# WHITE DWARF CONSTRAINTS ON DARK MATTER PARTICLES*

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Matter budget in the Universe together with primordial nucleosynthesis bounds on baryonic density suggests that dark matter in galaxies should have non-baryonic nature. On the other hand, considerable agreement of a variety of astrophysical observations with standard physics can serve as a source of constraints on non-standard ideas. In this context we consider G117-B15A pulsating white dwarf for which the rate of period change of its fundamental mode has been accurately measured. This star has been claimed the most stable oscillator ever recorded in the optical band. Here we use this object to derive a bound on theories with large extra dimensions as well as to constrain supersymmetric dark matter.

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## 1. Introduction

The existence of dark matter at galactic scales (dark halos) is now a well established fact. It is not only supported by flat rotation curves and other dynamical considerations but also by gravitational lensing clearly indicating that masses of galaxies acting as lenses for foreground sources (quasars) are greater than could be accounted for by their luminous constituents. The best-motivated non-baryonic dark matter candidates are Weakly Interacting Massive Particles (WIMPs), which are stable massive particles, neutral and weakly interacting with ordinary matter. Currently WIMPs are supposed to be of supersymmetric nature [1] (*e.g.* neutralino is a favorite one).

In this paper we present astrophysical constraints on such "exotic" physics obtained by means of pulsating white dwarf G117-B15A. Approaches from two different point of view are investigated. In the first case we consider

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possibility of production of new types of weakly interacting particles, such as Kaluz–Klein gravitons. It is done within the framework of the multidimensional ADD (Arkani-Hammed, Dimopoulos, Dvali [2]) model. If such particles were produced in stellar interiors they could serve as an additional source of energy loss. On the other hand, we also examine the case of a star immersed in a supersymmetric dark halo. This time we rather expect the existence of an additional energy source. Both effects could affect in many ways the course of stellar evolution.

## 2. G117-B15A as a tool for fundamental physics

Since discovery of its variability in 1976 G117-B15A has been extensively studied and its basic physical properties are quite well established (for references see *e.g.* [3, 4]). This star belongs to the class of DAV white dwarfs (*i.e.* pulsating white dwarfs with hydrogen atmosphere) which exhibit non-radial pulsations in g-modes. There are three fundamental modes observed with periods 215, 271 and 304 s, respectively. In our case the simplest, yet accurate enough Mestel law of white dwarf cooling $\mathcal{L} \simeq -\frac{dU_{\rm ion}}{dt} = -C_{\rm V} M_{\rm WD} \dot{T}$ can be used, $C_{\rm V}$ denotes constant volume specific heat. Within this approximation, the change of the pulsation period is given by the following formula[1]

$$\frac{\dot{P}}{P} \propto -\frac{\dot{T}}{T} = -\frac{\mathcal{L}}{C_{\rm V} M_{\rm WD} T}\,. \tag{1}$$

For this particular white dwarf we have at our disposal precise measurement of the rate of period increase $\dot{P}$ for the 215.2 s mode[2]. The most recent determination gives the value[3] $\dot{P}_{\rm obs} = (3.57 \pm 0.82) \times 10^{-15}$ s s$^{-1}$ [5]. We also have theoretical expectations concerning this mode, namely $\dot{P}_{\rm theor} = 3.9 \times 10^{-15}$ s s$^{-1}$ [6]. Consequently, a mismatch between theoretical and observed rates of cooling, can be translated into additional (*i.e.* unaccounted for by standard astrophysics) source of luminosity $\mathcal{L}_X$ and the following formula holds

$$\mathcal{L}_X = \frac{\dot{P}_{\rm obs} - \dot{P}_{\rm theor}}{\dot{P}_{\rm theor}} \mathcal{L}\,, \tag{2}$$

where $L$ represents standard photon cooling.

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[1] Such approach, first used by Isern *et al.* [7] for a similar purpose of constraining axion, was subsequently confirmed by rigorous evolutionary calculations [6].

[2] It has been claimed that this mode of G117-B15A is the most stable oscillation ever recorded in the optical band (with a stability compared to millisecond pulsars).

[3] Careful assessment of various factors influencing period changes strongly suggests that observed $\dot{P}$ value is really due to evolutionary effects.

One can notice that theoretical prediction falls within one-sigma interval of the observed value. The case of an agreement leads to constraints on "exotic" physics. Therefore current observational knowledge concerning G117-B15A pulsating star and associated consequences for the $\dot{P}$ of the 215 s mode can be translated into the following bound for the magnitude of additional luminosity:

$$|\mathcal{L}_X| \leq 0.21\,\mathcal{L} = 1.298 \times 10^{30}\ \mathrm{erg\,s^{-1}}\,. \tag{3}$$

If one took just the difference between the observed and theoretical values the result would be $|\mathcal{L}_X| \leq 0.08\,\mathcal{L} = 4.944 \times 10^{29}\ \mathrm{erg\,s^{-1}}$.

## 3. Constraints on large extra-dimensions

The interest in physical theories with extra spatial dimensions has recently experienced considerable revival. In particular, it is has been conjectured [2] that compactification scale could be of the order of a TeV.

At an energy scale lower than compactification scale, one can construct an effective theory of KK gravitons interacting with the standard model fields. Because white dwarfs are dense and cool one can expect that dominant process of Kaluza–Klein graviton emission is gravi-bremsstrahlung of electrons. The specific (mass) emissivity estimated by Barger *et al.* [8, 9] is

$$\epsilon \;=\; 5.86\ 10^{-75}\frac{T^3 n_e}{\rho M_{\mathrm{s}}^4}\sum_j n_j Z_j^2 \qquad \text{for} \quad n=2\,, \tag{4}$$

$$\epsilon \;=\; 9.74\ 10^{-91}\frac{T^4 n_e}{\rho M_{\mathrm{s}}^5}\sum_j n_j Z_j^2 \qquad \text{for} \quad n=3\,, \tag{5}$$

where: $T$ is the temperature of isothermal core, $\rho$ is the density, $n_e$ and $n_j$ are the number densities of electrons and ions, respectively. Total Kaluza–Klein graviton luminosity can be obtained as

$$L_{\mathrm{KK}} = \int_0^{M_{\mathrm{WD}}} \epsilon\, dm\,. \tag{6}$$

By virtue of relation (2) the recently established secular stability of the fundamental oscillation mode of G117-B15A implies that

$$M_{\mathrm{s}} > 8.8\ \mathrm{TeV}/c^2 \qquad \text{for} \quad n=2\,. \tag{7}$$

We restricted our attention to the case of $n=2$ since respective graviton emission rates for $n=3$ (and greater) turned out to be negligible [8, 10].

Among existing astrophysical bounds on Kaluza–Klein theories with large extra dimensions only the supernova constraints are more restrictive [8, 11]. However, they are based on a different mechanism of Kaluza–Klein graviton emission — the nucleon–nucleon bremsstrahlung.

## 4. WIMPs capture and stellar energetics, bound on WIMP scalar cross-section

Now we would like to consider a picture of star immersed in the bath of WIMPs dark matter halo. When a WIMP enters the star it may interact with nuclei and lose enough kinetic energy to be trapped by the gravitational potential well. The WIMP gas tends towards thermalization with baryonic matter with a timescale much shorter than the time scale of stellar evolution. Supersymmetric WIMP particles (such like neutralino) are assumed to be Majorana particles. Therefore, once captured, they can annihilate with themselves at certain annihilation rate $\Gamma_{\rm a}$. In a steady state, which is a reasonable assumption in order to prevent star acquiring mass indefinitely, the capture and annihilation rates should be equal. This way the capture of Majorana particles could become an additional source of energy in stellar interior (irrespective of annihilation channel). Estimated additional luminosity due to WIMP annihilation [12] is equal

$$\mathcal{L}_X = \sqrt{\frac{8}{3\pi}}\frac{3}{2}\rho_{\rm DM}\frac{v_{\rm esc}^2}{\overline{v}}\frac{M_{\rm WD}}{m_p}\sigma_{\rm si}\sum_{i=O,C} X_i A_i^3 \,, \tag{8}$$

where: $\rho_{\rm DM}$ denotes the dark matter (WIMP) density around the star, $\overline{v}$ is the WIMP velocity dispersion, $v_{\rm esc}$ is the escape velocity at the surface of the star, $\sigma_{\rm si}$ denotes scalar interaction elementary cross-section, $M_{\rm WD}$ is the stellar mass, $m_p$ is proton's mass, summation goes over the species of atomic number $A_i$ and mass fractions $X_i$.

Taking the expression (2) for additional luminosity due to WIMPs one can convert it for the scalar cross-section

$$\sigma_{si} = \frac{\mathcal{L}_X}{\sqrt{\frac{8}{3\pi}}\frac{3}{2}\rho_{\rm DM}\frac{v_{\rm esc}^2}{\overline{v}}\frac{M_{\rm WD}}{m_p}\sum\limits_{i=O,C} X_i A_i^3} \,. \tag{9}$$

Therefore for the purpose of our order of magnitude assessment it would be sufficient to approximate $\overline{v}$ and $\rho_{\rm DM}$ in G117-B15A environment with the values near the Sun $\rho_{\rm DM} = 0.3$ GeV/cm$^3$ and $\overline{v} = 270$ km/s. Combining all this with our estimate on $|\mathcal{L}_X|$ from the rate of change of the period we arrive at the bound for scalar interaction cross-section

$$\sigma_{\rm si} \leq 2.08 \times 10^{-37}\ {\rm cm}^2 \,. \tag{10}$$

If one took just the difference between observed and theoretical rates of change of the period, one would obtain $\sigma_{\mathrm{si}} \leq 8.37 \times 10^{-38}$ cm$^2$ which, of course, looks more stringent.

## 5. Conclusions

It is really amazing that classical astrophysics starts providing bounds on new physics inaccessible as yet in direct experiments. Among existing astrophysical bounds on Kaluza–Klein theories with large extra dimensions only supernova constraints are the most restrictive. They are, however, strongly model dependent. The bound derived in this paper is based on white dwarf cooling. The physics underlying this process is very simple hence one can expect that the result is robust.

The idea of WIMPs dark matter is so appealing both to astrophysical community and particle physicists that several experiments are operating (or being upgraded) with aim to detect the elusive traces of WIMPs existence (annihilation signal) in our Galaxy's halo in solar neutrino signal or try to detect WIMP dark matter directly in underground detectors [13]. In this paper we posed a question: what is the bound for scalar interaction cross-section of WIMPs imposed by G117-B15A. We chose this pulsating white dwarf, because its rate of cooling has been measured accurately (with asteroseismological techniques) and proved to be consistent with theoretical expectations.

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