White dwarf constraints on a secularly varying gravitational constant

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A secular variation of the gravitational constant modifies the structure and evolutionary timescales of white dwarfs. Using an state-of-the-art stellar evolutionary code we compute white dwarf cooling sequences with a varying G. White dwarf evolution is computed in a self-consistent way, including the most up-to-date physical inputs, non-gray model atmospheres and a detailed core chemical composition that results from the calculation of the full evolution of progenitor stars. These fully evolutionary cooling sequences offer the possibility of measuring a hypothetical variation of the gravitational constant, by comparing our theoretical predictions with the observational data, and in particular with the observed luminosity function of disk white dwarfs. Using the most recent and reliable determination of the luminosity function of disk white dwarfs we derive an upper bound for the secular variation of the gravitational constant which compares well with those obtained using other stellar evolutionary properties.

Keywords: Stars; white dwarfs; gravity.

1. Introduction

The most widely accepted theory of gravitation, General Relativity, relies on the equivalence principle. This means that it is based on the assumption that the gravitational constant, G, is indeed a true constant, that does not depend on the location nor varies with cosmological times. Although this is a fair assumption it needs to be proved, as modern grand-unification theories predict that the gravitational constant is a slowly varying function of low-mass dynamical scalar fields[1,2]. For this endeavour we need stellar objects with well known physical characteristics, sensitive to the precise value of G, and preferably with very long evolutionary timescales, since the expected variation of G over cosmological time is small. Hence, white dwarf stars are best suited for this task, as they fulfill all three requirements.

During the last years, several constraints have been placed on the variation of the fine structure constant, and other constants of nature[2]. However, very few works have tried to set upper limits on a hypothetical secular variation of the gravitational constant. The most stringent bounds on such possible variation are those obtained using Lunar Laser Ranging[3] ($\dot{G}/G \lesssim (0.2 \pm 0.7) \times 10^{-12}$ yr^{-1}), helioseismology[4] ($\dot{G}/G \lesssim 1.6 \times 10^{-12}$ yr^{-1}), white dwarf asteroseismology[5,6] ($\dot{G}/G \lesssim 1.3 \times 10^{-10}$ yr^{-1}), and Big Bang nucleosynthesis[7,8] (-0.3×10^{-12} yr$^{-1} \lesssim$

$\dot{G}/G \lesssim 0.4 \times 10^{-12}$ yr^{-1}). However, Lunar Laser Ranging and asteroseismology provide only local limits, since they are limited to very nearby objects, whereas Big Bang arguments are model-dependent. At intermediate cosmological ages the Hubble diagram of Type Ia supernovae can also be used to constrain the rate of variation of the gravitational constant[9,10], but the constraints are somewhat weaker $\dot{G}/G \lesssim 1 \times 10^{-11}$ yr^{-1} at $z \sim 0.5$. Also, at intermediate distances the open, metal-rich, globular cluster NGC 6791 has been used to derive a competitive upper bound[11], $\dot{G}/G \lesssim 1.2 \times 10^{-12}$ yr^{-1}. Here we use the luminosity function of disk white dwarfs to place an upper limit to the secular variation of G. A clear advantage of using the disk white dwarf luminosity function is that it gathers information for the ensemble population of white dwarfs and does not rely on determinations made using individual objects. However, an obvious drawback of this technique is that it is limited as well to short distances, as we lack reliable observations for distant white dwarfs allowing an accurate determination of the luminosity function for large volumes. Nevertheless, the very large amount of data for distant white dwarfs that the astrometric satellite *Gaia* will collect in a near future[12] will allow deriving more precise, non-local upper bounds to $\dot{G}/G$.

2. Main sequence and white dwarf lifetimes

Any possible variation of G translates directly in the evolutionary times of stars. For the specific case of white dwarfs this effect is particularly noticeable[13,14], as the mechanical structure of these compact stars is supported by the pressure of degenerate electrons, which is sensitive to the value of G. Hence, any variation of G changes the hydrostratic equilibrium balance, and releases energy, that must be radiated away. Thus, since the evolution of white dwarfs is driven by the release of gravothermal energy their cooling rate is severely affected. However, being this effect important, there is another effect that also affects the total evolutionary times of white dwarfs. Specifically, the evolutionary properties of white dwarf progenitors are also modified by a rolling G, and particularly their ages[15,16] are markedly different when G varies over cosmological timescales.

We assessed the effects of a secularly varying G on the evolutionary timescales of white dwarf progenitors by computing the evolution in the main sequence of two model stars of 1.0 and $2.0\,M_{\odot}$. We considered three typical values of the rate of change of G, namely $\dot{G}/G = -5 \times 10^{-11}$ yr^{-1}, $\dot{G}/G = -1 \times 10^{-11}$ yr^{-1}, and $\dot{G}/G = -1 \times 10^{-12}$ yr^{-1}. All the evolutionary calculations were done using the `LPCODE` stellar evolutionary code[16,17], appropriately modified to deal with a varying G. Despite the small rates of change of G adopted here, the evolution of white dwarf progenitor stars is drastically modified. We found that the evolutionary timescales can be modelled using rather simple scaling arguments. In particular, it turns out that the main sequence lifetimes when a varying G is adopted can be well approximated by the following expression:[11]

$$\tau_{\rm MS} = \frac{1}{\gamma\left|\frac{\dot{G}}{G}\right|} \ln\left[\gamma\left|\frac{\dot{G}}{G}\right|\left(\frac{G_0}{G_i}\right)^{\gamma}\tau^0_{\rm MS}+1\right], \quad (1)$$

with $\gamma = 3.6$. In this expression G_0 is the present value of the gravitational constant, and $\tau^0_{\rm MS}$ stands for the progenitor lifetime computed using G_0.

For the white dwarf cooling times we adopted the most recent and reliable white dwarf evolutionary sequences available so far[14], which incorporate the most up-to-date physical inputs and were computed taking into account the effects of a secularly varying G self-consistently. Specifically, these cooling sequences consider ^{22}Ne diffusion and its associated energy release[16,18,19], as well as the effects of carbon-oxygen phase separation upon crystallization[20,21], and together with the main sequence lifetimes given by Eq. (1) allow us to derive accurate total ages for any reasonable value of $\dot{G}/G$.

3. Results

Fig. 1 displays, employing solid black lines, the theoretical white dwarf luminosity functions for several representative values of $\dot{G}/G$, ranging from 0 to -5×10^{-11} yr^{-1}, which encompass the plausible values for the rate of variation of G. In this figure we also show, using red dashed lines, the observed white dwarf luminosity function[22] for a sample of disk white dwarfs with distances smaller than 40 pc. This luminosity function is thought to be nearly complete. Hence, it provides a reliable measure of the density of white dwarfs as a function of the luminosity.

The observed white dwarf luminosity function has two prominent features. The first one is a monotonically increasing branch for moderately high luminosities — that is bolometric magnitudes $M_{\rm bol} \lesssim 14.7$ mag. This branch reflects the cooling rate of white dwarfs, and to a first approximation is proportional to the characteristic cooling time, $\tau_{\rm cool}$. Since the heat capacity of white dwarfs is mostly provided by the non-degenerate ions of the nearly isothermal core, and thus it is proportional to the core temperature, it is straightforward to realize that, as stars cool, the characteristic cooling time increases, and so does the number density of white dwarfs per unit bolometric magnitude. The second important feature of the observed white dwarf luminosity is a pronounced cut-off at low luminosities — say $M_{\rm bol} \simeq 17.0$ mag. This fall-off of the number counts of disk white dwarfs at low luminosities is not the consequence of observational limitations, but of the finite age of the Galactic disk, and can be employed to measure it[23,24]. The argument, nonetheless, can be reversed. If an independent estimate of the age of the Galactic disk is available, the cut-off of the white dwarf luminosity function can be employed to derive useful constraints on a varying G. The age of the Galactic disk can be estimated using nucleocosmochronology. Accurate determinations[25] of the age of the Galactic disk using this method suggest a relatively young disk. Specifically, the age of the Galactic thin disk obtained using Th/Eu nucleocosmochronology is

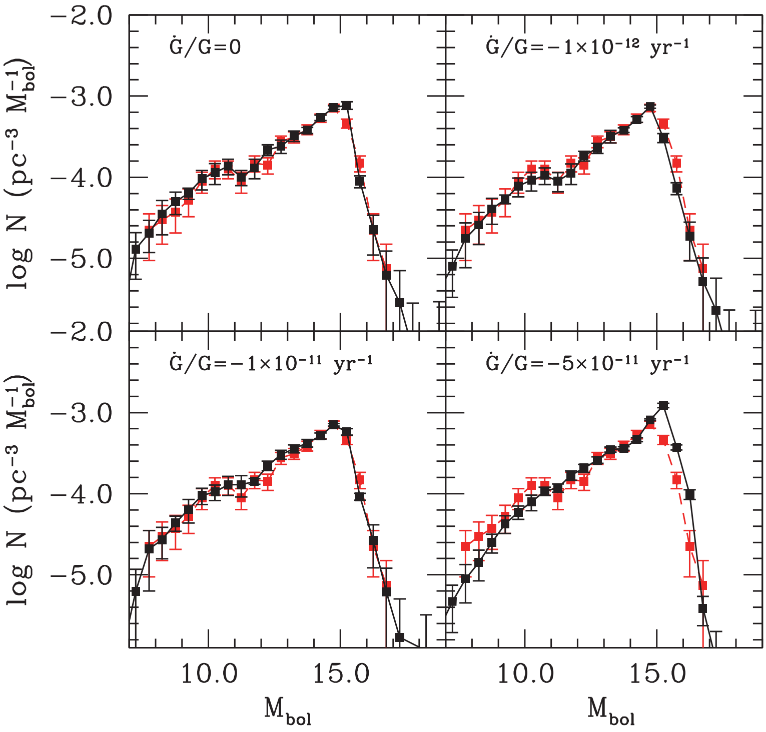

Fig. 1. Theoretical white dwarf luminosity functions for several values of $\dot{G}/G$ (solid black lines), compared to the observational luminosity function (dashed red line).

~ 8.5 Gyr. The theoretical luminosity functions presented in Fig. 1 have been computed using an age of the Galactic thin disk of 9.0 Gyr, in good agreement with this independent estimate.

As can be seen in the top left panel of Fig. 1, the agreement between theory and observations is excellent when $\dot{G}/G = 0$. We emphasize that our theoretical models reproduce all the salient features of the observed luminosity function, including the change in slope at $M_{\rm bol} \simeq 11$, which is due to a recent burst of star formation. Also, our calculations reproduce very well the maximum and the shape of the cut-off of the white dwarf luminosity function. As can be seen in the rest of the panels of this figure, when a value of $\dot{G}/G$ different from zero is adopted the bright portion of the white dwarf luminosity function remains essentially unaffected, but the amplitude of the maximum and position of the cut-off of the luminosity function change. This allows to place a constraint on the rate of variation of the gravitational constant, which turns out to be $\dot{G}/G \lesssim 2.0 \times 10^{-11}$ yr^{-1}.

4. Summary and discussion

In this work we studied how a possible variation with cosmological times of the gravitational constant affects white dwarf cooling. We have shown that the evolutionary timescales of cool white dwarfs are noticeably affected. We have also studied the impact of a variation of G on the progenitor ages of white dwarfs, and we have modeled the full evolutionary results employing scaling arguments, which lead to a simple and compact expression. Using these times we modeled the luminosity function of thin disk white dwarfs, and compared the resulting theoretical models with the observed data. We found that when $\dot{G}/G = 0$ is adopted the agreement between theory and observations is excellent (see Fig. 1). We then varied the value of $\dot{G}/G$ within a reasonable interval of values, and found that a rolling G modifies both the amplitude of the peak of the luminosity function and the position of its cut-off. By comparing these luminosity functions with observations we were able to obtain an upper limit to the rate of variation of G, $\dot{G}/G \lesssim 2.0 \times 10^{-11}$ yr^{-1}. This upper bound is less stringent than that obtained using the luminosity function of white dwarfs in the close, well-populated, metal-rich, open cluster NGC 6791, $\dot{G}/G \lesssim 1.2 \times 10^{-12}$ yr^{-1}. However, in a near future the European astrometric satellite *Gaia* will provide us with an unprecedented wealth of data for distant white dwarfs and, hence, this upper bound to the rate of variation of G could be easily improved.

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