Axions and the white dwarf cooling anomaly

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Axions & IAXO in Spain
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Some examples of using WD to bound physics theories:

- Axion [Raffelt’86; Isern+’92,08;Isern & Garcia-Berro’08]
- Secular drift of $G_N$ [Vila’69; Garcia-Berro+’95; Benvenuto+’04]
- Magnetic monopoles [Freese’84]
- Neutrino magnetic momentum [Blinnikov & Dunina-Barkovskaya’94]
- Extradimensions [Malec & Besiada’01]
- Formation bh by high energy collisions [Giddings & Mangano’08]
- WIMPS [Bertone’07]
- Dark forces [Dreiner+’13]
White dwarf cooling

\[ L + L_v + (L_e) = - \int_{M_{WD}} c_v \frac{dT_c}{dt} \, dm - \int_{M_{WD}} T \left( \frac{\partial P}{\partial T} \right)_{v,x} \frac{dV}{dt} \, dm + (l_s + e_s) \dot{m}_e + (\varepsilon_e) \]

A \( L(T_c) \) relationship is necessary to solve this equation. It depends on the properties of the envelope.

\[ L \propto T^\alpha \]

\[ \alpha \approx 2.5 - 2.7 \]

Two ways to test the evolution of WD:

# From the secular drift of their period of pulsation
# From their luminosity function
Astrophysical implications

During their cooling, WD find some instabilities and they experience Luminosity fluctuations: DOV, DBV, DAV
Non-radial g-modes

- Long period waves $\sim 10^2 - 10^3$ s
- Gravity is the restoring force

$$\frac{\dot{P}}{P} = -a \frac{\dot{T}}{T} + b \frac{\dot{R}}{R}$$

- The period increases as the star cools down and decreases as it contracts.

- The radial term can be neglected for cool enough stars (DAV, DBV)
\[ \dot{\Pi} = (12.0 \pm 3.5) \times 10^{-15} \text{ s/s} \]

The first value (Kepler et al’91) was a factor of 2 larger than expected.
Three solutions:
- Observational error
- Whited warfs with “IME” cores
- Exotic source of cooling
\[ M_{bol}(t) = -2.5 \log L(t) + ctn \]

\[ \varepsilon_a = 1.08 \cdot 10^{23} \alpha \frac{Z^2}{A} T_7^4 F(\Gamma) \]

\[ \alpha = \frac{g_{ae}^2}{4\pi} \]

DFSZ axions
Bremmsstrahlung is dominant
Nakagawa et al 1987, 1988

\[ g_{ae} \sim 2.2 \times 10^{-13} \quad (m_a \sim 8 \text{ meV}) \] Isern+’92, 10
The existence of axions of moderate mass (~meV) able to interact with electrons introduce subtle effects in the properties of stars during their late evolutionary stages:

- Red giants: Brighter than expected tip (Viaux+'13)
- HB stars: An excess of HB as compared with RGB (Ayala+'15)

These anomalies can be detected and used as tools to check the consistence of physics.

These effects will largely benefit from Gaia results.
The diagram shows a horizontal axis labeled \( g_{ae} \times 10^{13} \) with points at 0, 1, 2, 3, 4, 5, and 6. The vertical axis lists the following materials: HB, RGB, R548, G117-B15A, and WD1F. A red arrow indicates the range of \( g_{ae} \) from 1 to 6 for WD1F, with the note \( g_{ae13} < 7 \).
The luminosity function

Number of white dwarfs per unit of volume and magnitude versus luminosity

\[ n(L) = \int_{M_I}^{M_u} \Phi(M) \Psi(T_G - t_{cool} - t_{ps}) \tau_{cool} \, dM \]

1. \( n(L) \) is the observed distribution
2. \( \Phi, \Psi \) are the IMF and SFR respectively.
   \( T_G \) is the age of the Galaxy
3. \( t_{cool} \) is the cooling time
   \( t_{ps} \) is the lifetime of the progenitor
   \( \tau_{cool} \) is the characteristic cooling time

Hidden an IFMR

If the 3 ingredients are known it is possible to use the WDLF to test new physics
Comparison between cooling models

Hansen & Liebert'03

---: Renedo et al 2010
---: Salaris et al 2000
Age of NGC6791
Turn off Main Sequence: 8 Gyr
WD age (no sed): 6 Gyr (green)
WD age (sed): 8 Gyr (red)

García Berro et al’10, Nature, 465,194
Surveys are more and more accurate and significative

Sloan sample of WD: ‘High’ precision LF
~ several 1000s stars

~ few 100s stars
Uncertainties:
• Distances
• Internal structure
• Emission rates
• Transparency of the envelope
• Initial-final mass relationship
• IMF
• Pathological SFR
• Ages of MS progenitors
• Metallicities
• Galactic migrations
• Observational systematics
• ....
Influence of the SFR & IMF

\[ n(l) \propto \left\langle \tau_{\text{cool}} \right\rangle \int_{M_i}^{M_{\text{max}}} \Phi(M) \Psi(\tau) dM \]
The best fit is obtained for $m_{a}\cos^2\beta \sim 5$ meV  
Isern+’08

Many uncertainties:  
- Internal structure  
- Emission rates  
- Transparency of the envelope  
- Initial-final mass relationship  
- IMF  
- Pathological SFR  
- Ages of MS progenitors  
- Metallicities  
- ....
$g_{ae} = 0.0$

$1.12 \times 10^{-13}$

$2.24 \times 10^{-13}$

$4.48 \times 10^{-13}$

Harris+’06

Krzesinski+’09
$g_{ae} = 0.0$

$1.12 \times 10^{-13}$

$2.24 \times 10^{-13}$

$4.48 \times 10^{-13}$

DA WDLF
DeGennaro+’07
 Obtained from the SCSS, that is completely independent.
1: Harris et al: $m_a < \sim 2.5$ meV
2, 3, 4: De Genaro, Rowell, Isern: $m_a \sim 5-7$ meV
The WDLF is not very dependent on the IMF as far as low mass stars ($< 1 \, M_\odot$) are effectively produced.
Conclusions:

The recent luminosity functions and the measurement of the secular drift of the pulsation period of DAV suggest that WDs cool down more quickly than expected. But this last result must be revised.

Axions or light bosons able to couple to electrons could account for this ($m_a \sim 5$ meV) extracooling. IAXO could solve the problem.

Because of its simplicity, WD could play an important role in the development of new ideas in Physics. Nevertheless, to obtain robust results it will be necessary to remove the uncertainties listed before:

* Extend the observational LF to high and low luminosities
* Obtention of the LF for massive white dwarfs
* Improvement of the cooling models. Envelope is crucial
* Role of binaries

GAIA can provide the necessary precision & accuracy.
LSST will probably provide the definitive thrust.
\[ M_{\text{bol}}(t) = -2.5 \log L(t) + ctn \]

DFSZ axions
Bremmsstrahlung is dominant

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\[ \epsilon_a = 1.08 \cdot 10^{23} \alpha \frac{Z^2}{A} T_7^4 F(\Gamma) \]

\[ \alpha = \frac{g_{ae}^2}{4\pi} \]

\[ g_{ae} = 2.8 \times 10^{-14} m_a [\text{meV}] \cos^2 \beta \]