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Article

Keywords:

Posted Date: March 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9123221/v1

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Additional Declarations: There is **NO** Competing Interest.

Magnetic White Dwarfs as Indicators of the Evolution of the Galaxy's Magnetic Properties

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Abstract

Cool (old) white dwarfs with strong large-scale magnetic fields (MWDs) demonstrate, on average, significantly higher field strengths and frequency of occurrence than hot (young) MWDs, despite the fact that the magnetic fields and abundance of such stars should, theoretically, decrease over time. In a series of previous papers we proposed an explanation for this effect by the gradual slowdown of the thermal evolution of MWDs due to magnetically induced suppression of their surface convection. Our modeling showed that this mechanism can explain the increase in the occurrence of extremely cool MWDs. Meanwhile, observations reveal an increasing number of MWDs among significantly younger stars of this class. In this work, we revisit this problem. Unlike previous models, where the birth probability of MWD progenitor stars was considered independent of the age of the Galaxy, we account for the decreasing probability of occurrence of strongly magnetic stars (MWD progenitors) with the age of the Galaxy. Introducing this parameter allowed us to describe the increase in the occurrence of MWDs. This result argues that the population of massive MWD progenitor stars decreases with the age of the Galaxy, apparently due to the weakening of its magnetic properties in the process of evolution.

MAIN

Most moderate- and low-mass stars in the Galaxy end their evolutionary journey as white dwarfs (WDs). This class of stars has been studied sufficiently to understand its fundamental characteristics; however, a number of unanswered questions remain. One such question concerns the origin of isolated white dwarfs with strong large-scale magnetic fields (MWDs), whose strengths exceed tens of kilogauss or more [1-16]. Early studies suggested that MWDs are the final stage in the evolution of magnetic Ap/Bp stars [1] (as with MWDs, from here on, by magnetic stars we mean any stars with spectropolarimetrically detectable large-scale magnetic fields, not local ones like those of solar-type stars). Later studies showed that MWDs can be

descendants of stars of other classes [3, 17-18], and also formed as a result of the merger of two WDs [19-22].

Studies devoted to the evolution of MWDs have revealed several peculiarities. One of these is an increase in the frequency of occurrence of these objects with age [3, 20, 23-25]. While theory suggests [26-27] that the magnetic fields of white dwarfs should decay with time, observations indicate an increase in the proportion of MWDs in the overall age distribution of the WD population with age. Several mechanisms have been proposed to explain this strange manifestation of MWD magnetism. One of the most discussed mechanisms to date is that, as a white dwarf cools thermally, its magnetic field begins to grow due to a dynamo during the growth phase of the star's crystalline core [8]. This idea probably has a right to exist, but it has two problems that, in our opinion, are jointly insoluble. The first problem is that, in our opinion, the crystallization energy of the core of a cooling degenerate star is not sufficient to generate magnetic fields that are two orders of magnitude greater than those characteristic of young/hot MWDs still in the liquid phase (for an illustration, see Figure 11 in Kepler et al.[8]). And the second problem is that even if the authors [8] are right, why do only four percent [8] of white dwarfs exhibit such powerful generation?

Another mechanism for explaining the overestimated number of MWDs in the convective (cold) phase of their evolution is the blocking of convective heat transfer to the MWD surface by a strong magnetic field [7]. The idea is simple. In the radiative phase of white dwarf evolution, as it cools to temperatures of approximately 10,000–12,000 K, both highly magnetic MWDs and weakly magnetic, ordinary white dwarfs evolve in approximately the same way. Meanwhile, for lower-temperature white dwarfs, in which their outer layers are engulfed in convection, strong magnetic fields can significantly slow down, or even completely stop, the convective transfer of energy from their interiors. As a result, in this phase, MWDs significantly slow down the rate of evolutionary cooling and accumulate in excess, compared to their weakly magnetic counterparts [7].

Meanwhile, despite its apparent obviousness, the idea of slowing down the cooling of MWDs in the convective phase by a magnetic field also has critical remarks [28], according to which external convection does not participate in the process of heat removal from the interior of the white dwarf until convection reaches the isothermal core, establishing convective coupling with it. This coupling, according to the authors [28], occurs under conditions when the white dwarf has cooled to temperatures below 5500 K. If the magnetic field is strong enough (more than 1–2 MGs) to stop convection, convective coupling with the core will never be achieved. In this case, starting from the indicated temperatures, the rate of evolution of MWDs will slow down compared to its weakly magnetic counterpart. The frequency of occurrence of such MWDs

will indeed be higher as a result. However, there are still very few such cold magnetic white dwarfs evolutionarily in our Galaxy, therefore the high frequency of occurrence of MWDs, starting immediately from temperatures below 8000K, according to the authors [28], cannot be explained by magnetic effects.

In continuation of the study of the issue of blocking heat removal from the interiors of MWDs by a magnetic field, it was recently shown [29] that convective coupling occurs at temperatures significantly higher than previously predicted [28]. Furthermore, we consider the argument that the magnetically induced stoppage of surface convection before the onset of coupling with an isothermal core does not affect the rate of thermal evolution to be questionable. The argument that the adiabatic regime of surface convection, occurring without heat exchange with the environment, does not affect the thermal evolution of a white dwarf is indisputable. However, in the case of blocking surface convection, the adiabatic temperature gradient will inevitably rearrange itself in the direction of the radiation gradient, which is by definition greater than the adiabatic one. This means that if the external convection of a white dwarf is stopped by a magnetic field, the temperature from the interior to the surface will decrease faster than in the presence of convection. This will lead to reddening and, consequently, a decrease in the rate of heat loss to the surrounding space. Hydrostatic equilibrium, in the absence of thermonuclear combustion in the white dwarf's interior, can persist indefinitely. Therefore, we believe that the impact of surface convection blocking on the rate of thermal evolution of MWDs still requires comprehensive study.

In light of the above, we undertook theoretical modeling of the evolution of a population of MWDs, taking into account the suppression of convection by a magnetic field [30-31]. The modeling object was the MWD luminosity function and its comparison with the standard white dwarf luminosity function [30-31]. The details of the modeling are described in the Methodology section. Here, before presenting the results, we briefly discuss our choice of the luminosity function as an evolutionary test.

The luminosity function gives the distribution of stars in a unit volume as a function of their absolute magnitude [32]. For a population of white dwarfs with a relatively small range of radii, absolute magnitude, with an uncertainty of up to one magnitude, is a fairly reliable indicator of their age. Direct age calculations, especially for white dwarfs with strong magnetic fields, are much more model-dependent, and so we did not use them.

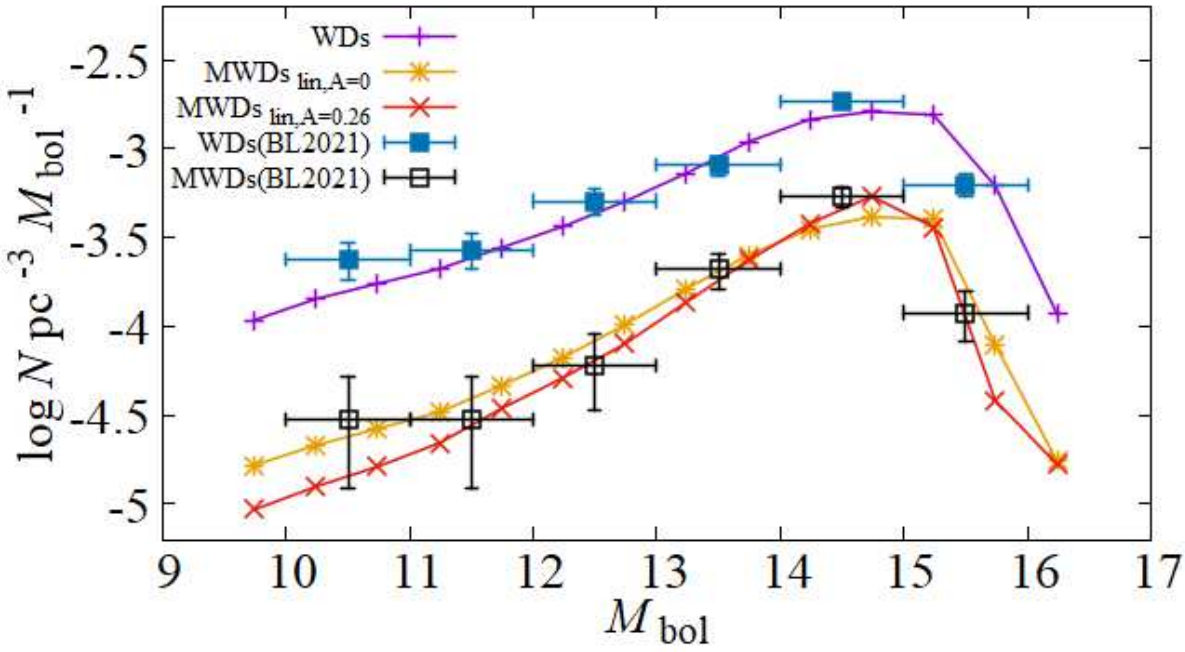


Fig. 1: Observed (symbols with error bars) and synthesized (solid lines) luminosity functions for known white dwarfs in the solar neighborhood of radius 20 pc (BL2021 [33]). The filled blue squares with vertical and horizontal error bars illustrate the observed luminosity function for the entire sample of white dwarfs. The solid purple line is its model. The empty black squares with vertical and horizontal error bars illustrate the observed luminosity function of MWDs in the considered volume. The orange line is the model taking into account the monotonic decrease in the birth rate of MWD progenitor stars during galaxy evolution. The red line is the same with the inclusion of the convection suppression process.

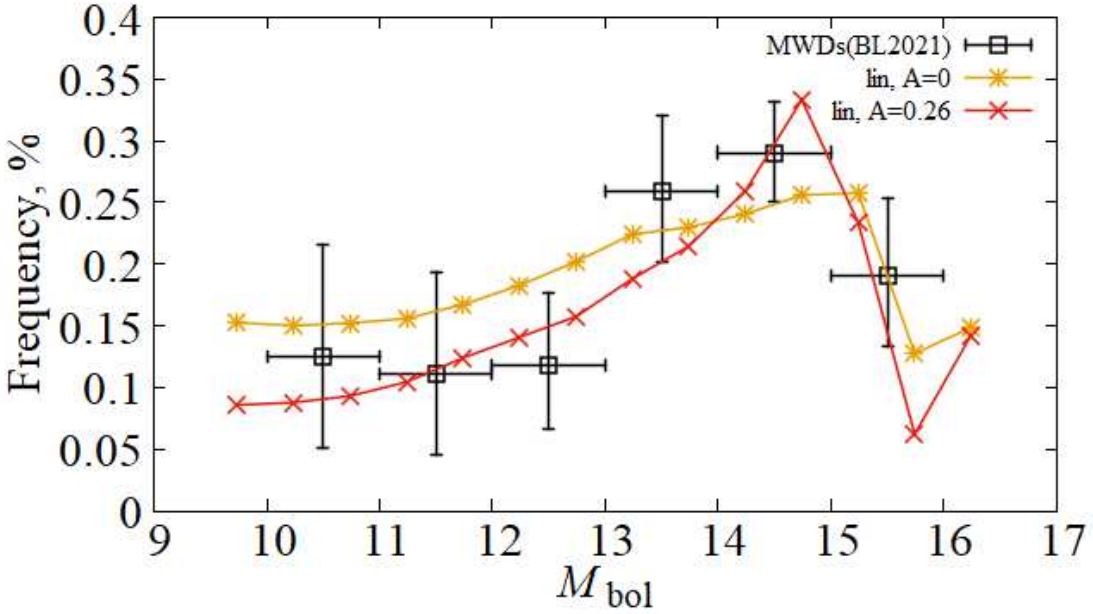


Fig. 2: Observed (symbols with error bars) and synthesized (solid lines) occurrence rates for known white dwarfs in the solar neighborhood of 20 pc (BL2021 [33]). Six empty squares with vertical and horizontal error bars in black illustrate the observed occurrence rates of MWDs as a function of their absolute

magnitude. The orange solid line is the model occurrence rate of MWDs, taking into account the monotonic decrease in the production of their progenitor stars with large-scale magnetic fields during the evolution of the Galaxy. The red line is the same, but with the convection suppression process included.

In previous studies [30-31], we simulated and compared with observations the luminosity function of MWDs under the assumption that convection is suppressed by their strong (from several to hundreds of megagauss) large-scale magnetic fields. An empirically selected parameter A, the cutoff function for the fraction of convective energy removal relative to the case with zero magnetic field [30], was used as the suppression factor. The parameter A = 0 corresponds to the case with zero magnetic field. The value A = 1 corresponds to the case of convection completely stopped by the magnetic field. For comparison, we used the observed and theoretically calculated frequencies of occurrence of MWDs as functions of their absolute stellar magnitude. The theoretical frequencies were obtained by dividing the synthetic luminosity function of MWDs by the standard luminosity function of white dwarfs. The simulated frequencies were compared with the frequencies obtained from observations. As a result, for the case of extremely large values of the parameter A (A>0.8), we obtained a sharp increase in the frequency of occurrence in the region of the coldest/oldest white dwarfs with effective temperatures T_{eff} below 6000 K. In the temperature range of 6000–8000 K, however, we did not obtain an increase in the number of MWDs, but rather their deficit, which is associated with their reddening due to the suppression of convection by the magnetic field and a more rapid shift of this population of MWDs to the right on the scale of absolute stellar magnitudes $M_{bol}=12^m.0–13^m.5$ (see Fig. 3 in [30]). For absolute magnitudes greater than $13^m.5$, the population of MWDs begins to grow again due to the slowing down of their lifetimes and in the region of $M_{bol}>15^m.0$ begins to demonstrate an excess, which is reflected in an increase in the frequency of their occurrence on the scale of absolute stellar magnitudes. Observations demonstrate an increase starting from $M_{bol}>13^m.0$.

An attempt to explain the observed apparent discrepancy between theory and observation by underestimating the presence of chemical fractions heavier than hydrogen (in particular, helium) in the outer envelope of white dwarfs also failed to yield a positive solution. Therefore, we attempted to search for an alternative mechanism that, within the framework of the hypothesis of the relic nature of MWD magnetic fields, could explain the observed frequency distribution of MWDs by age. Such a mechanism was found.

A number of studies [34-36] of magnetic stars conducted at the Special Astrophysical Observatory of the Russian Academy of Sciences have shown that the birth rate of medium- and large-mass stars with strong large-scale magnetic fields (it is from these stars that MWDs are

subsequently born) in young regions of active star formation is twice as high as that of field stars [36-37]. Surface fields also have higher intensities. The physics of the process is clear. Such active regions with powerful gas-dust turbulent centers of star formation may well generate significant relic magnetic fields. The subsequent collapse of these highly magnetized clouds into stars will produce an increased number of magnetic Ap/Bp stars, compared to the highly evolved field stars. Assuming that the processes of generating strong magnetic fields in young local regions of active star formation, for example in the Orion Nebula, illustrate global processes of magnetic star formation in the initial epoch of the evolution of our Galaxy, we took this difference as a basis for modeling the observed luminosity function of MWDs.

It is generally accepted [38] that the early stages of the birth and evolution of our Galaxy were accompanied by violent turbulent processes of fragmentation of colossal masses of gas and dust clouds with their subsequent collapse into stars. It is obvious (although this has not yet been sufficiently studied) that the energy of interstellar magnetic field generation under such conditions at the time of the primary formation of the Galaxy was higher than at present. All this argues for the idea that the oldest massive main-sequence stars had large-scale magnetic fields and, accordingly, the frequency of occurrence of such stars was significantly higher than at present. Billions of years of Galaxy evolution, a gradual decrease in the energy of magnetic field generation in the interstellar medium and the general ohmic attenuation of relic fields with age should lead to the fact that stars with large-scale magnetic fields, from which MWDs will subsequently arise, become less magnetized and the frequency of their detection will decrease. This idea formed the basis for testing our model method by considering the variable occurrence rate of MWD progenitor stars over time.

RESULTS AND DISCUSSION

In our model, in which previously [30-31] the birth rate of magnetic stars-progenitors of MWDs was considered independent of time, we introduced a variable linear function of decrease of this rate with time. Since the birth rate of magnetic stars with time is unknown, we tried various coefficients of this function. Preference was given to those for which the model luminosity function better corresponded to the observed luminosity function of the MWD (black squares in Fig. 1). The resulting values of the birth rate of magnetic stars were P=52% at the initial moment, and P=21% at the present moment of the Galaxy evolution. The results of the modeling are presented in Figs. 1, 2 of this study. Fig. 1 shows the observed and synthesized luminosity functions for known white stars in the solar neighborhood with a radius of 20 pc (BL2021 [33]). The observed luminosity function for the entire sample of white dwarfs in this volume (blue squares with error bars) is described by the standard model without considering the

magnetic properties of MWDs (solid purple line). The orange line is a model that takes into account the monotonic decrease in the production of MWD progenitor stars with large-scale magnetic fields. Figure 2 presents the observed and synthesized occurrence rates from the same volume. Six squares with vertical and horizontal error bars in black illustrate the observed occurrence rates of MWDs as a function of their absolute stellar magnitude. The solid orange line is the model occurrence rates of MWDs that take into account the monotonic decrease in production during the evolution of their progenitor Galaxy. The effect of convection suppression is not included in this version of the calculation.

As can be seen from the comparison of the model with observations, introducing the reduction coefficient for the probability of birth of a highly magnetized MWD progenitor star into the calculation qualitatively explains the observations. Meanwhile, as can be seen from Fig. 2, the observed contrast remains unsatisfactory. Including the process of reduction of heat removal by convection in the model completely agrees the model with observations. Figure 2 presents a model with a variable birth rate of magnetic MWD progenitor stars and taking into account magnetically induced convection inhibition (red line). The star formation and convection suppression parameters were also selected to better fit the observed MBC luminosity function (black squares). The resulting value of the cutoff function parameter A = 0.26 and the birth rate of magnetic MWD progenitor stars P = 59% at the initial stage, and P = 10% at the present moment of the Galaxy's evolution. It is worth noting that the resulting birth rate in modern times corresponds to the frequency of occurrence of magnetic stars in the upper part of the main sequence (10% [39] and references therein).

The obtained result, on the one hand, explains the long-discussed phenomenon of the uneven distribution of MWD occurrence with their age. On the other hand, it illustrates an algorithm for studying the global properties of the Galaxy's magnetism during its evolution. Of particular interest is the fact that the model of an evolutionary decrease in the number of magnetic Ap/Bp stars – the progenitors of MWDs – with the age of the Galaxy, supported by the mechanism of convective suppression of energy removal from the white dwarf's interior, ultimately perfectly explains the observed frequency distribution of MWDs during their evolutionary cooling and the 10% fraction of the number of Ap/Bp magnetic stars in the modern Galaxy. Ignoring convection in our model yielded an incorrect estimate of this fraction. This study, therefore, argues, among other things, for the need to revise the MWD cooling theory for the case of strong magnetic fields.

METHODOLOGY

A method for modeling the WDs luminosity function is described, for example, in [40]. The function integrates the convolution of the white dwarf mass distribution with the star formation rate and the derivative of the cooling time with respect to stellar magnitude. Similar to [40–42], we used the power-law mass distribution described in [43] with an exponent of −2.35. The distribution for MWDs was taken from [44]. As initial data on the cooling times, we used the sequences [41] for low-mass WDs, up to 1 $M_{\odot}$, with CO cores and the dependence presented in [45] for massive ones with ONe cores (M = 1.06–1.28$M_{\odot}$).

In this paper, we investigated the influence of the birth rate of MWD progenitor stars on their occurrence during evolutionary cooling. We considered various variants of the linear decline in their birth rate with increasing age of the Galaxy. To construct the luminosity function of non-magnetic WDs, we used a constant star formation rate similar to [40-42]. The luminosity function for each specific stellar magnitude was calculated as follows:

1. From all known WD cooling sequences for fixed masses [41, 45], sequences for intermediate-mass WDs were formed by linear interpolation. Derivatives of the cooling time with respect to absolute stellar magnitudes were linearly interpolated based on the resulting sequences.

2. The calculation was performed only for the Galactic disk population, since we are dealing with the immediate solar environment. If the cooling time for a given mass and magnitude, combined with the time the star spent before the WD stage, exceeded the disk age (9.3 billion years, [41]), then the value of the integral at this point for a given mass was set to zero.

3. The star formation rate of MWDs was determined by fitting the rate of decline of their formation rate with the age of the Galaxy. Using the least-squares method, the resulting functions were compared with the observed luminosity function presented in [33]. For the luminosity function of non-magnetic WDs, we achieved consistency with the luminosity function from [46].

4. Convection suppression was accounted for using the empirical model described in [30]. In the case of suppressed convection, the star formation parameters of the MWD progenitor stars were selected independently.

5. The resulting MWD occurrence rates as a function of absolute magnitude were obtained by dividing the MWD luminosity function by the luminosity function modeled for all WDs.

ACKNOWLEDGMENTS

This work was supported by the Russian Science Foundation (RSF), project No. 25-12-00003. Observations at the SAO RAS telescopes are supported by the Ministry of Science and Higher Education of the Russian Federation.

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