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ON THE ORIGIN OF THE DB WHITE DWARFS

by

ATSUKO NITTA, B.S.

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To Papa, Mama, Akira and Hitoshi.

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ABSTRACT

ON THE ORIGIN OF THE DB WHITE DWARFS

by

Atsuko Nitta, M.A.
The University of Texas at Austin, 1996

Supervisor: D.E. Winget

Most stars in the universe become white dwarfs (WDs) at the end stage of their evolution. Understanding the structure of the WDs will constrain the evolution prior to this stage. We know there are two major classes of WDs, the ones with H atmosphere (DAs) and the ones with He atmosphere (DBs). How the bifurcation of WDs occurs is still not well understood. Most of the proposed scenarios to explain it has involved single star evolution. But there is one type of system observed which must inevitably produce the DBs as the end product. These are the interacting binary white dwarfs (IBWDs) (Nather, Robinson & Stover 1981).

Do the DBs evolve from the binary systems only? How significant is binary evolution to the DBs? The answers to these questions are very important in our understanding of stellar evolution in our galaxy. One way to answer these questions is by tagging the DBs by their origin.

We will do this by using the observations of the DBs' normal modes which give us the information on their internal structure. The DBs coming from different evolution scenarios will have different thermal structure. If these differences give rise to observable differences in the periods of the normal modes, we can use data from pulsating DBs to determine if they are the product of single or binary evolution.

In this project, we constructed DB models simulating the thermal structure expected from IBWDs. We then compared the normal modes of these models with that of the DB models simulating DBs from single star evolution. We found in our analysis that the differences between them are potentially observable. We then applied this method to the best–studied DBV, GD358. The results showed that GD358 does not have the period structure expected from binary evolution. Therefore we believe that there are two channels leading to the DBs, the single star evolution and binary evolution.

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Chapter 1

Introduction

We are confident that white dwarf stars (WDs) are the end points of stellar evolution for all low and intermediate mass stars (mass less than about $8M_\odot$). This amounts to $98 - 99\%$ of all stars (Weidemann 1990; Kepler & Bradley 1995). Therefore WDs contain information about the history of a majority of the stars in the galaxy. If we find where they come from and how they are made, we will significantly advance our understanding of star formation and evolution of the stellar population of our galaxy.

There are two major spectral types of WDs. WDs which show H lines, but no He or metal lines in their spectra are classified as DAs, and WDs which show He with no H are called DBs (Sion et al. 1983). Both DAs and DBs apparently have similar mean total stellar mass, $< M_{total} > \approx 0.6\mathrm{M}_\odot$ (Koester et al. 1979; Wickramasinghe & Reid, 1983; Oke, Weidemann & Koester 1984; Beuchamp et al. 1996). What causes the bifurcation of the WDs? Observation shows that there are H-rich planetary nebula nuclei (PNNs) and He-rich PNNs. Interestingly, the fraction of He-rich PNNs to H-rich PNNs match the fraction of DBs to DAs. This fact seems to suggest some connection between the WD's spectral types and the chemical composition of the PNNs.

The change in number ratio of non-DAs to DAs as a function of temperature was first pointed out by Liebert (1986). Figure 1.1, adopted from Figure 3 of the paper by Fontaine & Wesemael (1987), shows the number fraction of non-DAs to total number of WDs as the temperature changes. At high temperature, when the WDs are just formed, there are no DAs. The temperature is too high for the H lines to be seen. At this temperature, H in the envelope would be ionized, therefore we see no H lines, hence no DAs. We start observing DAs around $80,000K$ and by the time the temperature is about $45,000K$, all WDs are DAs. Between $45,000K$ and $30,000K$, we find only DA white dwarfs. Then at around $30,000K$, DBs appear suddenly on the white dwarf cooling track. The temperature range in which we find no DBs ($45,000K$ to $30,000K$) is called the DB gap.

The idea that the bifurcation of WDs is directly connected to the H-rich and He-rich PNNs have difficulty interpreting the DB gap. The spectral evolution theory (Fontaine & Wesemael 1987) explains the change in spectral types of WDs with temperature due to the WDs changing their spectral types as they evolve as caused by stratification of elements, convection, and accretion from interstellar matter. Although this theory explains chemical evolution of the WDs beautifully, the recent observation of H mass in the WDs is inconsistent with the H mass currently allowed by this theory.

On the other hand, there are objects we observe that produce DBs as their end products: the interacting binary white dwarfs (IBWDs). IBWDs consist of two WDs with extreme mass ratio which are going through mass transfer. The less massive WD transfers its mass to the more massive one. From their spectra, we know that He is being transferred. The mass transfer will continue until the less massive one loses its mass completely and the

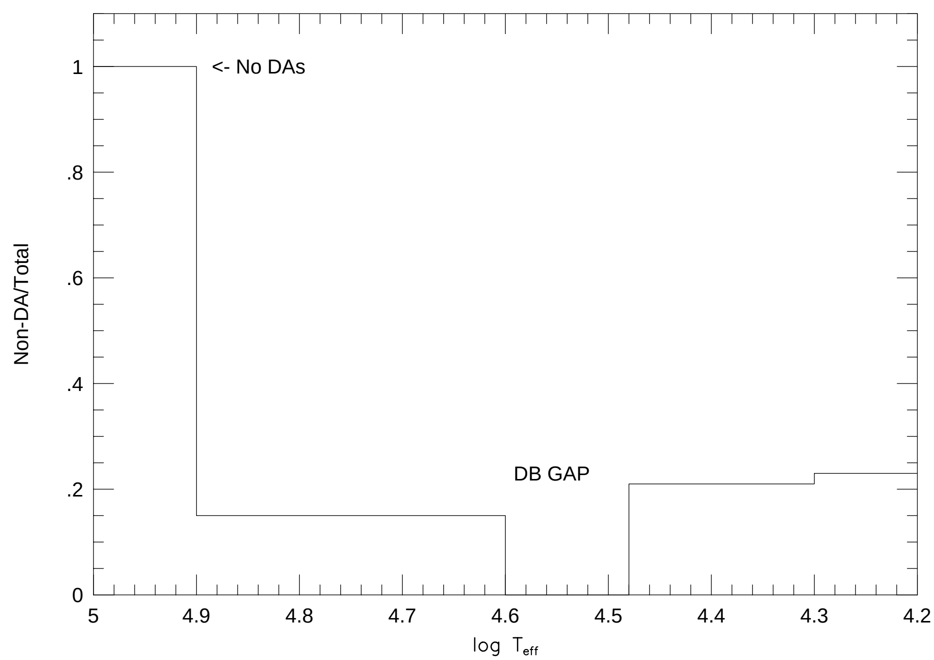

Fig. 1.1.— Fractional number of non-DA stars as a function of effective temperature. The DB gap was first noted by Liebert (1986). This plot was adopted from Figure 3 of Fontaine & Wesemael, 19 87.

end result is one He layered WD, a DB. The well studied IBWD, AM CVn, has an effective temperature(T_{eff}) of about $25,000K$. If AM CVn keeps this temperature till it produces a DB, its T_{eff} would be $25,000K$, a temperature which incidentally is below the DB gap. Do all DBs form from IBWDs? Is that why there are no DBs above $30,000K$?

In this project, we tried to approach the question of the origin of the DBs by comparing DB models from different evolutionary paths, single star evolution and binary star evolution. The thermal structure of a star is determined by its history. A DB from single star evolution would not have the same thermal structure as a DB from binary evolution. If we could see the internal structures of the DBs, it would help us understand how and where they came from. The pulsating DBs (DBVs) give us an opportunity to study their interior using the techniques of asteroseismology. Asteroseismology, a study of normal modes in the star, has proven to be a very powerful tool to study the internal structure of WDs (Winget et al. 1994, Bradley & Winget 1994, Winget et al. 1991).

We constructed numerical models of DBs that simulate the thermal structure unique to their evolutionary paths. We then studied the periods of the normal modes in each model to search for observable differences caused by the differences in the thermal structure arising from the different evolutionary paths the models represent. If there are observable differences, then we could, in principle, determine the origin of the DBs by comparing the data from DBVs to our theoretical models. We have data from GD358, the best studied DBV, which we can use for our project.

In the remainder of this chapter, we will go over the single star and binary star evolution scenarios we considered for this project. In Chapter 2, we explain the models we used. We then will go over what the normal modes of the models tell us and the comparison between the models and GD358 in Chapter 3.

1. Single Star Evolution Scenario

The fact that both DAs and non-DAs have a mean mass of about $0.6M_\odot$ seems to suggest that all WDs have similar origin unless there is a fundamental physical consideration which decides the mass of the WDs in all evolutionary paths leading to the WDs. According to Shipman's review (1989), there are two different scenarios explaining the existence of the classes of WDs through single star evolution. One scenario says that whether a star becomes a DA or a DB is decided by the evolution before the star's WD phase (called "the primordial theory" by Shipman). The other scenario argues that processes during the WD cooling phase are responsible for the different spectral classes of WDs ("spectral evolution theory"). Stars experience mass loss during the planetary nebulae (PN) phase. In both scenarios, the amount of H left in the envelope after the PN phase is set by the onset of the mass loss by a hypothetical "superwind" (Iben & MacDonald 1985). The differences in the scenarios come mainly from what happens after the PN phase.

1.1. Primordial Theory

In this scenario, a star with sufficient H remaining after the PN phase will evolve into a DA, and a star left with less than $10^{-16}M_\star$ of H evolves into a non-DA, becoming a hot, He-rich pre-white dwarf star (DO) and then later becoming a DB. The observed proportion of H-deficient objects among planetary nebulae nuclei agrees nicely with the fraction of DBs to DAs. Unfortunately, this theory cannot explain the observational fact that there are no DBs observed in the temperature range of $30,000K < T_{eff} < 45,000K$, the so called DB gap (See Figure 1.1).

1.2. Spectral Evolution Scenario

To explain the existence of WDs with different spectral types at different temperatures, spectral evolution theory was introduced (Fontaine &1989 Wesemael 1987). This theory proposes that WDs change their spectral types as they cool due to the stratification of elements caused by their high gravity, convection, and accretion of interstellar matter. According to the spectral evolution scenario, DOs with a very small amount of H are the progenitors of all WDs. The amount of H in the DOs is determined in the PN phase, as in the primordial theory. As the DOs evolve, stratification of elements takes place, i.e. the heavier He sinks while the lighter H rises. When enough H has accumulated on the surface, the star will appear to be a DA. If all DOs have enough H to make them appear as DAs, there will be only DAs and no DBs. To make all WDs appear as DAs by the time they cool to $T_{eff} = 45,000K$, there must be at least $10^{-16}M_\star$ of H mixed in the envelope. After further cooling down, the convection zone of the star, which is located right beneath the H layer, breaks into the H layer. If the H layer mass is less than $10^{-15}M_\star$, H is once again mixed with He and the star appears as a He-rich WD, a DB. If the H layer mass (M_H) is larger than $10^{-15}M_\star$, there will be insufficient mixing of H and He and the star will remain a DA. The observation that DAs are found only with $T_{eff} < 80,000K$ gives us an upper limit to the amount of H mixed in the envelope with He of $10^{-11}M_\star$. To summarize, the H layer mass necessary for spectral evolution is between $10^{-15}M_\star < M_H < 10^{-11}M_\star$ for DAs and $10^{-16}M_\star < M_H < 10^{-15}M_\star$ for DBs (Fontaine & Wesemael 1987).

Recently there has been some implication that the actual H layer mass of DAs is larger than it was previously thought. Fontaine et al. reported that after reexamination of a DAV G226-29 using their new adiabatic pulsation code, they estimated the H layer thickness of $M_H = 10^{-4.4} or 10^{-6.6}M_\star$ depending on the the identification of the observed 109.3 sec mode (Fontaine et al. 1992). J. C. Clemens, who studied the group properties of hot DAVs using asteroseismology, found that all hot DAVs have remarkably similar pulsation properties, hence they all have similar H layer mass. His estimate of H layer mass is about $10^{-4}M_\star$ (Clemens 1993). Robinson et al. found that the H layer mass of G117-B15A, another DAV, lies between $1.0 \times 10^{-6} M_\odot - 6.0 \times 10^{-5} M_\odot$ (Robinson et al. 1995). All these H layer mass estimates are inconsistent with spectral evolution theory: this is too much hydrogen for DAs to change their spectral types.

2. Binary Evolution Scenario

Since both of the above scenarios have serious flaws, let us consider a third, relatively ignored possibility. Nather, Robinson, & Stover (1981) proposed a totally different evolutionary path possible for DBs. They suggested that interacting binary white dwarf (IBWD) system would produce a single DB in its final stage of evolution. IBWDs consist of two WDs with extreme mass ratio going through mass transfer. Because WDs are degenerate objects, the less massive one is, the larger it is in radius. Therefore it is the less massive WD which fills its Roche lobe and transfers its mass through an accretion disk. As long as the secondary fills its Roche lobe, the accretion process continues and the secondary loses mass. There are two effects to be considered here: the redistribution of angular momentum through mass transfer which causes the separation between two stars to increase, and the loss of angular momentum by gravitational radiation which causes the separation to decrease. These are counteracting effects working on the system simultaneously. As a result, the secondary always fills the Roche Lobe and the mass is transferred continuously. The rate of transfer is determined by the strength of the gravitational radiation. Eventually, the mass transfer ends by the secondary losing its mass completely to the primary. Then the primary is left as a single white dwarf with a pure He atmosphere: a DB. Mass transfer rates for IBWDs have been estimated (Faulkner, Flannery & Warner 1972, Nather, Robinson & Stover 1981; Wood 1990; Provencal 1994) and they range from $10^{-11}\mathrm{M}_{\odot}/yr - 10^{-8}\mathrm{M}_{\odot}/yr$ This means that it would take roughly $10^{6} - 10^{10}$ years to evert the mass donor star completely onto the mass accretor.

If DBs are produced through IBWDs, comparing the birthrates of IBWDs and DBs should tell us what fraction of the DBs are created through binary evolution. The estimates show that they are roughly of the same order, suggesting at least some fraction of the DBs might be made from IBWDs (Nather, Robinson & Stover 1981; Provencal 1993).

3. Possibility of Finding a Planet

At the end of the binary evolution, the mass donor WD becomes too small to sustain its degeneracy and becomes a planet. Even so, gravitational radiation removes the angular momentum of the system, forcing the separation between the two objects to become smaller, but somewhat more slowly. This mass transfer ends when the secondary planet is totally consumed by the primary DB.

What is the likelihood that we observe the secondary planet around the DB before terminal mass transfer takes place? We will use PG1346 as an example for this exercise. The first question is, how long does the "DB–planet" phase last. If the DB–planet stage is very short, it becomes very difficult to observe the system in this stage. According to Taam, Flannery & Faulkner (1980), the formula which gives us the timescale for the gravitational radiation to remove the angular momentum is,

$$\tau_{GR} = 7.87 \times 10^{7} \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} P^{8/3} \; [yr] \tag{1.1}$$

where τ_{GR} is in years, M_1 and M_2 are masses of the primary and secondary, and P is the orbital period in hours. Assuming the mass of the primary is $0.6 M_{\odot}$ and the mass of the secondary is $\approx 0.02 M_{\odot}$ and using the orbital period of 1482.6 sec from Provencal 1994,

$$\tau_{GR} \approx 5 \times 10^{8} \; years \tag{1.2}$$

This is comparable to the timescale of the accretion phase, 10^6 to 10^8 years. Assume the secondary orbits around the primary in a circular orbit.

Since the primary is much more massive than the secondary, this is not a bad assumption. From Kepler's law,

$$P^2 = \frac{GM_1}{4\pi^2} d^3 \tag{1.3}$$

where d is the separation between the two stars and G is the gravitational constant. Using this, we can estimate the separation between two WDs. For PG1346, $d \approx 2.0 \times 10^{10}\ cm \approx 0.3\mathrm{R}_\odot$. Let us further assume that this is the separation between the two stars when the accretion phase ends and that the secondary becomes a planet of about Jupiter size $R_2 \approx 0.1\mathrm{R}_\odot$ (R_2 is the radius of the secondary). We know from numerical calculation that the size of the $0.6\mathrm{M}_\odot$ WD is about the size of the earth, $R_1 \approx 0.01\mathrm{R}_\odot$ (R_1 is the radius of the primary). We can observe the eclipse of the primary due to the planetary secondary if the viewing angle θ is,

$$0 < \theta < \theta_{MAX} \tag{1.4}$$

in which the maximum viewing angle θ_{MAX} satisfies,

$$sin\theta_{MAX} = \frac{R_1 + R_2}{d} \tag{1.5}$$

For PG1346, we get,

$$\theta_{MAX} \approx 22.6° \tag{1.6}$$

The viewing angle of any system can be between 0°, which is edge on, to 90°, which is face on. Therefore our probability of observing an eclipse for

PG1346 becomes $22.6/90 \approx 0.25$, therefore, 25 %. Do we see an eclipse in one out of four of the DBs? Robinson & Winget did a survey to find pulsating DB white dwarfs (Robinson & Winget). They observed each star for at least $10,000$ *sec* and found no eclipse in any of the 30 DBs they studied. This suggests that the IBWD channel leading to the DBs is not significant.

4. Asteroseismology

Asteroseismology is the study of a star's normal modes. All objects, including stars, have normal modes just like all bells have their own tone. By hitting a bell and listening to the tone it makes, we can tell the size, the shape and the material it is made of. We can do a similar thing with stars. We observe how the star's brightness varies in time, and identify the periods of the modes in which a star pulsates. Then, by trying to reconstruct theoretical models which reproduce the normal modes we observe in the star, we obtain knowledge about the star, e.g. its mass, its chemical composition, its absolute luminosity (hence its distance from us) etc. Although all stars have normal modes, only some of them have their normal modes driven into oscillations, allowing us to observe them. We know several classes of pulsating WDs: DAVs, DBVs, DOVs which show He II in their spectrum and PNNVs (planetary nebulae nuclei variables). Since all the pulsating WDs are otherwise normal WDs, the information we get about the pulsating WDs apply to all non-pulsating WDs (Winget 1988).

We characterize each pulsation mode by three integers much like the energy level of an electron around a hydrogen atom. The three numbers used to describe the nonradial pulsation modes are the radial overtone number k, the degree of spherical harmonic ℓ and the azimuthal quantum number m.

The periods of the modes and the average period spacing in a model depend strongly on the total mass and the temperature of the model. The period spacing is defined as

$$\Delta P_k = P_{k+1} - P_k \tag{1.7}$$

where P_k is the period of the radial overtone number k mode. If a star is truly homogeneous, $\Delta P_k = constant$ for all k's. Any deviation from a homogeneous structure will make $\Delta P_k \neq \ constant$ which is why asteroseismology works as a powerful tool to study the internal structure of the WDs. The periods of the modes give us information about the inside of the star where we cannot see.

When we compare the periods of the modes from models with different mass, but characterized by the same (k, ℓ, m) values, the modes of the more massive models have a shorter period (just like the stiffer spring has a shorter period.). The heavier a WD is, the more compact it is. This means the more massive model has higher surface gravity, and larger Brunt-Väisälä (oscillation) frequency. The larger Brunt-Väisälä frequency means a larger restoring force and hence shorter average period spacing.

The period of the mode changes with time as the WD cools. The rate of period change with time, $\dot{\rm P}$, for a mode whose period is P has the following relation (Winget, Hansen & Van Horn 1983),

$$\frac{\dot{\mathrm{P}}}{P} \approx -\frac{1}{2}\frac{\dot{\mathrm{T}}}{T} + \frac{\dot{\mathrm{R}}}{R} \tag{1.8}$$

where T is the temperature of the period formation region, and R is the stellar radius. Since the WDs maintain roughly constant radius once they become degenerate, the temperature term is the one that is important. Cooling means negative $\dot{\mathrm{T}}$, therefore $\dot{\mathrm{P}}$ comes out to be positive. The cooler it is, the longer the period of the individual mode. Also, as the model cools down, the temperature of the outer part drops faster than the inner part of the model. Since the large k modes sample the outer part more than the inner region, the $\dot{\mathrm{P}}$ of the higher k modes are larger than the lower k modes. Therefore the period of the higher k modes become longer more quickly than the lower k modes, and this results in an increased average period spacing.

To determine if the normal modes of the models are nonradial g-mode or not, we use the local dispersion relation and the propagation diagram. The local dispersion relation tells us the relation between the two important parameters of oscillation, the local wave number $2\pi/\lambda$ (λ is the local wave length) and the frequency of the mode. The most familiar dispersion relation is $c = \nu\lambda$, the relation between the speed of light (c), the frequency (ν) and the wavelength (λ) of the light. The local dispersion relation for adiabatic nonradial oscillation is (Unno et al. 1989)

$$k_r{}^2 = \frac{1}{\sigma^2 c_s{}^2}(\sigma^2 - N^2)(\sigma^2 - S_l{}^2) \tag{1.9}$$

σ is the angular frequency, k_r is the wave number, c_s is the sound speed, N is the Brunt-Väisälä frequency, the oscillation frequency due to the buoyancy, and S_l is the acoustic frequency for mode ℓ. ${S_l}^2$, N^2 and Γ_1 are defined as

$$ {S_l}^2 = l(l+1)\frac{{c_s}^2}{r^2} \tag{1.10} $$

$$ N^2 = -g(\frac{dln\rho}{dr} - \frac{1}{\Gamma_1}\frac{dlnP}{dr}) \tag{1.11} $$

$$ \Gamma_1 = (\frac{dlnP}{dln\rho})_{ad} \tag{1.12} $$

The wave number k_r is a natural number (integer) and gives a positive value for ${k_r}^2$. The dispersion relation gives us two frequency domains that would make ${k_r}^2 > 0$. The frequency domain which corresponds to the g-modes is

$$ \sigma^2 < N^2, \sigma^2 < {S_l}^2 \tag{1.13} $$

The other domain,

$$ \sigma^2 > N^2, \sigma^2 > {S_l}^2 \tag{1.14} $$

corresponds to the pressure modes or p-modes. The propagation diagram is a plot of Brunt-Väisälä frequency and acoustic frequency through the model. An example is shown in Figure 1.2 for $25,000K$ DB.

A propagation diagram gives useful information about the model. It describes in which region the nonradial g-modes propagate, the frequency range the nonradial g-modes would have, and the strength of the restoring force throughout the model. Since the period (P) and σ are related as

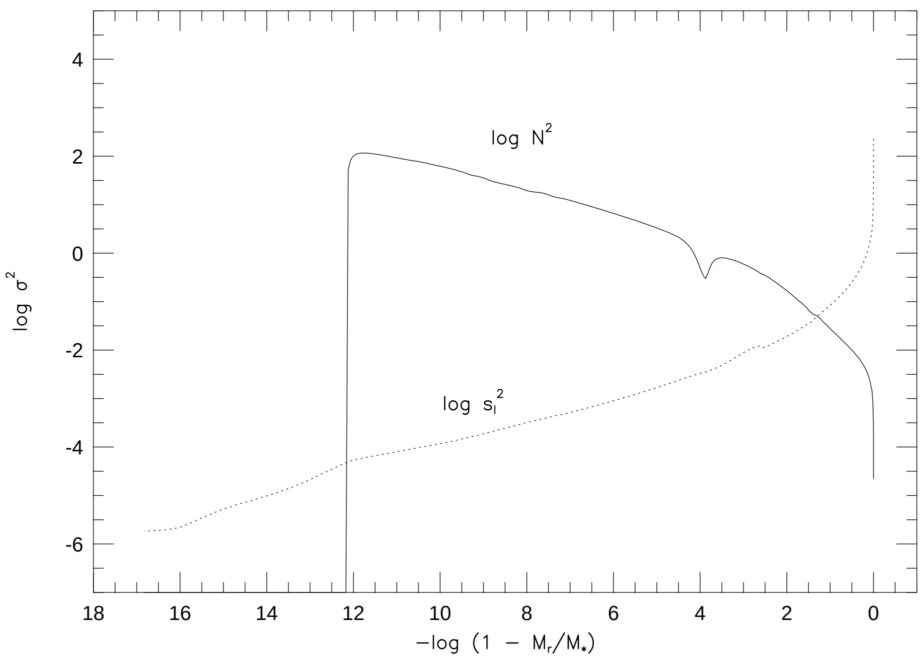

Fig. 1.2.— Propagation diagram for 25,000K DB model. The solid line represents $logN^2$ and the dotted line shows ${logS_l}^2$

$\sigma = \frac{2\pi}{P}$, the period range we see in the DBVs, 100 to 1000 sec, corresponds to $-4.4 < log\sigma^2 < -2.4$. From equation (1.7) and the propagation diagram, we can see that this range corresponds to g-modes. The Brunt-Väisälä frequency is a measure of the restoring force due to gravity. A larger value of Brunt-Väisälä frequency implies a larger restoring force. As you go further out from the center of the star, the mass enclosed within increases, leading the gravity to increase also. You can see in the propagation diagram how the Brunt-Väisälä frequency becomes larger as you go further out from the center of the star until you hit the bottom of the convection zone at $-log(1 - \frac{M_r}{M_\star}) = 12.3$. In the convection zone, at $-log(1 - \frac{M_r}{M_\star}) > 12.3$, the gravity no longer acts as the restoring force.

5. The Goal of This Project

Observations of IBWDs suggest that they produce DBs at the end stage of their evolution. Then the following question naturally arises: do the IBWDs make a significant contribution to the DB population? The goal of this project is to find out if there are observable differences between the DB models simulating the two different evolutionary scenarios: the single star evolution model and the binary evolution model.

A single white dwarf will simply cool with time, heat flowing from the core to the surface. But because of accretion, evolution of WDs in interacting binary systems will not be a simple cooling process; accretion will change the thermal structure of the envelope. Even after the accretion process has stopped, and the surviving white dwarf is left alone to cool, it will retain the memory of the thermal structure built during the accretion process, for a time determined by the nature and the duration of the accretion process.

Nature provides us with an opportunity to study the internal structure of the hot DBs through their normal modes. The DBs pulsate in nonradial g-modes around $20,000K - 25,000K$. If the IBWD stars serve as a channel producing DBs with different thermal structure compared to the DBs from the single star evolution, we have the chance of observing the differences in the normal modes of the DBVs.

If we find out that it is possible to sort DBVs by its origin observationally, then we will use our method to determine the origin of the best studied DBV, GD358.

Chapter 2

Models

In this chapter, we describe the two types of models used in this project: models describing DBs from single star evolution (the thermally homogeneous models) and binary evolution (the hybrid models).

1. Homogeneous Models

For DB models from single star evolution, the equilibrium models of the latest version of the evolution code provided by Matt Wood were used. This code uses state-of-the-art opacity tables and neutrino rates (Wood 1994 and references therein). We call the output models of the evolution code "homogeneous models".

We used two thermally homogeneous models with different effective temperatures for this project.

- $25,000K$ model / hot model
  $M_\star = 0.6M_\odot$, $M_{He} = 10^{-4}M_\star$, $T_{eff} = 25,000K$
- $12,000K$ model / cool model
  $M_\star = 0.6M_\odot$, $M_{He} = 10^{-4}M_\star$, $T_{eff} = 12,000K$

As mentioned in Chapter 1, the mean mass of DBs is about $0.6M_\odot$ which is the mass we selected for our models. The theoretical constraints on the He layer mass is 10^{-8} $M_\odot$ to $10^{-2}M_\odot$, the lower limit coming from the minimum amount required for the partial ionization of He to provide the driving of the nonradial g-modes in the WDs, and the upper limit coming from maximum mass of He before the nuclear burning occurs at the bottom of the He layer (Bradley & Winget 1994). The He layer mass of our models fall within this constraints.

We chose the effective temperature of the hot model based on the the effective temperature of GD358 and AM CVn, the well-studied DBV (Koester, Weidemann & Vauclair 1983; Oke, Weidemann & Koester 1984, Koester et al. 1985; Liebert et al. 1986; Thejil, Vennes & Shipman 1991) and IBWD respectively (Provencal 1994). In the IBWD system, once two WDs are formed, they orbit around each other for a long time, slowly cooling off before the last mass transfer takes place. The time scale of this is equal to the timescale for the gravitational radiation to carry away the momentum of the system so that the two WDs are close enough and the mass donor (the less massive one) fills its Roche Lobe. This takes about 10^8 to 10^9 years (Chapter 1). A DB with the mass of $0.6M_\odot$ and $M_{He} = 10^{-4}M_\odot$ that has been cooled for that long would have a core temperature of about $10^7 K$, according to model calculation (Wood 1990). This core temperature corresponds to roughly $T_{eff} \approx 12,000K$. Therefore our cool model represents a model before the final mass transfer in the IBWD takes place.

2. Hybrid Models

Evolution of a single WD is a simple cooling process. WDs no longer have nuclear fusion and they just radiate away their thermal energy, the heat flowing from the core to the surface of the star. The evolution of a WD in a binary system is more complicated. At the very end of the binary evolution, the more massive WD experiences mass transfer from its less massive companion. An accretion disk surrounds the more massive WD and heats it up from the surface. This would cause the mass accreting WD to have an envelope that is hotter than it would have otherwise. Unfortunately we have no evolution code which simulates binary evolution, and creates a DB model expected from the binary evolution scenario. Construction of a self-consistent binary evolution code, with accretion built in, is well beyond the scope of a second year project. For the purposes of our investigation, we created models to simulate the thermal structure of the DBs resulting from binaries by replacing the atmosphere of a homogeneous model with that of an another homogeneous model with higher effective temperature. These new models are called "the hybrid models". These models give us a preliminary look at the structure of the DBs produced in binaries.

We created four hybrid models from the two thermally homogeneous models described in the previous section. We call three of them "dm6", "dm4", "dm2" after the amount of the mass that was replaced from the cool model. For instance, dm6 means that the outer part of atmosphere $dM = 10^{-6}\mathrm{M}_\star$ of the cool model was replaced with that of the hot model.

We made a fourth model by replacing the outer part of the cool model from the degeneracy boundary. This corresponds to replacing the outer $dm = 10^{-5.35}\mathrm{M}_\star$ of the cool model with the envelope of the hot model. We call this model “deg”. In the binary system, the heat from the accretion disk flows from the surface inward and would eventually hit the degeneracy boundary. Inside the model where it is degenerate, the heat conduction is very efficient. This makes a nearly isothermal core. Figure 2.1 shows the temperature throughout the models. The x-axis of the figure displays the envelope of the model. It shows that a large part of the model is isothermal. For instance, in the cool model the region $-log(1-\frac{M_r}{M_\bigstar})<3$ is isothermal where M_r is the mass inside the radius r. This means $\frac{M_r}{M_\bigstar}=0.999$, i.e. the inner 99.9% of the mass of the cool model is isothermal.

When the heat flow reaches the degeneracy boundary, the heat is conducted throughout the core, raising the whole core temperature. WDs are non-centrally condensed and have relatively large cores, which contain more than 90% in the mass. Because of this, it takes very long to heat up the core by any significant amount, making it a heat sink. It is easier to see this in a simple equation form.

$$L_{acc}\tau_{acc}=C_v(core)\delta T M_{core} \tag{2.1}$$

The left hand side of the equation tells how much energy flowed into the star from the accretion disk by heating it with luminosity L_{acc} for time τ_{acc}. The core increases its temperature due to this energy and stores it. The right hand side of the equation tells how much energy is stored in the core whose mass is M_{core} and heat capacity per unit mass is $C_v(core)$ due to temperature increase δT. The total heat capacity of the core is $C_v(core)M_{core}$, which is very large compared to that of the envelope, making the core a heat sink. The accretion must last a long time before the core is heated up any

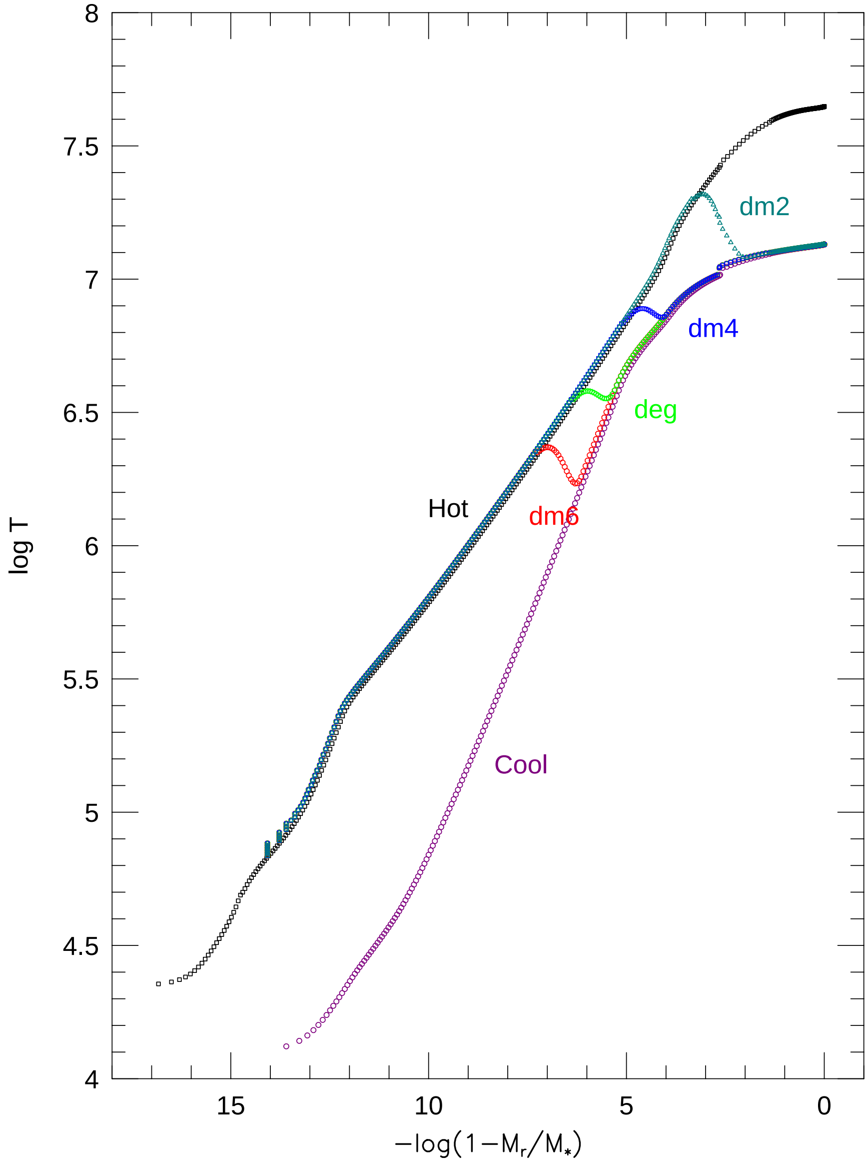

Fig. 2.1.— Temperature Profile of the Models. The cool model is in black, dm6 is in red, deg is in green, dm4 is in blue, dm2 is in bluegreen curve, and the hot model is in purple.

significant amount. This justifies our usage of these hybrid models, dm6 and deg, as a preliminary study of the structure of DBs from binary evolution. We note that dm4 and dm2 are unphysical, in the sense of representing DBs of binary systems, but we will use them to help us understand the trend of how the normal modes are affected by the replacement of mass in our models.

2.1. Construction of Hybrid Models

We made the hybrid models by patching two homogeneous models. First, we decided on the amount of mass to be replaced, dm, then we found the corresponding shell numbers of the models which would be replaced, $n_c + 1$ outward for the cool model and $n_h + 1$ for the hot model. To be realistic, the hybrid models must have smooth thermal profiles. For instance if pressure has a discontinuity, hydrostatic equilibrium requires the mass within this point to be infinitely large. And if there is a temperature discontinuity, there will be an infinite flux going from the cooler region to the hotter region. These are clearly unphysical. So we smoothed the parameters at the boundary of the two homogeneous models by taking a weighted average for 20 shells. The hybrid models are the same from shell number 1 to n_c as the cool model. Between shell number $n_c + 1$ to $n_c + 20$ of the hybrid models we defined the physical quantities $x(n)$ for the the shell number n using the physical quantities of the cool model $x_c(n)$ and the hot model $x_h(n)$.

For l= 1 to 20,

$$x(n_c + l) = w x_c(n_c + l) + (1 - w) x_h(n_h + l) \tag{2.2}$$

with the weight, w,

$$w = \exp^{-l^2/144} \tag{2.3}$$

And finally from $n_c + 21$ till the last shell, the physical parameter from the hot model's $n_h + 21$ are used. All four hybrids created this way have $M_\star = 0.6M_\odot$, $M_{He} = 10^{-4}M_\star$, and $T_{eff} = 25,000K$. The temperature profile of the hybrid models are shown in Figure 2.1

2.2. Accretion Timescale

The amount of mass replaced to create the hybrid models is related to the length of time assumed for the heating of the star (τ_{acc}). The longer the model is heated, the greater is the mass fraction of the star heated up from its original equilibrium state.

$$L_{acc}\tau_{acc} = C_v \delta T dM \tag{2.4}$$

As we saw in the similar equation in the last section, the left hand side of the above equation tells how much energy flowed into the star from the accretion disk by heating it with luminosity L_{acc} for τ_{acc} and the right hand side of the equation tells how much energy was stored in mass dM whose heat capacity per unit mass is C_v by raising the temperature δT. Our hybrid models represent a situation where the $12,000K$ cool model is heated up by luminosity that corresponds to the $25,000K$ accretion disk till the outer dM of the star became the same thermal structure as the hot model. In most of the envelope, the heat capacity does not change much and the heat capacity of the cool model ($C_v(cool)$) and the hot model ($C_v(hot)$) are roughly the same: $C_v(cool) \approx C_v(hot)$ (see Figure 2.2). From Figure 2.1, the temperature of the hot model is not uniformally hotter than the cool model everywhere in the model. But to estimate roughly the accretion timescale, we take $\delta T \approx 0.5T(hot)$ (T(hot) is the temperature of the hot model and T(cool) is the temperature of the cool model). Using $L_{acc} = L(hot)$, the accretion timescale becomes,

$$\tau_{acc} \approx 0.5 \frac{C_v(hot)T(hot)dM}{L(hot)} \tag{2.5}$$

This corresponds to the half of the time the photon takes to travel from the surface to the outer mass dM in the hot model. The thermal time scale of a model is the time it takes a photon to travel from the center to the surface of the star. So the above timescale is the half of the thermal timescale of the hot model at mass dM from the surface. The accretion timescale for all the models are estimated to be,

$$\tau_{acc}(dm6) \approx 40 \ years \tag{2.6}$$

$$\tau_{acc}(deg) \approx 260 \ years \tag{2.7}$$

$$\tau_{acc}(dm4) \approx 10^4 \ years \tag{2.8}$$

$$\tau_{acc}(dm2) \approx 10^6 \ years \tag{2.9}$$

If the accretion phase lasts long enough, the accretion disk would heat up the cool model completely so that it would have the same thermal structure as the hot model. We estimated the timescale of this as we did for the above accretion timescale for the hybrid models and found that timescale is roughly the same as the thermal timescale for the hot model, $\tau_{th}(hot)$,

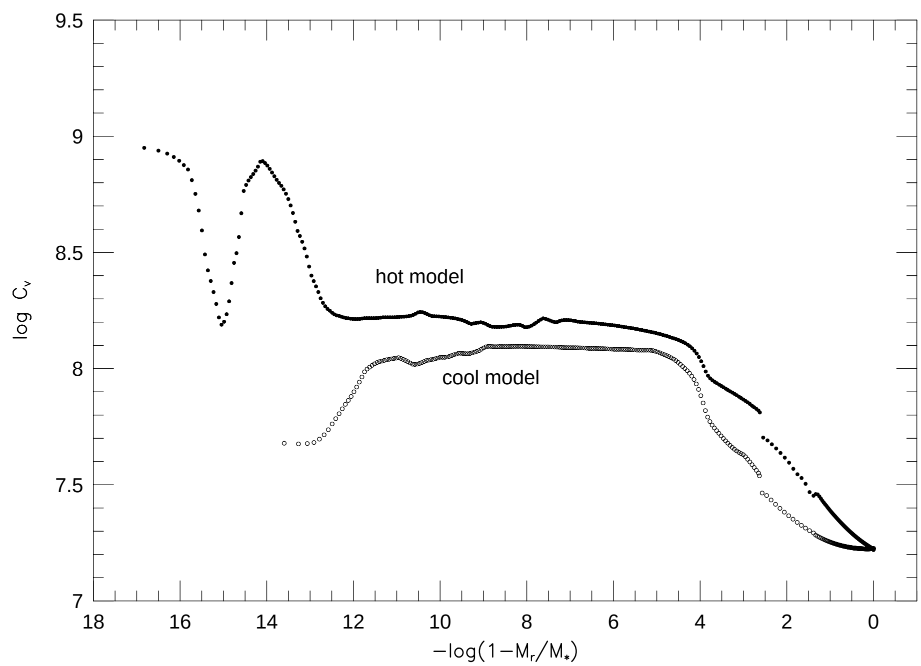

Fig. 2.2.— Heat capacity for the hot model (filled circle) and the cool model (the open circle).

$$\tau_{acc}(hot) \approx \tau_{th}(hot) \approx 10^8 \ years \tag{2.10}$$

Remember that the theoretical estimate of the duration of accretion phase was about $10^6 - 10^9$ years (Chapter 1). Unless all the IBWDs have the accretion time lasting for 10^8 years or longer, a DB resulting from binary evolution would not be heated up to have the thermal structure of the $25,000K$ DB from single star evolution. Thus, it should be possible to distinguish between the DBs from the binary evolution and DBs from single star evolution.

A summary of the models created with their effective temperature and accretion time is shown in Table 2.1.

Table 2.1. Models with their T_{eff} and accretion time

model	T_{eff} (K)	τ_{acc} (years)
cool	12,000	0
dm6	25,000	40
deg	25,000	260
dm4	25,000	10^4
dm2	25,000	10^6
hot	25,000	10^8

Chapter 3

Results

1. Propagation diagram

Once we created all models described in Chapter 2, the first thing we did was to plot the propagation diagrams for each models. This is to check what frequency range g-modes have in each models. Our goal was to see if there were any observable differences in nonradial g-modes between DBs from different evolutionary paths. To achieve this, we first must find out the period range of the nonradial g-modes in the hybrid models. The observed periods of the DBVs are 100 to 1000 sec. If the hybrid models do not have any nonradial g-modes in the range where we find in DBVs, then we may suspect that DBs that have similar temperature as DBVs, around $20,000K$ to $25,000K$, but do not pulsate are likely to be DBs from binary evolution. If the hybrid models which represents the DBs from binary evolution show g-modes in this range, then we can compare the g-modes periods between the hybrids models and the homogeneous models in more detail to look for observable differences.

Figure 3.1 shows the propagation diagrams for all the models used in this project. The observed g-mode periods, 100 to 1000 sec, corresponds to $-4.4 < log\sigma^2 < -2.4$ (σ is the angular frequency, $\sigma = 2\pi/period$). This

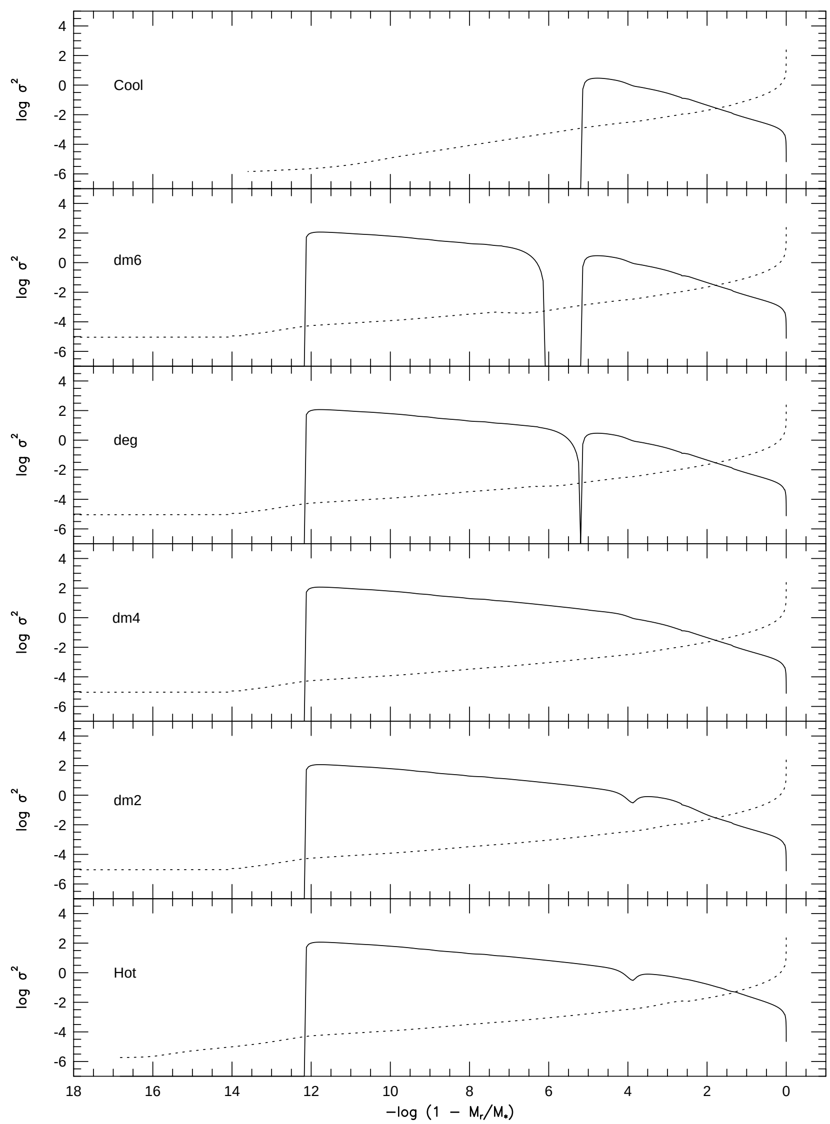

Fig. 3.1.— Propagation diagram for all the models. From the top panel, the Cool model, dm6, deg, dm4, dm2 and the Hot model. Solid line represents $logN^2$ and the dotted line shows $logS_l{}^2$.

frequency range satisfies the condition (1.13) which means that all the models we used exhibit g-mode oscillations whose periods are in the observed period range. We therefore cannot expect to find non-variable DB stars as relics of binary mergers. The next step is find observable differences in nonradial g-modes between the hybrid models and the homogeneous models.

2. Period spacing

To obtain the normal mode periods of the models, we used the adiabatic nonradial pulsation code. This code solves the adiabatic nonradial oscillation equation with the Runge-Kutta-Fehlberg scheme (Kawaler, Hansen & Winget 1985). The g-modes propagate and their periods are determined in the region where $\sigma^2 < N^2$ and $\sigma^2 < {S_l}^2$ (Chapter 1). This condition is satisfied below the convection zone where the adiabatic treatment of the pulsation equation is valid. For this project, we ran the code to solve for $l = 1$ modes and investigated their period distribution in the various models.

Figure 3.2 shows the period vs. model plot. The x-axis is taken as the $log\tau_{acc}$ where τ_{acc} was defined for all models in the previous chapter (See Table 2.1). The periods for all the models in the figure ranges from k= 1 to k= 18. All four hybrid models are essentially spectroscopically identical: effective temperature 25,000K, 0.6$M_\odot$, DBs (see Table 2.1). But the normal modes which probe inside the models tell us how these models have different thermal structures. Figure 3.2 shows clearly that the low k modes and the period spacing of the hybrid models are longer than what we would expect from the homogeneous hot model with the same effective temperature. Since we replaced the outer part of the cool model's envelope to create the hybrid

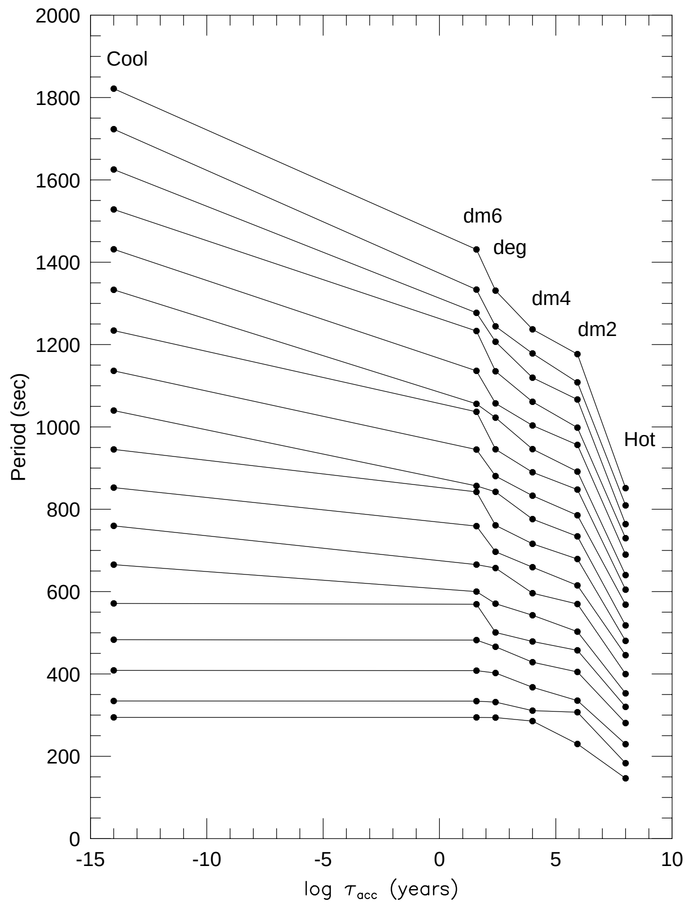

Fig. 3.2.— Periods vs. All Models

models, the high k modes which samples the outer part more than the low k modes are affected more strongly than the low k modes. The net effect of this is the shorter average period spacing for the models replaced with larger mass. We computed the average period spacing for all models and got the following.

$$< \Delta P(cool) >= 90.4\ sec \tag{3.1}$$

$$< \Delta P(dm6) >= 67.8\ sec \tag{3.2}$$

$$< \Delta P(deg) >= 62.5\ sec \tag{3.3}$$

$$< \Delta P(dm4) >= 58.0\ sec \tag{3.4}$$

$$< \Delta P(dm2) >= 56.4\ sec \tag{3.5}$$

$$< \Delta P(hot) >= 41.1\ sec \tag{3.6}$$

As discussed in Chapter 1, among the models with same total mass, the cooler model shows longer period spacing than the hotter model. A similar trend is seen in the hybrid models. The more mass is replaced from the cooler to the hotter model, the smaller the period spacing. The four hybrid models and the hot model (which are all spectroscopically identical) have very different period spacing. The average period spacing is then an indicator of the origin of the DB. If a DBV shows a longer average period spacing than the thermally homogeneous model with same temperature, mass and chemical composition, that suggest that its origin is a binary system.

The periods of the low k modes are also good indicators of the DBV's origin. For instance, the thermally homogeneous hot model has $P_1 = 146\ sec$ while the deg has $P_1 = 294\ sec$, which is twice as long as the hot model. If we observe a DBV pulsating in a very short period, it means that there is no evidence of an accretion history in its thermal structure. Hence it evolved as a single star or it went through unusually long ($\tau_{acc} = 10^8$ $years$) accretion.

In Figure 3.2, the slope of the lines that connects the modes with the corresponding k tells us how much the period changes as the model is heated up longer. The slope connecting dm6 and deg produces the largest change in the periods. Nonradial g-mode pulsations make the mass move predominantly in the horizontal direction. Large mass motion occurs in the envelope rather than in the core where it is degenerate (Unno et al. 1989; Cox 1980; Winget, Van Horn & Hansen 1981). Therefore changing the thermal structure of the whole non-degenerate region of the model produces the largest effect on the periods of the modes, as we might expect. This is why the slope connecting the modes from dm6 to deg is steeper than the others.

There are several modes which have a larger change in period compared to others. Note how the periods of k= $5, 9, 12, 15$ modes change from dm6 to deg. These are the trapped modes in dm6. Kinetic energy of the modes come from the small mass displacement in the core and the large displacement in the envelope. The trapped modes have much less energy contributed from the core than from the envelope. The trapped modes have this name because their energy comes mostly from the non-degenerate envelope, hence "trapped" in the envelope modes (Bradley, Winget & Wood 1993, Unno et al. 1989). This makes the trapped modes the most sensitive modes to the different thermal structure in the envelope among all the normal modes. The larger slope seen for the trapped modes in dm6 is the result of that.

We have demonstrated that the thermally stratified models simulating the DBs from binary evolution show observable differences in the normal modes compared to the models simulating the DBs from the single star evolution. The models showed that DBs from binary evolution have longer periods and longer average period spacing than the DBs from single star evolution with the same effective temperatures. Next we compare the data from GD358 with our crude models to investigate its origin.

3. GD358

To compare data from GD358 and our models, we plotted a period spacing diagram (Fig 3.3). The model whose period structure is closest to GD358 is the hot model. The average period spacing of GD358 is 39.2 sec (Winget et al. 1994). GD358 either went through an extremely long accretion phase, which would be pushing the theoretical limit, or came from single star evolution.

Bradley and Winget (1994) compared the GD358 data with the thermally homogeneous models and concluded that the model that best fits the data has a total mass of $0.61 M_{\odot}$, $10^{-5.7} M_{\star}$ and $T_{eff} = 24,000K$.

GD358 does not have any signature in its thermal structure indicating it was once in a binary system. Our investigation suggests that it came from single star evolution. What about the other DBVs? A recently discovered DBV, EC20058-5234 (Patterson et al. 1992; Wood 1987; O'Donoghue & Kilkenny 1989), has modes whose period is as small as 134 sec. Comparing the periods in Figure 3.2 suggests that this DBV is also from single star evolution. We must check the rest of the DBVs to find out their origins.

Finally, if all DBVs are from single star evolution, where are the DBs

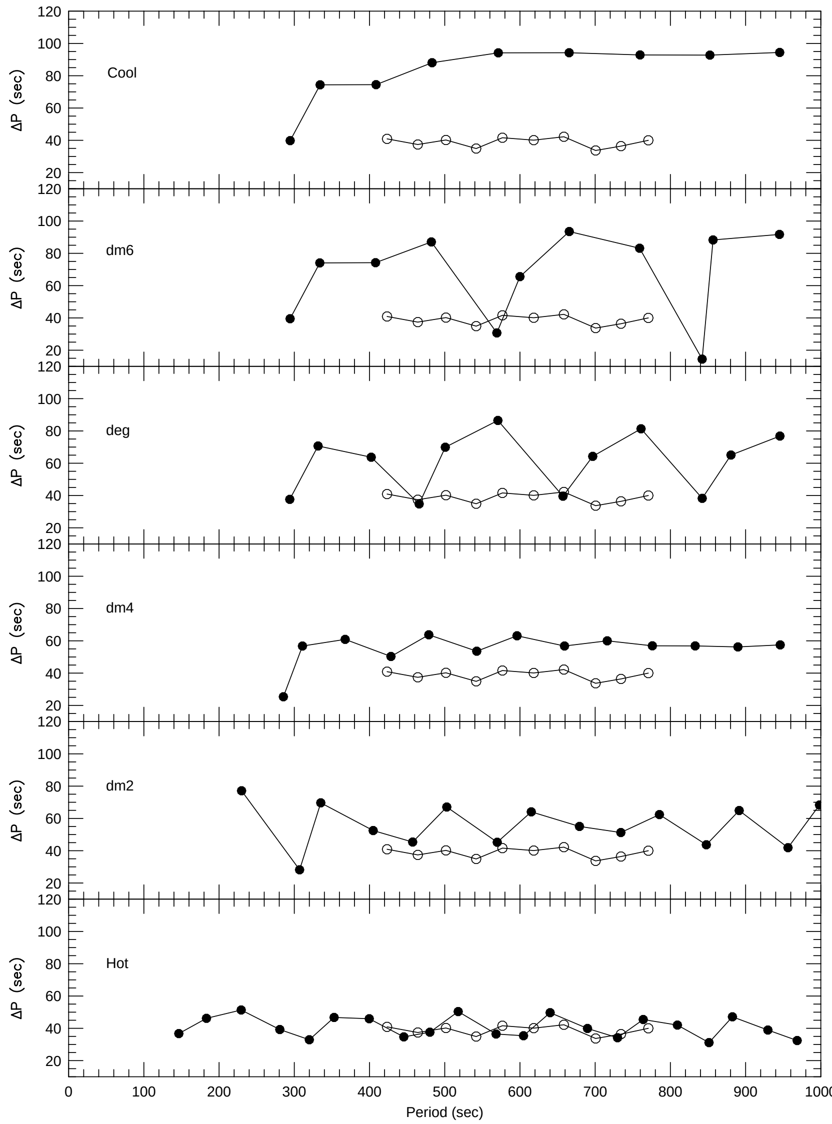

Fig. 3.3.— Period spacing diagram for all the models. From the top panel, the Cool model, dm6, deg, dm4, dm2 and the Hot model. The filled circle shows the period and the period spacing of the models and the open circle shows the data from GD358.

from binary evolution? The effective temperature of the other IBWDs are lower than AM CVn (Patterson et al. 1992; Wood 1987; O'Donoghue & Kilkenny 1989). Therefore the DBs from those IBWDs might have effective temperatures lower than the DB instability strip. We also should not forget the He-rich PNNs and H-rich PNNs. Is there any connection between the spectral types of WDs? It is hard to imagine the number ratio of He-rich PNNs to the H-rich ones is the same as the number ratio of the non-DAs to the DAs by accident. There are still a lot to be studied before we can understand the spectral types and evolutions of WDs.

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Vita

Atsuko Nitta was born on August 21, 1996, in Tokyo, Japan, as the daughter of Isamu and Michiko Nitta. After graduating from Toho Girls' High school in 1985, she entered Ochanomizu University. She majored in physics and received a B.S. in March 1990. She continued her studies in physics at graduate school of Ochanomizu University. She received Ishizaka Foundation Scholarship in 1991 and came to the physics department of University of Texas at Austin. In the spring, 1993, while she was a physics student, she met Don Winget and Ed Nather and started working in the Whole Earth Telescope lab. She transferred to astronomy department in 1994.

Permanent address: 2-26-10 Ikebukuro Honcho, Toshima-ku, Tokyo,
170, Japan

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