MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

The impact of non-ideality effects in dense plasma on the evolution of white dwarfs

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Abstract. Recently made possible observations of cool and faint white dwarfs using the Gaia and other telescopes provide rich material for refining the modeling of the final stage of their evolution, which in turn can be used to study the behavior of matter under extreme conditions. In this paper, we simulate the thermal evolution of white dwarfs for different atmospheric compositions using equations of state for non-ideal dense plasma. By taking into account the effects of non-ideality in the code for the evolution of white dwarfs, it is possible to reach the stage of crystallization at the center of the star. The subsequent acceleration of cooling is significant for massive white dwarfs ($M \approx 1.3\,M_{\odot}$), for which the cooling time at $T_{\rm eff} \approx 3 \times 10^3$ K decreases almost 10 times compared to the calculation without non-ideality effects.

Keywords: stars: evolution, white dwarfs; dense matter; equation of state; plasmas

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1 Introduction

Gradually cooling down throughout their lives, white dwarfs (WD) reach temperatures of several thousand Kelvin on the surface and ages of the order of the age of the universe. Studying the population of these stars can make it possible to reconstruct the history of Galaxy formation, cosmochronology, and investigate the properties of plasma under conditions unattainable on earth. The coldest objects found so far have temperatures of $T_{\text{eff}} \approx 3050$ K and $T_{\text{eff}} \approx$ 3340 K and the age of about 10 and 9 billion years old, respectively (Elms et al. 2022). In such stars, plasma can pass into the liquid or crystal phase. A large number of observational data requiring explanation on the one hand, as well as the most accurate theories of the plasma state on the other, lead to a demand for the creation of detailed models of the evolution of white dwarfs up to the late stages of cooling, when non-ideality and quantum effects on.

In this paper, the thermal evolution of white dwarfs is modeled using the code created by S. I. Blinnikov and N. V. Dunina-Barkovskaya, which allows to calculate the cooling of white dwarfs on time scales of the order of the age of the universe (Blinnikov & Dunina-Barkovskaya 1993, 1994). Blinnikov's models were originally created for hot white dwarfs. For such objects, plasma can be described by the equation of state of Nadyozhin for an ideal gas, since Coulomb interactions between particles can be neglected (Blinnikov et al. 1996). However, at later stages of evolution, when the temperature decreases it becomes necessary to take them into account, and a different equation of state is needed.

Taking the equation of state for a non-ideal plasma, we have obtained a noticeable decrease in cooling time, which is especially pronounced for massive objects. This is an expected result, since there is a Debye suppression of the heat capacity for a low temperature crystal, which should lead to faster cooling.

Section 2 describes the equations of state and the operation of the program. Section 3 presents obtained evolutionary curves. In Section 4, we discuss the results and consider opportunities for further improvement of the models.

2 The technical part

The construction of models is done in three stages: first, we take the equation of state of matter, then an initial object is created from it, and then its evolution is considered.

We replaced the code block responsible for the equation of state of matter, using Potekhin–Chabrier equations of state (version 2022). These analytical equations for non-ideal plasma allow to calculate the stages of a Coulomb liquid and a crystal consisting of atomic nuclei and a homogeneous electron background, and also take into account quantum effects that are important for late stages of the evolution of WD (Potekhin & Chabrier 2013). The code for the equation of state is publicly available.[1]

For detailed calculations of the evolution, the code uses differential hydrodynamic equations in Lagrangian form for a spherically symmetric star. To start evolution, it is necessary to build initial artificial hydrostatic models, for which cooling is further simulated. These models are built using the Nadyozhin–Razinkova method, the initial radius of the simulated object is much larger than the typical radii of white dwarfs (Nadyozhin & Razinkova 1986).

An important value for describing matter in white dwarfs is the non-ideality parameter Γ, or the Coulomb coupling parameter. This quantity shows the ratio of the forces of interaction between particles to their kinetic energy, showing the degree of applicability of the ideal gas approximation to the description of matter.

For ions, the value of the Coulomb coupling parameter will be as follows:

$$\Gamma_i = \frac{(Ze)^2}{a_i k_B T} = \Gamma_e Z^{5/3}, \tag{1}$$

where a_i is the average distance between ions, $a_i = \left(\frac{4}{3}\pi n_i\right)^{-1/3}$, T and n_i are the temperature and concentration of ions respectively, Γ_e is the Coulomb coupling parameter for electrons.

At $\Gamma << 1$, matter can be described with good accuracy using the ideal gas approximation. Crystallization begins at $\Gamma \approx 180$ (Segretain & Chabrier 1993; Potekhin & Chabrier 2010).

3 Results

The initial models of objects, for which cooling was subsequently calculated, did not differ from each other for the Potekhin and Nadyozhin equations of state, since the effects of non-ideality appear only when the white dwarf has cooled sufficiently so that the interaction between the particles becomes significant.

Figure 1 show the series of obtained cooling curves for luminosity for different values of the mass of a white dwarf and different atmospheric compositions.

For the ages of the white dwarf of the order of a billion years, the differences between models with different equations of state are practically not noticeable, since the white dwarf is still hot enough for Coulomb interactions between particles not

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[1] http://www.ioffe.ru/astro/EIP/

to play a role in it. However, later there is a significant increase in the cooling rate for models with the Potekhin equation of state. The crystallized matter cools down faster, as the thermal conductivity decreases according to Debye's law.

The more massive the white dwarf is, the higher the pressure and Coulomb coupling parameter values in it, and the faster it will reach a stage at which Coulomb interactions between particles will be commensurate with kinetic energy. Therefore, the most significant difference between the models is for massive white dwarfs.

Also in Fig. 1, models are shown for two chemical composition options: with a thin ($q_{\rm H} = 10^{-10}\, M_\odot$, $q_{\rm He} = 10^{-2}\, M_\odot$) and a thick layer of hydrogen ($q_{\rm H} = 10^{-4}\, M_\odot$, $q_{\rm He} = 10^{-2}\, M_\odot$). It can be seen that the thick hydrogen-helium shell of the white dwarf slows down cooling due to the high opacity value.

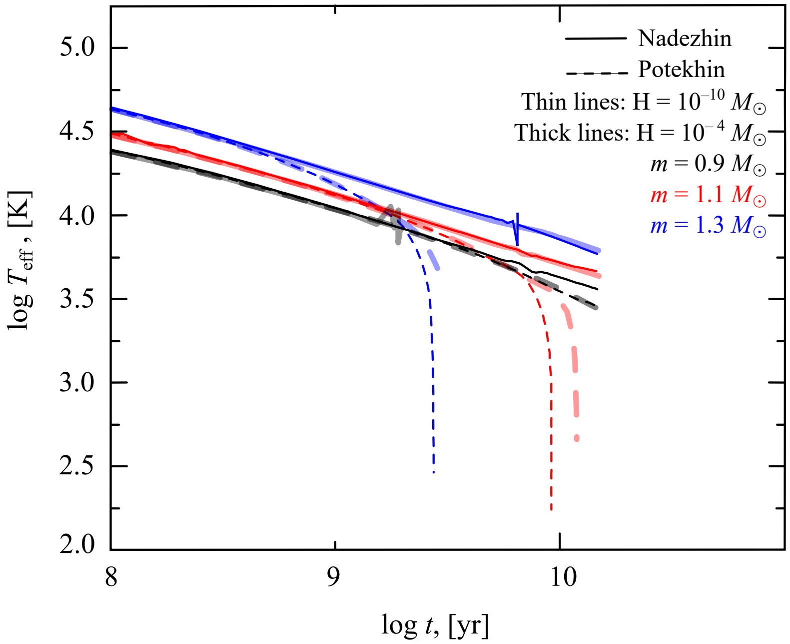

Fig. 1. Dependence of the logarithm of luminosity on the age of white dwarfs. Different colors correspond to models with different values of stellar mass. Dashed curves correspond to models with the Potekhin equation, solid curves correspond to models with the Nadyozhin equation. Thin and opaque curves were plotted for the thin shell model with $q_{\rm H} = 10^{-10}\, M_\odot$, $q_{\rm He} = 10^{-2}\, M_\odot$, thick and translucent corresponds to a model with a thick shell with $q_{\rm H} = 10^{-4}\, M_\odot$,$q_{\rm He} = 10^{-2}\, M_\odot$.

Figure 2 shows a comparison between the evolutionary tracks obtained from three models: with the equation of state of Nadyozhin, Potekhin and the Bergeron model (all models are constructed for a thin layer of hydrogen in atmospheres) (Fontaine et al. 2001; Bédard et al. 2020). For medium-mass white dwarfs, it can be seen that Bergeron models show faster cooling, since our models do not calculate convection, so the white dwarf reacts slowly to the release of heat in the core, which is of great importance for such objects. For objects with masses 1.0 $M_\odot$ and higher, stars in the model with Potekhin's equation of state cool faster. It is in this range of parameters that the effects of plasma non-ideality are most clearly manifested due to the changes in the heat capacity of the crystal.

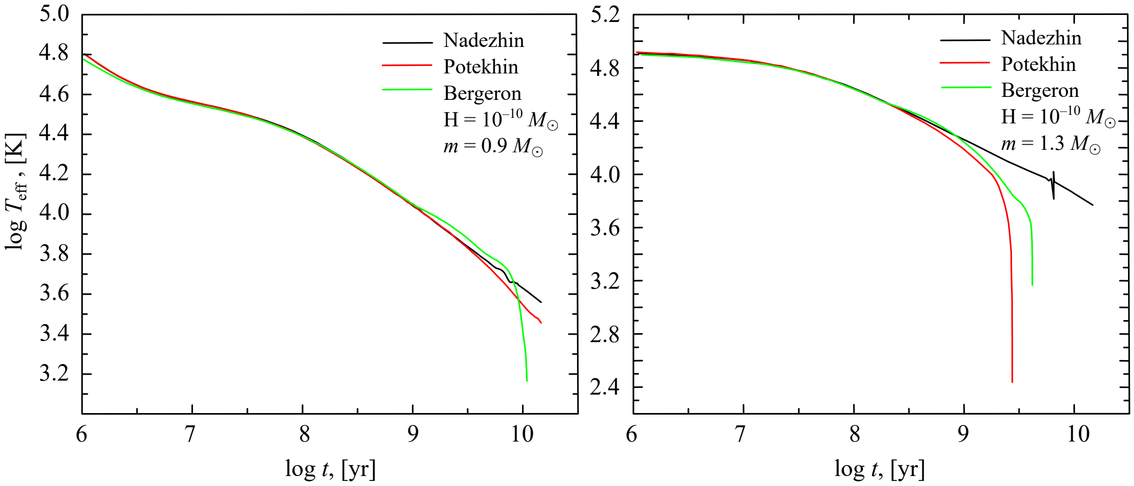

Fig. 2. Dependence of the logarithm of the effective temperature on the age of the white dwarf for three models: the Bergeron model (green line), the model with the Potekhin state equation (red line), the model with the Nadyozhin equation of state (black line) for different masses and thin atmospheres with the masses of hydrogen and helium, respectively $q_{\mathrm{H}} = 10^{-10}\, M_\odot$, $q_{\mathrm{He}} = 10^{-2}\, M_\odot$.

4 Discussion

We simulated the evolution of white dwarfs using the equation of state for non-ideal dense plasma. This made it possible to reproduce the crystallization and Debye cooling phases.

Our cooling curves do not account for convection, so heat transfer is not as efficient and fails to reproduce the peak in luminosity from the release of latent heat of the phase transition. This also explains the differences from the cooling curves obtained by Bergeron's group for medium-massive white dwarfs. In the region of Debye cooling for massive white dwarfs, our model predicts a faster cooling rate than other studies.

There are ways to further improve the model and account for more subtle effects. Convection must be taken into account to correctly describe the transfer of heat from the interior of a white dwarf to the surface. Also, used equation of state makes it possible to simulate multicomponent plasma (up to 10 elements). Our code uses only mixtures of oxygen and carbon.

Adding neon to the core of a white dwarf and taking diffusion into account makes it possible to run processes such as neon settling and separation of liquid and crystalline phases, which leads to the release of gravitational energy. This factor also affects the cooling rate, so it is taken into account in many works (Bauer 2023), (Camisassa et al. 2022).

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