The nuclear reactions that occur in the stellar progenitors of white dwarfs (WDs) lead to an internal composition of $^{12}\text{C}$, $^{16}\text{O}$, and a “contaminant” nucleus, $^{22}\text{Ne}$. The $^{22}\text{Ne}$ is produced by helium captures on $^{14}\text{N}$ left from hydrogen burning via the CNO cycle. By virtue of its two excess neutrons (relative to the predominant $A=2Z$ nuclei), a downward force on $^{22}\text{Ne}$ is exerted on $^{22}\text{Ne}$ in the WD interior. This biases its diffusive equilibrium, forcing $^{22}\text{Ne}$ to settle toward the center of the WD. We discuss the physics of the gravitational settling when the WD is in the liquid state and the luminosity generated by it. This modifies the cooling of WDs with masses in excess of $M_\odot$. The current uncertainties in the microphysics even allow for solutions where a 1.2 $M_\odot$ WD remains mostly liquid for a few gigayears because of the internal heating from $^{22}\text{Ne}$ sedimentation. This highlights the need for an accurate calculation of the interdiffusion coefficient, especially in the quantum liquid regime relevant for high-mass WDs. There is also time in old, liquid WDs (such as those found in cataclysmic variables and possibly in accreting Type Ia progenitors) for partial settling.

**Subject headings:** diffusion — novae, catalytic variables — stars: abundances — stars: interiors — supernovae: general — white dwarfs

### 1. INTRODUCTION

The slowest step in the CNO cycle is the proton capture on $^{14}\text{N}$. This results in all CNO catalysts piling up at $^{14}\text{N}$ when H burning is completed during the main sequence. During helium burning, the reactions $^{14}\text{N}(\alpha,\gamma)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$ ensue and convert the $^{14}\text{N}$ into $^{22}\text{Ne}$, resulting in a mass fraction of $^{22}\text{Ne}$, $X_{^{22}\text{Ne}} \approx Z_{^{14}\text{C}} \approx 0.02$ for Population I stars. The possibility that this nucleus plays an important role in the energetics of cooling white dwarfs (WDs) was first noted by Isern et al. (1991). They discussed the possibility of gravitational energy release if the $^{22}\text{Ne}$ phase separates at crystallization. This was followed by more detailed studies (Xu & Van Horn 1992; Ogata et al. 1993; Segretain et al. 1994; Segretain 1996) that differed in their conclusions about the final state once crystallization was complete, ranging from all the $^{22}\text{Ne}$ being in the stellar center to most of it having an unchanged profile.

What about $^{22}\text{Ne}$ sedimentation in the liquid state? Ogata et al. (1993) showed that demixing in the liquid state never occurs for the C/O/$^{22}\text{Ne}$ liquid (namely, it will remain in the fully mixed state when the temperature is safely above melting). This allows us to focus on the gravitational settling of individual $^{22}\text{Ne}$ nuclei in the liquid parts of the white dwarf (Bravo et al. 1992). This happens prior to the onset of crystallization in a cooling WD and during the lifetime of a WD that remains in the liquid state as a result of heating from accretion.

Degenerate electrons dominate the pressure in the WD interior, so that the upward pointing electric field at mass coordinate $m(r)$ is $eE \approx 2m_e g$, where $g = \frac{Gm(r)}{r^2}$ and $m_e$ is the proton mass. The downward force on an $^{22}\text{Ne}$ nucleus is $F = 22m_e g - 10eE = 2m_e g$, giving a potential energy drop $U(r) = \int_0^r 2m_e g dr$ between radius $r$ and the center. Across the whole star, this amounts to 285 keV for $M = 0.6 M_\odot$ and 1600 keV for $M = 1.2 M_\odot$. It is the excess neutrons of the $^{22}\text{Ne}$ nucleus (relative to $A=2Z$) that make it special (the same is true of the less abundant $^{56}\text{Fe}$). Differentiating forces on the carbon and oxygen nuclei only arise from the slight differences in masses from $A_{m_e}$ due to the nuclear binding, which is orders of magnitude smaller than the force on $^{22}\text{Ne}$.

The potential energy (the energy that would be released if all the $^{22}\text{Ne}$ sinks to the center) of a uniformly mixed model ($X_{^{22}\text{Ne}} = 0.02$ is constant) is $1.4 \times 10^{57}$, $3.2 \times 10^{57}$, $6.8 \times 10^{57}$, and $1.5 \times 10^{48}$ ergs for masses of 0.6, 0.8, 1.0, and 1.2 $M_\odot$. For 0.6 and 1.0 $M_\odot$, this corresponds to $5.8 \times 10^{13}$ and $1.7 \times 10^{16}$ ergs g$^{-1}$ of possible energy release from $^{22}\text{Ne}$ settling. At a temperature of $10^7$ K, the specific heat per oxygen ion is $7.7 \times 10^{15}$ ergs g$^{-1}$, so that the energy stored in $^{22}\text{Ne}$ is comparable to the thermal energy content of a cooling WD at late times.

In § 2, we estimate the interdiffusion coefficient for a trace $^{22}\text{Ne}$ nucleus in the liquid C/O interior. The settling timescale for $^{22}\text{Ne}$ is $\sim 10$ Gyr, making it critical for a more accurate calculation of the interdiffusion coefficient. The settling time decreases for more massive WDs. In § 3, we speculate on the modifications the $^{22}\text{Ne}$ settling is likely to have on accreting WDs and maybe Type Ia supernovae. We calculate in § 4 the luminosity from the gravitational energy release of sinking $^{22}\text{Ne}$. This affects the cooling of WDs prior to crystallization and can possibly heat them to a level hot enough to maintain them in the liquid state for a Hubble time.

### 2. DIFFUSION AND SETTLING OF THE $^{22}\text{Ne}$

We presume that the WD interior consists of a single element (either $^{12}\text{C}$ or $^{16}\text{O}$) of mass $\rho r$, and charge $Z e$ and that $^{22}\text{Ne}$ is a trace component at density $n_{^{22}\text{Ne}} = X_{^{22}\text{Ne}} / 22 m_e$. Our WD is constructed purely from the degenerate electron equation of state. For the properties we need for the $^{22}\text{Ne}$ diffusion problem, it is a fine approximation to neglect the ionic contribution to the pressure.

Relative diffusion of charged species in a correlated liquid is substantially different than the diffusion problem in the WD.
Type Ia progenitor. The lines show how long it takes an $^{22}\text{Ne}$ nucleus to fall to a given mass coordinate if it begins at the stellar surface. The set that begins at 1.2 (0.6) $M_\odot$ is for a WD of that mass.

In other liquids at small scales, where it is accurate at atomic dimensions (Hansen & McDonald 1986). An alternate route is to "slip" at the particle/liquid interface. This estimate works well in this case $^{22}\text{Ne}$ undergoing Brownian motion in a liquid of viscosity $\eta$, with $D = kT/4\pi\eta$, agrees with equation (2) to about 20% for all $\Gamma > 10$.

We also compared equation (2) to Fontaine’s (1987) rough fitting formula for the interdiffusion coefficients and found agreement to 30%. So, for now, we will use equation (2) for our estimate of $D$, keeping in mind that there has yet to be an appropriate microphysical calculation. We will show later that there is astrophysical motivation for a more accurate calculation of the interdiffusion coefficients, especially in the quantum liquid regime that is relevant for the massive WDs. For these WDs, the parameter $h\omega_0/kT$ exceeds unity long before crystallization sets in (Chabrier, Ashcroft, & DeWitt 1992; Chabrier 1993) and might well modify the diffusion coefficient by order unity.

Since $kT \ll U(r)$ over most of the stellar radius (equivalent to saying that the $^{22}\text{Ne}$ scale height is much less than the WD radius), most of the drift of the $^{22}\text{Ne}$ is dominated by "falling" at the local speed set by the diffusion coefficient $V \approx 2m_r g D/kT$, which with equation (2) gives

$$V = \frac{18m_r g}{Z\Gamma^{1/3} (4\pi\rho)^{1/2}}.$$  

In mass coordinates $m(r)$, the time it takes to fall from $m_1$ to $m_2$ is

$$\Delta t = \int_{m_1}^{m_2} \frac{Z\Gamma^{1/3}}{18m_r G(4\pi\rho)^{1/2}} \frac{dm(r)}{m(r)}.$$  

For a constant density star, this becomes $\Delta t \approx t_s |d\ln m(r)|$, where

$$t_s = \frac{\Gamma^{1/3} Z}{18} \left( \frac{e^2}{Gm_r^2} \right)^{1/2} \left( \frac{1}{4\pi\rho} \right)^{1/2} = 13 \text{ Gyr} \frac{Z\Gamma^{1/3}}{6\rho^{1/2}}.$$  

Using the central densities as an estimate, a pure oxygen $0.6 M_\odot$ WD at $T = 10^5$ K (this temperature is appropriate for rapidly accreting WDs) has $t_s \approx 19.6$ Gyr, so that complete sedimentation is not likely for the most common $0.6 M_\odot$ WDs. However, the strong density dependence means that this settling time decreases for massive WDs. For example, a pure oxygen $1.2 \text{ (1.3) } M_\odot$ WD at $10^4$ K has $t_s \approx 4.8 \text{ (3) Gyr}$, in rough agreement with the previous simple estimates of Bravo et al. (1992).

Figure 1 shows the time it takes for an $^{22}\text{Ne}$ nucleus that starts at the surface $[m(r) = M]$ to fall to the location $m(r)$. This is an integration of equation (4) with a model WD. The solid (dashed) lines are for pure oxygen (carbon) and bracket the C/O WDs. We show two masses, 0.6 and 1.2 $M_\odot$, making it clear that $^{22}\text{Ne}$ settles faster in a massive WD.

$$D \approx 3\omega_0 a^2 \Gamma^{-1/3},$$  

calculated by Hansen, McDonald, & Pollock (1975), where $\omega_0 = 4\pi\eta/(Ze)^2/m_r$ is the ion plasma frequency. How well does this agree with the Stokes-Einstein estimate? Using the numerically derived viscosity of the OCP, $\eta \approx 0.1\omega_0 a^2 (\Gamma/10)^{1/3}$ (Donko & Nyiri 2000 and references therein), and setting $a = a_r$, the derived $D = kT/4\pi\eta$ agrees with equation (2) to about 20% for all $\Gamma > 10$.

in the quantum regime, making it clear that $^{22}\text{Ne}$ settles faster in a massive WD.

atmosphere. In those less dense regions, traditional Coulomb cross sections and ideal gas equations of state dominate (e.g., Fontaine & Michaud 1979; Vaulclair & Vauclair 1982). As discussed by Paquette et al. (1986), there is substantial uncertainty in the diffusion coefficients in the regions of the WD where the ion Coulomb coupling becomes strong. For a classical one-component plasma (OCP) with ion separation $a$, defined by $a^2 = 3/4\pi n_e$, where $n_e = \rho/Am_r$, the importance of Coulomb physics for the ions is measured by

$$\Gamma \equiv \frac{(Ze)^2}{akT} = 57.7 \rho_e^{1/3} \frac{10^7 \text{ K}}{T} \frac{Z^2}{8} \left( \frac{16}{A} \right)^{1/3},$$  

where $\rho_e = \rho/10^6 \text{ g cm}^{-3}$. Crystallization occurs when $\Gamma$ exceeds 173 (see Farouki & Hamaguchi 1993 and references therein). We consider settling of $^{22}\text{Ne}$ only in the liquid state, or $1 < \Gamma < 173$, the presumption being that the dramatic increase in viscosity expected in the solid state will prohibit further gravitational sedimentation.

The interdiffusion coefficient $D$ of $^{22}\text{Ne}$ in a C/O mixture with $\Gamma \sim 1-100$ has not been specifically calculated, and so we construct here our best estimate. One way to estimate $D$ is to use the Stokes-Einstein relation for a particle of radius $a_r$ (in this case $^{22}\text{Ne}$) undergoing Brownian motion in a fluid of viscosity $\eta$, which gives $D = kT/4\pi\eta a_r^2$ when the fluid is allowed to "slip" at the particle/fluid interface. This estimate works well in other liquids at small scales, where it is accurate at atomic dimensions (Hansen & McDonald 1986).

The Figure 1 shows the time it takes for an $^{22}\text{Ne}$ nucleus that starts at the surface $[m(r) = M]$ to fall to the location $m(r)$. This is an integration of equation (4) with a model WD. The solid (dashed) lines are for pure oxygen (carbon) and bracket the C/O WDs. We show two masses, 0.6 and 1.2 $M_\odot$, making it clear that $^{22}\text{Ne}$ settles faster in a massive WD.
3. ACCRETING WHITE DWARFS AND TYPE Ia PROGENITORS

Unlike cooling WDs, the interiors of massive, accreting WDs are maintained in the liquid state by the heating from accretion. For slowly accreting ($M \sim 10^{-10} M_\odot$ yr$^{-1}$) WDs in cataclysmic variables below the period gap, the core temperatures are in the range $T \approx (1-3) \times 10^7$ K (Nomoto 1982), so that they remain liquid while accreting for a few gigayears. A $1 M_\odot$ pure oxygen WD in such a setting will undergo neon settling in the outer layers as $t \approx 12.6$ Gyr at $T = 3 \times 10^7$ K.

Although the debate rages regarding appropriate Type Ia progenitor models, most favor rapidly accreting WDs that ignite carbon once the mass is near the Chandrasekhar value. The accretion rates considered are too rapid to allow $^{22}$Ne settling during this phase of accretion. However, prior evolution at lower accretion rates or an extended period as a cooling WD will have allowed for some neon settling. Although unclear how important this will be, the effects of $^{22}$Ne settling for the Type Ia ignition of a near-Chandrasekhar mass WD are important to note. The most obvious one is that $^{22}$Ne settling will develop a gradient in the electron mean molecular weight. This would modify the convective criterion in the ignited core and possibly affect the evolution from the thermal runaway to a propagating flame front (Garcia-Senz & Woosley 1995).

The $^{22}$Ne abundance in a Type Ia progenitor is also critical to the overproduction of the neutron-rich isotopes $^{54}$Fe and $^{58}$Ni (Thielemann, Nomoto, & Yokoi 1986). The neutron excess in the inner parts of an exploding WD is fixed by electron captures. Modifying the production of these elements at that location would require a substantially enhanced $^{22}$Ne abundance there (e.g., a pure $^{22}$Ne core would set the initial $Y_e \approx 0.46$). Outside of $0.3-0.4 M_\odot$, the production of $^{54}$Fe and $^{58}$Ni is fixed by the local $^{22}$Ne abundance (Iwamoto et al. 1999). Hence, the production of these elements can be reduced if the $^{22}$Ne sinks away from the outer regions (Bravo et al. 1992). Our calculation suggests there is time for $^{22}$Ne settling in the outer liquid layers of a massive WD if accreting at a low rate. The final answer to this puzzle awaits a time-dependent evolution on a cosmological timescale of the diffusion equation with a realistic starting abundance profile and accretion history.

There is also a $^{22}$Ne settling calculation relevant to classical novae. Many lines of evidence (ejected masses and overly abundant heavy elements) point to the ejected material in classical novae containing matter dredged up from the underlying C/O WD (see Gehrz et al. 1998 and Starrfield 1999 for overviews). Livio & Truran (1994) noted that the neon abundances measured in many of these ejecta are consistent with the $X_{\text{Ne}} \approx 0.02$ expected in a C/O WD. Hence, there is no need to invoke the presence of an O/Ne/Mg WD for those events. However, this will remain true only if the $^{22}$Ne has not gravitationally settled out of the outer C/O layers of the WD that are about to be dredged up.

We can assess this by finding how far the $^{22}$Ne falls in the surface C/O layers, where $g$ is constant. This is a simple case, where we integrate equation (4) for an isothermal layer. Using pressure as a coordinate, we find that the time it takes for $^{22}$Ne to fall to a pressure $P$ starting from the surface is

$$\Delta t \approx 0.8 \text{ Gyr} \left( \frac{10^8 \text{ cm s}^{-2}}{g} \right)^{0.7} \left( \frac{P}{10^{30} \text{ ergs cm}^{-2}} \right),$$

where $\Gamma_g$ is the value of $\Gamma$ at pressure $P$ and exceeds 1 at the time of ignition.

Since the accreted material appears to dredge up a WD layer of mass comparable to the accreted layer, we just need to compare the $^{22}$Ne settling time to the time it takes to accumulate the fuel, $t_a = 4\pi G M P / g^2 M$. The ratio of these timescales gives

$$\frac{\Delta t}{t_a} \approx 150 \frac{P}{M_{\odot}} \left( \frac{M}{10^{-9} M_{\odot}} \right) \left( \frac{2 \times 10^{29} \text{ ergs cm}^{-2}}{P} \right)^{0.3},$$

where we have written the pressure in units of the typical ignition pressure (Livio 1994). Thus, for $M > 10^{-11} M_\odot$ yr$^{-1}$ (which applies to most classical novae; Livio 1994), the underlying C/O material should have $^{22}$Ne present at $X_{\text{Ne}} \approx 0.02$, allowing for neon enrichment on a C/O WD in those classical novae that are constantly undergoing dredge-up.

4. LUMINOSITIES FROM FALLING $^{22}$Ne IN COOLING WHITE DWARFS: SEDIMENTARS

The rate of energy release from the falling $^{22}$Ne is given by the integral of the power, $F V$.

$$L_e = \int F V n_{\text{Ne}} 4\pi r^2 \, dr.$$

Since the $^{22}$Ne settling time is longer than the time it takes to cool to the onset of crystallization in the core [about 2 (0.3) Gyr for a 0.6 (1.2) $M_\odot$ WD; Benvenuto & Althaus 1999], we presume that the abundances are nearly unchanged from the initial state. This integral is evaluated with $X_{\text{Ne}} = 0.02$ and the core temperature $T_c$ being constant. For a pure oxygen WD at $T_c = 10^4$ K, this gives $L_e = 1.1 \times 10^{39}, 5.9 \times 10^{38}, 1.2 \times 10^{38}$, and $4.6 \times 10^{38}$ ergs s$^{-1}$ for $M = 0.6, 0.8, 1.0, \text{ and } 1.2 M_\odot$.

For massive WDs, $L_e$ becomes comparable to the cooling luminosity $L_T$ for the same $T_c$. This raises the important question of how much the settling luminosity can affect the WD cooling curves and thus the inferred age of the Galactic disk from the faint end of the WD luminosity function (see Leggett, Ruiz, & Bergeron 1998 for a recent overview).

We begin with the common 0.6 $M_\odot$ WDs. The hatched region in the top panel of Figure 2 shows $L_e$ for $X_{\text{Ne}} = 0.02$ as a function of $T_c$. The upper (lower) bound of the hatched region is for a pure carbon (oxygen) WD and denotes the range of possibilities for arbitrary C/O mixtures. The sharp downturn at $T_c \approx 3-4 \times 10^4$ K is due to core crystallization. We allow for sedimentation only in the liquid parts of the WD so that, as $T_c$ decreases and the solid core increases, $L_e$ decreases. If we allowed for continuing sedimentation throughout the solidifying WD, the hatched region would just continue to the left.
Fig. 2.—Luminosity from $^{22}$Ne settling in a 0.6 $M_\odot$ (top panel) and 1.2 $M_\odot$ (bottom panel) WD with $X_0=0.02$. The hatched region shows the luminosity from $^{22}$Ne settling as a function of WD core temperature. The upper (lower) bound is for a pure carbon (oxygen) WD and should bracket the range of possible C/O mixtures. The dashed lines are the $T_c - L$ relations for cooling DA WDs from Benvenuto & Althaus (1999). Both have helium layers of $M_{\text{He}} = 10^{-7} M_\odot$, while the 0.6 (1.2) $M_\odot$ WD has a hydrogen layer mass of $10^{-11}$ ($10^{-6}$) $M_\odot$. The 0.6 $M_\odot$ model is close to that of Hansen (1999) and Chabrier et al. (2000).

with the same slope. The dashed line is the $L-T_c$ relation for a cooling 0.6 $M_\odot$ WD (see caption). For 0.6 $M_\odot$, $L_c$ is always at least a factor of 10 lower than the exiting luminosity $L$ at that $T_c$.

However, this competition gets closer as the WD mass increases. The bottom panel of Figure 2 shows the same curves for 1.2 $M_\odot$. In this case, $L_e$ is a factor of 5 or so smaller than $L_c$, which means that the WD cooling trajectory would be affected considerably. It is a coincidence that $L_e$ drops off before becoming dominant and then remains nearly parallel to the $L-T_c$ relation. This would not occur in a pure helium WD, as crystallization never sets in. However, in that case, there would be no $^{22}$Ne present. It would just be the settling of the other, less abundant, neutron-rich metals, such as $^{56}$Fe. Although it appears unlikely that the settling of iron will modify the cooling of a low-mass helium ($M < 0.4 M_\odot$) WD, substantial settling will occur in 1 Gyr.

The point we wish to make here is that the uncertain microphysics of the diffusion coefficient clearly allows for an alternative view of cooling for massive WDs. Namely, it is possible that the settling luminosity can heat a WD well enough to keep it in the liquid state for a very long time. For example, increasing $D$ by a factor of 6 for the 1.2 $M_\odot$ WD would shift the $L_e$ curves up enough so that the WD could be powered by sedimentation alone—hence, we dub these solutions “sedimentars.” Or, if we allow for continued sedimentation once the core is supposedly solid (say, it is supercooled), the lines would intersect at $L \approx 2 \times 10^{-9}$ erg s$^{-1}$ for a 1.2 $M_\odot$ WD, which would then take a time in excess of 10 Gyr to radiate all of the sedimentation energy. This sedimentar would live for many gigayears at an effective temperature of 11,350 K. For a pure oxygen 1.36 $M_\odot$ WD, this crossover would occur at $L \approx 10^{-11}$ ergs s$^{-1}$ or $T_{\text{eff}} \approx 21,000$ K, still too cold to help explain the possible excess of hot, massive WDs reported by Vennes (1999).

5. CONCLUSIONS

Our initial calculations suggest a number of important problems to address in the future. The coincidence of the settling time with the Hubble time forces us to reconsider the physics of the interdiffusion coefficients, especially in the quantum liquid realm. This is critically important for the cooling of massive WDs, where there is some chance for the WD to shine for gigayears on the power of $^{22}$Ne sedimentation. These gravitationally powered sedimentars would be a new astrophysical object that behave differently than the conventional cooling WD.

The time-dependent evolution of the $^{22}$Ne abundance in different astrophysical settings is the subject of our future work. In that paper, we evolve both cooling and accreting WDs with active $^{22}$Ne settling. This will allow for an accurate calculation of the evolution of the $^{22}$Ne abundance from starting conditions that reflect the prior stellar evolution. For cooling WDs, we can follow the $^{22}$Ne throughout the star as it crystallizes and assess the possibility of altering the nature of the phase separation at freezing via enhanced $^{22}$Ne abundances.

The downward diffusion speed is very slow, and it is natural to question whether such slow speeds are actually relevant. We believe so, as there is no expectation for active convection to undo it. Comparably weak diffusive settling also appears in the Sun, where inclusion of the slow gravitational settling of helium dramatically improves the agreement of the solar interior model with that measured by seismological inversions (Christensen-Dalsgaard et al. 1996; Basu, Pinsonneault, & Bahcall 2000).

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