitting based on different sets of evolutionary models, they conclude that their result indicates a “preference for ages derived from models incorporating convective overshoot”.

The importance of the test of traditional age determinations with this new and completely independent method can hardly be overstated. It is also clear that the work discussed above and that of others demonstrate the method, but have not yet reached completely unambiguous and convincing results. Problems of background contamination, statistical subtraction of background sources, the demonstration that the bottom of the sequence has been identified, and finally the spectroscopic proof that the objects are really cluster WDs, are not yet solved.

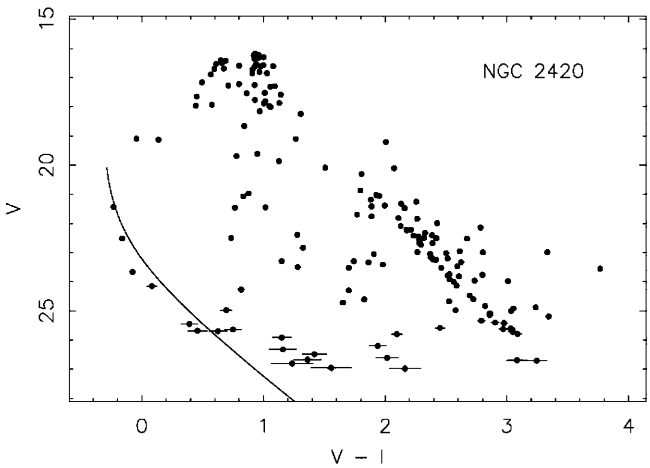

Fig. 8. Color-magnitude diagram for 2 fields in the open cluster NGC 2420 obtained with the HST WFP2 Camera. The solid line is the cooling curve for a 0.7 $M_\odot$ white dwarf at the cluster distance. The uncertainty of the theoretical curve is very likely smaller than the observational uncertainties, at least down to the assumed bottom of the WD sequence near V = 25.7 in this cluster. From von Hippel & Gilmore (2000)

4.2. Open clusters and the Initial-Final Mass Relation (MIMF)

While the age determination still has its problems, another area will undoubtedly profit from the ongoing efforts to obtain deep and accurate CMDs for open clusters (e.g. von Hippel & Sarajedini, 1998; Kalirai et al., 2001): the relation between the initial mass of a main sequence progenitor and the final white dwarf remnant mass, as well as the related question of the main sequence upper mass limit $M_{\rm WD}$ for the formation of WD vs. neutron star/black holes. This is the only empirical method to determine the total integrated mass loss of a star, and thus important for the evolution of galaxies. $M_{\rm WD}$ is a very important number, e.g. to understand the statistics of supernovae and pulsars.

Koester and Reimers (see Koester & Reimers, 1996, and references therein) — following the pioneering work of Romanishin & Angel (1980) — have in a series of papers studied these questions using white dwarfs in open clusters, which has led to the now generally accepted value of $M_{\rm WD} \sim 8\ M_\odot$. The method was to use rich, young clusters (a high turnoff mass gives the tightest constraints on $M_{\rm WD}$) in the Galactic plane (to avoid extragalactic background). WD candidates were identified as faint blue objects from photographic Schmidt plates and then followed up with spectroscopy. After identification as white dwarf the spectra are analyzed with a grid of model atmospheres and the atmospheric parameters $T_{\rm eff}$, $\log g$, mass, M_V determined. The distance modulus $V - M_V$ is used as another argument for or against cluster membership. This spectroscopic follow-up is a very essential extension of the Romanishin & Angel (1980) work, because it eliminates the need for statistical arguments in establishing cluster membership, and leads to a very direct determination of initial and final masses.

In the most simple interpretation the identification of a white dwarf in a cluster with a turnoff mass of 5 $M_\odot$ already indicates that $M_{\rm WD}$ must be larger than 5 $M_\odot$. With accurate atmospheric parameters, which have become relatively easy to obtain

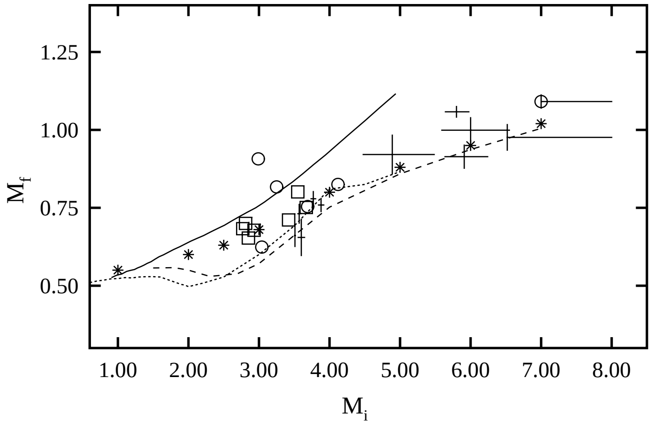

Fig. 9. The initial mass – final mass relation for the nearby cluster white dwarfs: Praesepe (open circles), Hyades (open squares). The highest mass open circle is the Pleiad LB1497, plotted at its lower limit. The error bars correspond to WDs in NGC 2516 (near $M_i \sim 6\ M_\odot$) and NGC 3532 (near $M_i \sim 4\ M_\odot$). The errors do *not* include uncertainties in the cluster distances and ages. The empirical data are compared with theoretical predictions based on the evolutionary models of the Padova group (Girardi et al., 2000, solid line); the dotted line gives the core masses reached at the first thermal pulse, which is considered to be a firm (theoretical) lower limit. The dashed line shows these masses from a different set of models using the Frascati code (Domínguez et al., 1999). Asterisks give the semi-empirical relation derived by Weidemann (2000). From Claver et al. (2001)

with the large telescopes in recent years, the analysis can be much more sophisticated. $T_{\rm eff}$ and log g determine the cooling age of the WD, and with the help of a (temperature dependent) mass-radius relation also its mass. The difference between turnoff age of the cluster and cooling age determines the time the progenitor spent on the main sequence and giant phase and thus the original progenitor mass. In this way a relation between initial and final masses, the MIMF, can be constructed.

A recent paper by Claver et al. (2001) uses new results on Praesepe white dwarfs as well as a re-evaluation of several other clusters for a summary of the current status. Figure 9, from that paper, shows the empirical basis for the MIMF, together with theoretical calculations. There is clearly a well defined MIMF relation, with an upper limit for the white dwarf progenitor masses in the range 7 – 8 $M_\odot$. The one discrepant Praesepe WD may indicate, however, that other parameters besides original mass may occasionally influence the final result. This is an open question at the moment. Another recent discussion of problems related to the MIMF relation can be found in Weidemann (2000).

5. Searching for the supernova Ia progenitors

Supernovae of Type Ia (SN Ia) are probably the most important producers of iron in the universe, they are heat sources for the interstellar medium, and most recently have gained high prominence as standard cosmological candles, leading to new answers on old questions (Riess et al., 1998; Perlmutter et al., 1999; Leibundgut, 2001). Still, the exact nature of the explosion mechanism and the progenitor system are not known, in spite of a general consensus that a thermonuclear explosion of a C/O core white dwarf exceeding the Chandrasekhar limit due to accretion must be one of the necessary ingredients. Since a review of this topic has appeared very recently in this journal (Leibundgut, 2000), and a large number of other recent papers are available (e.g. Domínguez et al., 2001; Langer et al., 2000; Canal et al., 2001), we can be very brief on the general observational and theoretical aspects and concentrate on the WD progenitor system.

This progenitor system must be a binary, with matter being transfered to the WD from a companion until the critical mass is reached. But there are still two main options for the nature of the companion: either another WD in the so-called double degenerate (DD) scenario (Iben & Tutukov, 1985), or a main sequence star/red giant/subgiant in the so-called single degenerate (SD) scenario (Whelan & Iben, 1973), with the system possibly appearing as a symbiotic binary (Munari & Renzini, 1992) or a supersoft X-ray source (van den Heuvel et al., 1992). The solution of the SD vs. DD question is of great importance for the role of SN Ia as accurate cosmological probes, because it would constrain the possible explosion models. If the progenitors are indeed DDs, then one expects that the exploding objects will span a range of masses, depending on the sum of the two WDs in the binary. This would affect the light curves, and possibly the spectral evolution, and hints for such effects have been detected in the amount of nickel produced in SN Ia events (Mazzali et al., 1998; Contardo et al., 2000; Leibundgut, 2000). If the DD scenario is correct, there must be detectable systems with the combined mass of the two WD above the Chandrasekhar limit, and with a period short enough (a few hours) to merge due to the loss of angular momentum through the emission of gravitational waves within a Hubble time. Many authors have studied the theoretical predictions for the number of such systems and their period and mass distributions using population synthesis models. Several assumptions needed as input for these calculations are quite uncertain; as one example I mention the description and outcome of the “common-envelope” evolution, which almost certainly has to occur in the evolution of such close systems. For a very recent and comprehensive study the reader is referred to Nelemans et al. (2001).

Such systems necessarily would show large variations of radial velocity. Several systematic radial velocity searches for DDs have been undertaken, starting in the mid 1980’s (Robinson & Shafter, 1987). By now – combining all searches documented in the literature – about 180 WDs have been checked for RV variations with sufficient accuracy, which has led to the discovery of $\sim$ 20 DDs with period $P < 7.5$ days (Saffer et al., 1988; Bragaglia et al., 1990; Marsh, 1995; Marsh et al., 1995; Holberg et al., 1995; Moran et al., 1997; Saffer et al., 1998; Maxted & Marsh, 1999; Maxted et al., 2000a; Marsh, 2000; Maxted, 2001). From an analysis of all these data Maxted & Marsh (1999) estimate the fraction of close binary WDs at 2 – 20%; however, none of the known systems qualifies as a SN Ia progenitor, because the combined mass of the WDs is smaller than the Chandrasekhar limit. In fact, most of the masses seem to be smaller than $\sim 0.45\ M_\odot$, the approximate core mass limit for helium ignition, and are therefore helium-core white dwarfs. For them the evolution ended prematurely on their ascent on the giant branch, when they filled the Roche lobe and unstable mass transfer started. The observed prevalence of small masses is not really surprising, as theoretical simulations suggest that perhaps only a few percent of all DDs are in a system with supercritical mass (Iben et al., 1997; Nelemans et al., 2001).

The only likely SN Ia progenitor in this scenario, which has been found to-date, is not a DD, but the sdB/WD binary KPD 1930+2752 (Maxted et al., 2000b). The period is 2h 17m; assuming the canonical mass of $0.5\ M_\odot$ for the sdB, the companion mass is at least $0.97\ M_\odot$. With the small size of the system this must almost certainly be a white dwarf. Since the sdB will evolve directly to a WD and merge with the companion in less than 0.2 Gyr, this is indeed a very good – and so far the only – candidate for a SN Ia explosion.

The small fraction of predicted supercritical DDs suggests a search on a much larger scale then in the past. Such an attempt is currently underway as a Large Programme at the ESO/VLT (ESO Supernova Ia Progenitor Survey = SPY) led by Ralf Napiwotzki (Bamberg). The program is conceived as a "filler" for weather conditions (clouds, moon, seeing), which are unsuitable for most other programs; it is conducted in service mode with the high resolution UVES spectrograph at Unit Telescope 2 (Kueyen) of the VLT. Two spectra are take at arbitrary times for each candidate, and checked for differences in radial velocity, predominantly from the sharp NLTE cores of Hα. The accuracy of the radial velocity is 5 – 10 km s^{-1} depending on the S/N of the spectra, and with expected velocity amplitudes $>$ 100 km s^{-1} the detection probability for DDs in the interesting period range is larger than 90%. The ambitious aim is to observe 1500 white dwarfs, many of which are new WD candidates from the objective prism plates of the Hamburg/ESO (HE, Wisotzki et al. 1996; Wisotzki et al. 2000; Christlieb et al. 2001) and Hamburg (HS, Hagen et al. 1995; Homeier et al. 1998) bright quasar surveys, which are spectroscopically confirmed as white dwarfs in the course of this program. Obviously, independent of the DD search, this project yields an enormous amount of good spectra and derived parameters (mass distribution, luminosity function) from the largest homogeneous database ever collected for white dwarfs (e.g. Koester et al., 2001). At the time of this writing about 400 WD have been observed, yielding more than 50 new DDs. The subsequent follow-up observations necessary to determine radial velocity curves and masses for the systems have just begun: the first DD pair, HE 1414$-$0848, is with a total mass of $1.24 \pm 0.06\ M_\odot$ closer to the Chandrasekhar mass than any other known system; however, with a current orbital period of 12h25m the merging will take approximately 24 Gyr (Napiwotzki 2001, priv. comm.).

According to the theoretical predictions the number of viable progenitors could be as low as 2 – 4. Because of the very large sample involved, however, it seems certain that the result will give a definite answer to the question, whether DDs can be a significant or even the only source of the observed SN Ia. Moreover, independent of the outcome, the distribution of masses and periods of the $\sim$ 200 DDs expected to be found in the search – even if they do not qualify as progenitors – will be a very stringent tests on all models of binary evolution.

6. Selected highlights from other fields of WD research

While the previous sections discuss areas, which are new in WD research, or which a least reached maturity only in the last few years, there has of course been significant progress also in the more "traditional" fields. A search in the ADS abstract server lists $\sim$ 6000 references for the key "white dwarfs" over the last decade. Obviously it is impossible to do any justice to that huge amount of work with a short summary, and I apologize to all my colleagues for the personal bias in the selection.

6.1. Atmospheric parameters and mass distribution

The first step for almost any study using white dwarfs is the determination of T_{eff}, $\log g$, and all quantities derived from that using other basic data like parallaxes and photometric magnitudes. While much of the early work e.g. on the distribution of masses for the WD population (e.g. Koester et al., 1979) relied heavily on photoelectric colors (for example comparing the location in the UBV or uby two-color diagrams with theoretical grids), Bergeron and coworkers have demonstrated the superiority of spectral analysis in many papers (Bergeron et al., 1992, 1995a,c, to cite only a few examples), which has been the method of choice ever since. Similar analyses of large samples have been presented more recently by Marsh et al. (1997); Vennes et al. (1997); Vennes (1999); Finley et al. (1997); Napiwotzki et al. (1999); Silvestri et al. (2001). While some systematic differences in the derived parameters $T_{\rm eff}$ and $\log g$ remain (Napiwotzki et al., 1999), all studies agree on the fundamental result e.g. for the mass distribution of DA white dwarfs: there is a very narrow sharp peak near 0.60 $M_\odot$, with a tail extending towards larger masses (1.0 -1.2 $M_\odot$); the decline towards small masses is steep, but some studies find a secondary peak below 0.45 $M_\odot$, which should be helium-core WDs from binary evolution. This secondary peak is much more pronounced in samples biased towards lower effective temperatures and absent in “hot” samples selected by their EUV emission, in accordance with theoretical interpretation regarding the evolution of these objects (Napiwotzki et al., 1999). Figure 10 shows typical mass distributions for DA white dwarfs.

Much less work has been done on the smaller spectral groups, some notable exceptions being the analysis of DBs (HeI lines only, pure He atmospheres) by Beauchamp et al. (1996), and of DOs (HeII lines, He-rich atmospheres with probably some H) by Dreizler & Werner (1996). While DA atmospheres show only minor influence of NLTE effects at temperatures above 50000 K, these effects become important in the hot DO and even hotter PG1159 objects. Very sophisticated NLTE models, including the EUV blanketing of millions of spectral lines and most recently even self-consistent element diffusion, have been calculated and applied for spectral analysis by the groups of Werner and of Hubeny and their many collaborators (Werner, 1991; Werner et al., 1991; Dreizler & Werner, 1993; Lanz & Hubeny, 1995; Dreizler & Werner, 1996; Napiwotzki, 1997; Barstow et al., 1998; Dreizler et al., 1998; Rauch et al., 2000).

Near the cool end of the white dwarf cooling sequence, below 10000 K, the hydrogen and helium spectral lines necessary for the spectroscopic analysis become invisible. New methods had to be developed, which make use of optical and infrared colors, and of the parallaxes, which are known in many cases, because these cool objects can only be studied close to the sun. Our knowledge in this range down to $T_{\rm eff}$= 4000 K currently rests mostly on the fundamental studies by Bergeron et al. (1997, 2001), which are reviews by themselves, and strongly recommended reading.

The derivation of masses and ages from atmospheric parameters relies on theoretical calculations of evolution and mass-radius relations. The standard for many years have been the calculations of Wood (1992, 1995), which were generously made available and widely used. More recent calculations have already been discussed in Section 2 and many more references can be found in Fontaine et al. (2001). For “normal” WDs the calculations agree very well; differences are still significant for low-mass He-core white dwarfs (e.g. as companions in binary pulsars) and for the coolest white dwarfs important for deriving ages for the galactic disk or halo WDs.

6.2. Magnetic white dwarfs

About 60–70 single WDs are currently classified as magnetic, with field strength ranging from $3\,10^4$ – 10^9 G. The distribution over spectral types reflects that of

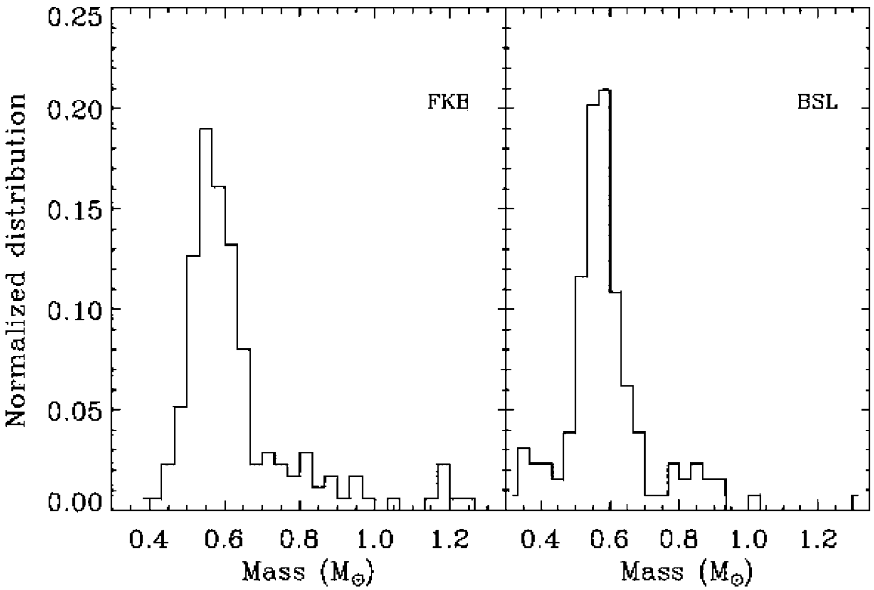

Fig. 10. DA mass distribution for the sample of Finley et al. (1997) (FKB) left, compared with the Bergeron et al. (1992) sample (BSL) right. Masses were binned in 0.033 $M_\odot$ intervals and normalized to a total of unity. From Finley et al. (1997)

nonmagnetic WDs: about 80% have hydrogen atmospheres with Balmer and Lyman lines only, the rest show lines of HeI or molecular bands of C_2 and CH and have helium-rich atmospheres. There is now growing evidence that the magnetic WDs as a group may have significantly larger masses than the nonmagnetic, a suggestion originally made by Liebert (1988). 25% of the high-mass WDs ($> 1\ M_\odot$) discovered from the EUVE survey are magnetic, and the two with the highest masses, close to the Chandrasekhar limit, are both magnetic (Vennes, 1999). One might speculate that magnetic fields play a role in post-main-sequence evolution influencing mass loss and angular momentum loss and modifying the initial-final mass relation for nonmagnetic stars.

The most spectacular breakthrough in recent years was the calculation of the energy levels of HeI in this difficult regime of magnetic fields, where magnetic and Coulomb forces on the electrons are of comparable strength and perturbation methods fail (Becken et al., 1999; Becken & Schmelcher, 2000, 2001). These calculations solved a longstanding puzzle in a number of objects with unidentified features, in particular in GD 229, which had been known to be strongly linearly and circularly polarized since Swedlund et al. (1974); Kemp et al. (1974), and been studied by many authors. Jordan et al. (1998, 2001) could finally identify most features with HeI lines in a magnetic field of 300-700 MG.

For an overview of other properties of magnetic WD, both isolated and in binaries, the reader is referred to the excellent recent review by Wickramasinghe & Ferrario (2000).

6.3. Pulsating white dwarfs

Nonradial pulsations are observed in 3 different instability strips – the PG1159 pre-white dwarfs, variable DB (DBV), variable DA (DAV or ZZ Ceti); a forth instability strip is known for pulsating central stars of Planetary Nebula. Pulsation periods range from 100 to 2000 s and the amplitudes from a few times 0.001 to about 0.2 magnitudes. A pulsation mode is characterized by the "quantum numbers" of the spherical harmonics l, m, where l is the number of node lines on the surface and m the number of node lines passing through a pole, and the radial number of nodes k. Modes of the same l, k in a spherically symmetric star are degenerate, that is they have the same energy or frequency. Rotation may lift this degeneracy, leading to a multiplet of $2l+1$ frequencies with constant splitting, depending on the rotation period. A prerequisite for any analysis and comparison is the identification of modes in the observed power spectra.

When observing the variations, the integration times need to be short (typically 5–10 s), but since there are often many pulsation frequencies with close spacings (e.g. rotationally split modes), the observations have to cover long periods to resolve the multiplets and have as few gaps as possible to avoid problems from aliases. These considerations led to the creation of the "Whole Earth Telescope" or WET (Nather et al., 1990), a collaboration of many observatories and scientists around the globe to achieve 10–14 day continuous light curve coverage of selected targets. All of these more than 20 observation campaigns to-date, most of them with WD targets, have secured invaluable data, and two of the very early ones have indeed been spectacular successes: on PG 1159-035 and GD 358, the two prototypes of their classes (Winget et al., 1991, 1994). In both objects more than 100 oscillation modes were identified with their quantum numbers, and masses, luminosities, rotation, and the chemically layered structure of the outer envelopes identified with unprecedented accuracy.

Later campaigns, however, have not been that spectacular, in particular those on larger period, larger amplitude ZZ Ceti. This is not a fault of the observational technique – the problem is that these objects do not behave "as they should", according to the simplest version of the theory. They can change their power spectra completely, with frequencies appearing or disappearing on time scales of days, and with completely different light curves from one year to the next. Progress with such objects cannot rely on one big WET run alone, but needs also very long and repeated observing runs from single sites. Kleinman has shown in a very ingenious way, how such long observing runs, and in addition taking the whole group of large amplitude ZZ Ceti stars at many different times together, can lead to the deciphering of their properties (Kleinman, 1995a,b; Kleinman et al., 1998).

These difficulties have also given new impetus to other methods of identifying pulsation modes by using time-series of photometric or more recently spectroscopic observations. These ideas have been pioneered for the case of variable white dwarfs by Robinson et al. (1982), and refined by Brassard et al. (1995). The basis of this method is that for nonradial pulsations with index $l \geq 1$ bright and dark areas on the surface lead to some cancellation effects, which decrease the amplitude. This effect depends on the amount of limb darkening, which is strongest in the UV in ZZ Ceti. Because then in a first approximation the central parts of the stellar disk contribute most of the light variation, cancellation is less in the UV. This wavelength dependence of pulsation amplitudes can be compared with model calculations and used to identify l (Robinson et al., 1995; Fontaine et al., 1996). Clemens et al. (2000) and van Kerkwijk et al. (2000) – using time-resolved spectroscopy from the Keck telescope for G 29−38

– have extended this method by including velocity fields. This is a very interesting step, since it may be possible to observe variations of this velocity field in DA slightly below the current observational red edge, even if light variations are unobservable. In spite of considerable progress made, the agreement between observed light amplitudes and model predictions is in most cases not really satisfactory, and may point to some complications not yet included; one possibility is that the spatial flux variation on the surface even of a single mode as defined by the pressure variation below the convection zone may not follow anymore a spherical harmonic (Ising & Koester, 2001) – an assumption inherent in all current interpretations.

The interpretation of power spectra uses the observed periods and their spacings in a comparison with theoretically predicted period spectra from large grids of white dwarf interior models. This method has now reached a high level of sophistication, as documented in Brassard et al. (1991, 1992a,b,c) and Bradley (1998, 2001).

The theoretical highlights of the last decade, however, are in my view the work by Brickhill, followed by the studies of Goldreich and Wu (Brickhill, 1983, 1990, 1991a,b, 1992a,b; Goldreich & Wu, 1999a; Wu & Goldreich, 1999; Goldreich & Wu, 1999b; Wu & Goldreich, 2001; Wu, 2001) for the ZZ Ceti stars. Initial calculations of unstable modes in these stars (Dziembowski & Koester, 1981; Dolez & Vauclair, 1981; Winget et al., 1981) were based on the assumption that the convective flux in the outer layers does not respond to the pulsations (“frozen convection”). These workers attributed mode excitation to the κ-mechanism in the partial ionization zone of hydrogen or helium. Pesnell (1987) pointed out that this assumption about the convective flux – hardly justified, since the oscillation periods are much longer than the thermal timescale in the layers of partial ionization – leads to an artificial driving contribution, which he called “convective blocking”. Noting the shortcomings of this approach, Brickhill assumed the opposite: convection responds instantaneously to the pulsational state. He demonstrated that this leads to a new type of mode excitation (“convective driving”) and used a very simple numerical calculation to present the first physically consistent picture of mode driving, mode visibility, instability strip width, and nonlinear effects in the light curves. Support for this new type of driving also came from the study by Gautschy et al. (1996), who found driving in calculations where convection is modeled by two-dimensional hydrodynamic simulations.

Building on Brickhill’s work but using different methods (semi-analytical perturbation analysis for the most part), Goldreich and Wu confirm most of his conclusions, in particular on the convective driving mechanism. They extend Brickhill’s work by going on to the prediction of amplitude saturation, and the phases and amplitudes of combination frequencies (sums and differences of mode frequencies) observed in variables with larger amplitudes. This work will very likely have a profound influences on the future directions of theoretical research as well as interpretation of observations.

A good starting point to get familar with current research on variable white dwarfs are the proceedings of the WET Workshops, held approximately every two years. The papers of the fifth workshop are published in the journal Baltic Astronomy, volume 9, 2000. Many further references can be found there.

6.4. The age of the galactic disk

The method of using the steep decline of the local WD luminosity function at $\log L/L_\odot = -4.4$ to infer the beginning of star formation in the galactic disk has been pioneered by Winget et al. (1987). Many authors have followed this up, with

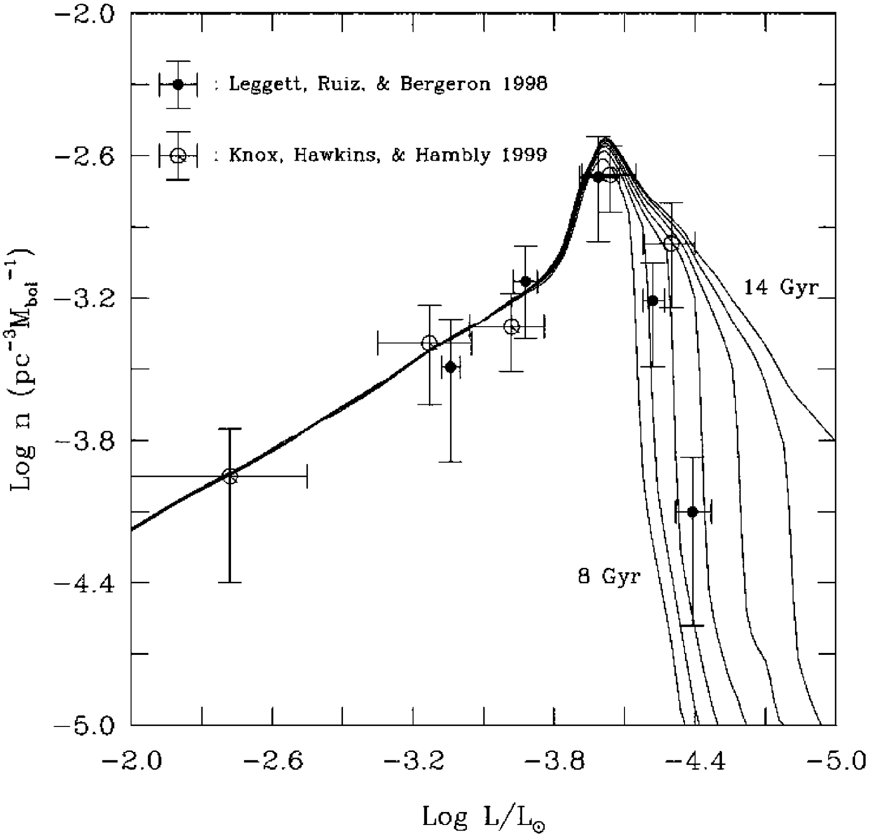

Fig. 11. Comparison of the observed and theoretical luminosity functions of local white dwarfs and the age of the disk. Observations come from Leggett et al. (1998); Knox et al. (1999). The solid curves are theoretical LFs for an assumed pure C core composition of the WDs. Various ages for the WD population of the disk are considered, from 8 to 14 Gyr. This figure originally appeared in the Publications of the Astronomical Society of the Pacific in Fontaine et al. (2001). Copyright 2001, Astronomical Society of the Pacific; reproduced with permission of the Editors

improvements in observational data and/or theoretical input. The current status has been competently reviewed very recently by Fontaine et al. (2001). However, because this topic has received so much attention from outside the smaller white dwarf community, a review would be incomplete without mentioning the latest results, summarized very nicely in Fig. 11 and 12 taken from that review.

Figure 11 shows the observational LF of disk WD from two sources, Leggett et al. (1998) and Knox et al. (1999). They are compared with theoretical calculations for different ages of the Galactic disk from 8 - 14 Gyr, using the best currently available input physics for cooling ages, IMF, MIMF etc., which suggest an age slightly less than 11 Gyr. Careful discussion of the remaining uncertainties allows a range of 8.5 - 11 Gyr, with the largest uncertainty coming from the unknown exact proportions of C and O in the cores of the WD.

The LF in Fig. 11 is an integration over all WD masses. It is very instructive to compare Fig. 12, which shows the individual positions of 135 cool WD in the mass-

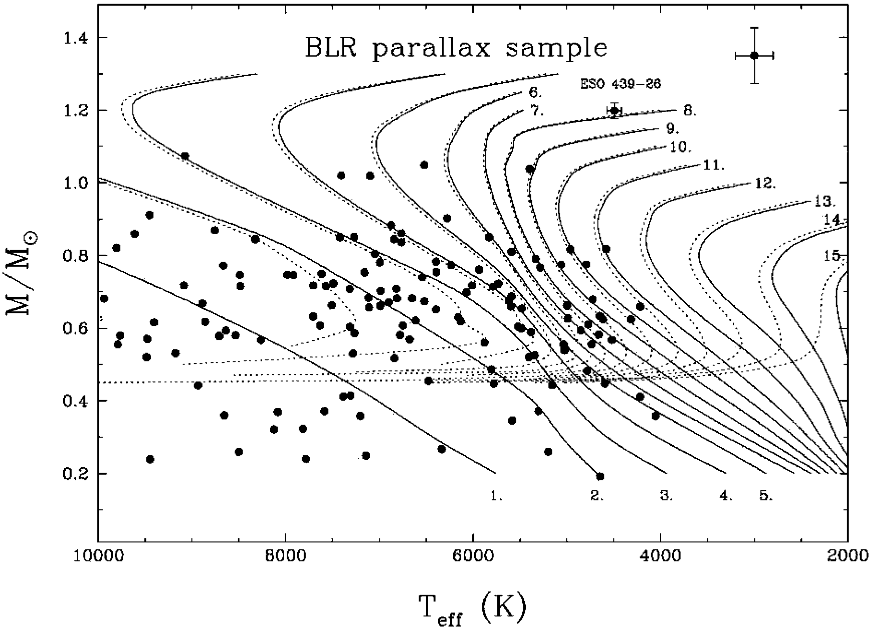

Fig. 12. Distribution of 135 cool white dwarfs from Bergeron et al. (2001, =BLR) in the mass-effective temperature diagram. The average uncertainties of mass and T_{eff} are indicated by the cross in the upper right corner. To compare with theoretical expectations, two sets of isochrones are shown: the solid lines correspond to the WD cooling time only, while the dotted lines take into account the main sequence lifetimes of the progenitor stars. Numbers give ages in Gyr. This figure originally appeared in the Publications of the Astronomical Society of the Pacific in Fontaine et al. (2001). Copyright 2001, Astronomical Society of the Pacific; reproduced with permission of the Editors

T_{eff} diagram, together with theoretical isochrones. The oldest stars in this sample are 11 Gyr old, in agreement with the above conclusion. However, the figure also clearly shows that the coolest WDs are not necessarily the oldest.

7. Final remarks

Since about 75 years now we know and basically understand white dwarfs as the most common endproduct of stellar evolution. Much has been learned about their properties; we can with confidence analyze their spectra and determine atmospheric parameters, masses, luminosities, and cooling ages. We understand the evolution as gravitational contraction, which due to the equation of state of degenerate electrons leads to a loss of thermal energy (cooling), contrary to the heating in normal stars with an ideal gas equation of state.

Some puzzles are still open and remain to be solved: origin of helium-rich WDs, and the likely change between spectral types during the evolution, the EOS in the regime of pressure ionization, the exact composition of interior cores, especially the C/O distribution, and their behavior upon cristallyzation, the evolution of WDs in close binaries, are among those puzzles. Nevertheless, our understanding is mature enough to shift the emphasis towards using white dwarfs as tools, and I have tried in this review to demonstrate that aspect. Independent estimates of the age of the disk in the solar neighborhood, distances and ages of open and globular clusters, are within reach and will certainly be a significant part of future WD research.

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