Draft version January 12, 2009
Preprint typeset using LATEX style emulateapj v. 10/09/06

AXIONS AND THE COOLING OF WHITE DWARF STARS

J. Isern[1,2], E. García–Berro[3,2], S. Torres[3,2], S. Catalán[1,2]

Draft version January 12, 2009

ABSTRACT

White dwarfs are the end product of the lifes of intermediate- and low-mass stars and their evolution is described as a simple cooling process. Recently, it has been possible to determine with an unprecedented precision their luminosity function, that is, the number of stars per unit volume and luminosity interval. We show here that the shape of the bright branch of this function is only sensitive to the averaged cooling rate of white dwarfs and we propose to use this property to check the possible existence of axions, a proposed but not yet detected weakly interacting particle. Our results indicate that the inclusion of the emission of axions in the evolutionary models of white dwarfs noticeably improves the agreement between the theoretical calculations and the observational white dwarf luminosity function. The best fit is obtained for $m_a \cos^2\beta \approx 5$ meV, where m_a is the mass of the axion and $\cos^2\beta$ is a free parameter. We also show that values larger than 10 meV are clearly excluded. The existing theoretical and observational uncertainties do not yet allow the confirmation of the existence of axions, but our results clearly show that if their mass is of the order of few meV, the white dwarf luminosity function is sensitive enough to detect their existence.

Subject headings: elementary particles — stars: luminosity function, mass function — white dwarfs

1. INTRODUCTION

One solution to the strong CP problem of quantum chromodynamics is the Peccei-Quinn symmetry (Peccei & Quinn 1977a, 1977b). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudo-scalar particle named the "axion" (Weinberg 1978; Wilczek 1978). This scale of energies is not defined by the theory but it has to be well above the electroweak scale to ensure that the coupling between axions and matter is weak enough to account for the lack of a positive detection up to now. The mass of axions and the energy scale are related by $m_a \approx 0.6(10^7\ \mathrm{GeV}/f_a)$ eV. Astrophysical and cosmological arguments (Raffelt 2007) have been used to constrain this mass to the range $10^{-2}\ \mathrm{eV} \geq m_a \geq 10^{-4}$ eV. For this mass range, axions can escape from stars and act as a sink of energy.

White dwarfs are the final evolutionary phase of low- and intermediate-mass stars ($M \leq 10 \pm 2\ M_\odot$). Since they are degenerate objects, they cannot obtain energy from thermonuclear reactions and their evolution can be described just as a gravothermal process of cooling. Therefore, if axions exist, the properties of these stars would be noticeably perturbed. Furthermore, white dwarfs have a relatively simple structure: a degenerate core that contains the bulk of the mass and acts as an energy reservoir and a partially degenerate envelope that controls the energy outflow. The vast majority of white dwarfs have masses in the range $0.4 \leq M/M_\odot \leq 1.05$ — although these figures are still uncertain — and have a core made of a mixture of carbon and oxygen. All of them are surrounded by a thin helium layer, with a mass ranging from 10^{-2} to $10^{-4}\ M_\odot$ which, in turn, is surrounded by an even thinner layer of hydrogen with a mass between 10^{-4} and $10^{-15}\ M_\odot$, although about 25% of white dwarfs do not have hydrogen atmospheres. White dwarfs displaying hydrogen in their spectra are called DA and the remaining ones are known as non-DAs. Because of the different opacities, DA white dwarfs cool more slowly than the non-DA ones.

The standard theory of white dwarf cooling can be summarized as follows (Isern et al. 1998). When the luminosity is large, $M_{\rm bol} < 8$, the evolution is dominated by neutrino emission. In this phase the main uncertainties come from our poor knowledge of the initial conditions. Fortunately, it has been shown that all the initial thermal structures converge toward a unique one (D'Antonna & Mazzitelli 1989). For smaller luminosities, $8 \leq M_{\rm bol} \leq 12$, the main source of energy is of gravothermal origin. In this phase, the Coulomb plasma coupling parameter is not large and the cooling can be accurately described. Furthermore, the energy flux through the envelope is controlled by a thick nondegenerate or partially degenerate layer with an opacity dominated by hydrogen, when present, and helium, and it is weakly dependent on the metal content since metals sink towards the base of the envelope by gravitationally induced diffusion. Below these luminosities, white dwarfs evolve into a region of densities and temperatures where the plasma crystallizes. When this happens, two additional sources of energy appear. The first one is the release of latent heat during crystallization. The second one is the release of gravitational energy induced by phase separation of the different chemical species (García-Berro et al. 1988a, 1988b; Isern et al. 1997, 2000). When the bulk of the star is solid the white dwarf enters into the Debye cooling phase and the only important source of energy comes from the compression of the outer layers. These late phases of cooling are not yet well understood (Isern et al. 1998).

Electronic address: isern@ieec.fcr.es
[1] Institut de Ciències de l'Espai, CSIC, Facultat de Ciències, Campus UAB, 08193 Bellaterra, Spain
[2] Institut d'Estudis Espacials de Catalunya, c/ Gran Capità 2–4, 08034 Barcelona, Spain
[3] Departament de Física Aplicada, Escola Politècnica Superior de Castelldefels, Universitat Politècnica de Catalunya, Avda. del Canal Olímpic s/n, 08860 Castelldefels, Spain

2. THE WHITE DWARF LUMINOSITY FUNCTION

One way to test the evolutionary properties of white dwarfs is using their luminosity function, which is defined as the number of white dwarfs per unit volume and magnitude. The first luminosity function was derived four decades ago (Weidemann 1968) and since then it has been noticeably improved. The most recent determinations use data from the Sloan Digital Sky Survey (SDSS). The first of these (Harris et al. 2006) was built from a sample of 6000 DA and non-DA white dwarfs with accurate photometry and proper motions culled from the SDSS Data Release 3 and the USNO-B catalogue, whereas the second one (DeGennaro et al. 2008) was constructed from a sample of 3528 spectroscopically identified DA white dwarfs from the SDSS Data Release 4 (see Fig. 1). The monotonic behavior of this function clearly proves that the evolution of white dwarfs is just a cooling process. The sharp cutoff at low luminosities is a consequence of the finite age of the Galactic disk. The luminosity function of white dwarfs can be computed as:

$$n(M_{\rm bol}) = \int_{M_{\rm l}}^{M_{\rm u}} \phi(M)\psi(T_{\rm G}-t_{\rm cool}-t_{\rm ps})\tau_{\rm cool}\,dM, \quad (1)$$

where $M_{\rm bol}$ is the bolometric magnitude, M is the mass of the parent star — for convenience all white dwarfs are labeled with the mass of its progenitor — $T_{\rm G}$ is the age of the population under study, $t_{\rm cool}$ is the time that a white dwarf with a progenitor of mass M takes to cool down to a bolometric magnitude $M_{\rm bol}$, $\tau_{\rm cool}$ is the characteristic cooling time of the white dwarf, $\tau_{\rm cool} = dt_{\rm cool}/dM_{\rm bol}$, and $t_{\rm ps}$ is the lifetime of the parent star. In equation (1) $M_{\rm u}$ is the maximum mass of white dwarf progenitors and $M_{\rm l}$ is the mass of the progenitor that satisfies the condition $T_{\rm G} - t_{\rm cool} - t_{\rm ps} = 0$, i.e., the minimum mass of a star able to produce a white dwarf of the required luminosity. The remaining quantities are the initial mass function, ϕ (here we have used Salpeter's law), and the star formation rate, ψ, which is not known a priori and depends on the population under study.

Since neither the star formation rate nor the total density of white dwarfs are known, theoretical luminosity functions are normalized to a given observational bin, usually the one with the smallest error bar. Figure 1 displays the observed luminosity functions and several luminosity functions obtained with the same DA cooling sequences (Salaris et al. 2000) and different star formation rates and ages of the Galaxy. The cooling models assume a nonhomogeneous distribution of carbon and oxygen in the core (Salaris et al. 1997), a pure helium layer of $10^{-2}\,M_*$ and on top of it a pure hydrogen layer of $10^{-4}\,M_*$, where M_* is the mass of the white dwarf. Since a relationship connecting the mass of the white dwarf and the mass of its progenitor is also necessary we have adopted the one that best reproduces the mass distribution of white dwarfs (Catalán et al. 2008).

An interesting feature of Figure 1 is that the bright part of the white dwarf luminosity function — that with bolometric magnitude $M_{\rm bol} < 13$ — is almost independent of the assumed star formation rate. This can be explained with simple arguments. Since the characteristic cooling time is not strongly dependent on the mass of the white dwarf, equation (1) can be written as

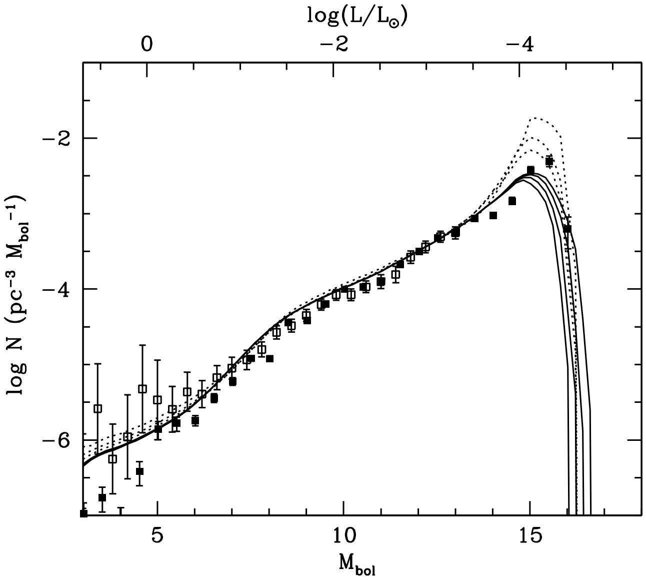

FIG. 1.— Luminosity functions of white dwarfs. Filled squares correspond to the luminosity function of white dwarfs (DA and non-DA types) obtained using the reduced proper motion method (Harris et al. 2006) and open squares to that obtained using spectroscopically identified DA white dwarfs (DeGennaro et al. 2008). The solid lines are the theoretical luminosity functions obtained for different ages of the Galaxy — from left to right: 10, 11, 12 and 13 Gyr — and a constant star formation rate. The dotted lines are the same for an exponentially decreasing star formation rate — $\psi(t) = \exp(-t/\tau)$ with $\tau = 0.5$, 3 and 5 Gyr — and the same age of the Galaxy, 11 Gyr. All the luminosity functions have been normalized to the same observational data point.

$$n \propto \langle\tau_{\rm cool}\rangle \int_{M_{\rm l}}^{M_{\rm u}} \phi(M)\psi(T-t_{\rm cool}-t_{\rm ps})\,dM. \quad (2)$$

Restricting ourselves to bright white dwarfs — namely, those for which $t_{\rm cool}$ is small — the lower limit of the integral is satisfied by low-mass stars and, as a consequence of the strong dependence of the main-sequence lifetimes with mass, it takes a value that is almost independent of the luminosity under consideration. Therefore, if ψ is a well-behaved function and $T_{\rm G}$ is large enough, the integral is not sensitive to the luminosity, its value is absorbed by the normalization procedure, and the shape of the luminosity function only depends on the averaged physical properties of white dwarfs. It is important to mention here that the initial-final mass relationship enters as a weight into the calculation of this average. Neverheless, since only those functions able to provide a good fit to the mass distribution of white dwarfs are acceptable, its influence on the shape of the bright branch of the luminosity function is minor. Here we use this property of the white dwarf luminosity function, together with the recently obtained high-precision observational luminosity function, to study the influence of the emission of axions, and to check which mass of the axion is compatible with observations. The idea of using the cooling times of white dwarfs to constrain the properties of axions is not new (Raffelt 1986), but the crudeness of the theoretical models and of the observational data prevented a definite conclusion and just a loose upper bound was obtained, $m_a < 30$ meV.

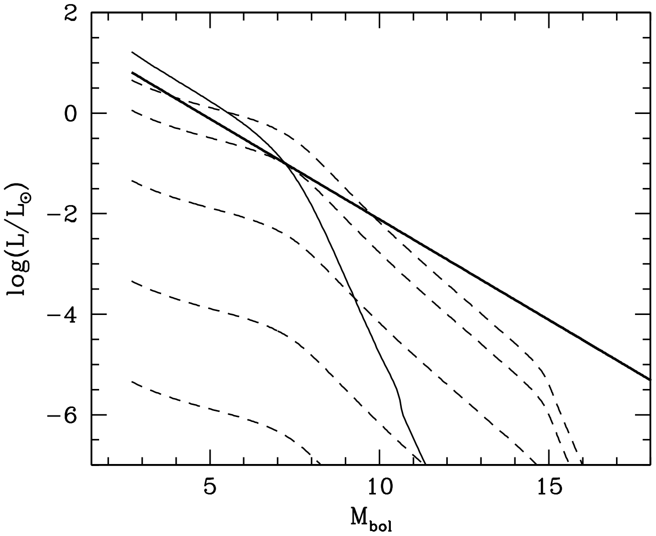

FIG. 2.— Energy losses for a $0.61\,M_\odot$ white dwarf as a function of the bolometric magnitude. The dashed lines represent the axion luminosity for different values of $m_a \cos^2\beta$ — from top to bottom: $m_a \cos^2\beta$ =10, 5, 1, 0.1 and 0.01 meV. The thick solid line is the photon luminosity, while the thin solid line shows the neutrino luminosity.

3. AXIONS AND THE WHITE DWARF LUMINOSITY FUNCTION

Axions can couple to photons, electrons and nucleons with a strength that depends on the specific implementation of the Peccei-Quinn mechanism. The two most common implementations are the KVSZ (Kim 1979; Shifman et al. 1980) and the DFSZ models (Dine et al. 1981; Zhitnitskii 1980). In the first case axions couple to hadrons and photons, while in the second they also couple to charged leptons. For the temperatures and densities of the white dwarfs under consideration, only DFSZ axions are relevant and in this case they can be emitted by Compton, pair annihilation and bremsstrahlung processes, but only the last mechanism turns out to be important. Figure 2 shows the energy losses for an otherwise typical $0.61\,M_\odot$ white dwarf as a function of the bolometric magnitude. The dashed lines represent the axion luminosity for different values of $m_a \cos^2\beta$. The axion emission rate (in erg g^{-1} s^{-1}) has been computed (Nakagawa et al. 1987, 1988) as $\varepsilon_a = 1.08 \times 10^{23}\alpha(Z^2/A)T_7^4 F$, where F is a function of the temperature and the density which takes into account the properties of the plasma, and $\alpha = g_{ae}^2/4\pi$ is related to the axion-electron coupling constant $g_{ae} = 2.8 \times 10^{-11} m_a \cos^2\beta/1$ eV. Since the core is almost isothermal it turns out that $L_a \propto T^4$ in the region in which axions are the dominant sink of energy. The thick solid line represents the photon luminosity (Salaris et al. 2000). For the region of interest $L_\nu \propto T^a$, with $a \sim 2.6$, although this value changes as the white dwarf cools down. The thin solid line represents the neutrino luminosity, which scales as $L_\nu \propto T^8$ and is also dominated by the plasma and bremsstrahlung processes (Itoh et al. 1996). Therefore, since the temperature dependence of the different energy-loss processes is not the same, the luminosity function allows to disentangle the different contributions.

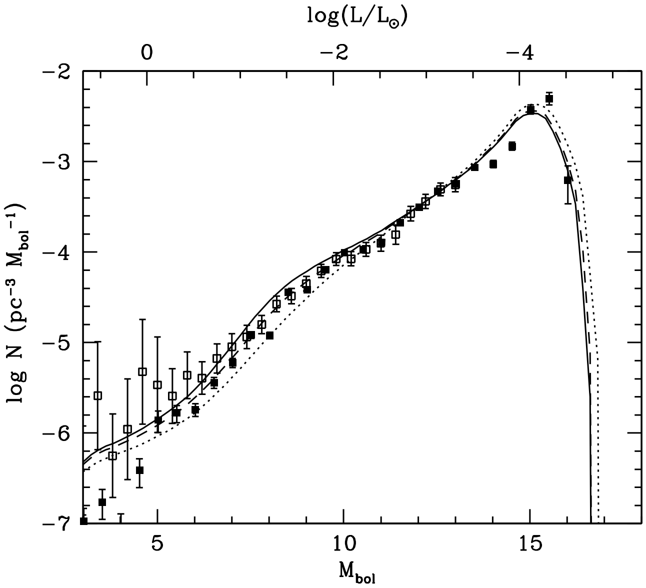

FIG. 3.— White dwarf luminosity functions for different values of the axion mass. The luminosity functions have been computed assuming $m_a \cos^2\beta = 0$ (solid line), 5 (dashed line) and 10 (dotted line) meV.

Figure 2 shows that in the region $M_{\rm bol} \sim 10$ the axion luminosity can be comparable with the photon and neutrino ones, depending on the adopted axion mass. It also shows that the region around $M_{\rm bol} \sim 12$ provides a solid anchor point to normalize the luminosity function because there the observational data have reasonably small error bars, models are reliable, neutrinos are not relevant and axions, if they exist, are not dominant.

4. RESULTS AND CONCLUSIONS

Figure 3 displays several luminosity functions obtained using different axion masses, adopting a constant star formation rate and an age of the Galactic disk of 11 Gyr. As already mentioned, it is important to realize that the bright branch of the luminosity function is not sensitive to these last assumptions. All the luminosity functions have been normalized to the luminosity bin at $\log(L/L_\odot) \simeq -3$ or, equivalently, $M_{\rm bol} \simeq 12.2$. The best-fit model — namely that which minimizes the χ^2 test in the region $-1 > \log(L/L_\odot) > -3$ (that is, $7.2 < M_{\rm bol} < 12.2$), which is the region where both the observational data and the theoretical models are reliable — is obtained for $m_a \cos^2\beta \approx 5$ meV and solutions with $m_a \cos^2\beta > 10$ meV are clearly excluded. Figure 4 displays the behavior of χ^2 as a function of the mass of the axion in our fiducial case (solid line) and in the case in which we use the initial-final mass relationship of Wood (1992), which is marginally compatible with the white dwarf mass distribution (Catalán et al. 2008). In both cases the behavior of the luminosity function is similar and gives similar values for the mass of the axion once one takes into account the present uncertainties. It is also important to notice that the largest contribution to the lack of accuracy comes from the brightest bins of the luminosity function, which have large error bars.

This result is completely compatible with the previously existing constraints (Raffelt 2007). Furthermore, these values are also compatible with the bounds imposed by the drift of the pulsational period of the ZZ

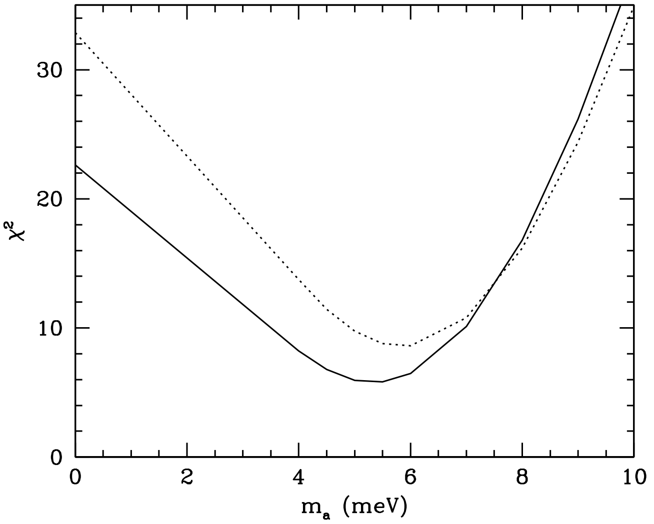

FIG. 4.— Value of χ^2 as a function of the mass of the axion for the case in which the initial–final mass relationship of Catalán et al. (2008) (solid line) and that of Wood (1992) (dotted line) are used.

Ceti star G117−B15A (Isern et al. 1992; Córsico et al. 2001; Bischoff-Kim et al. 2008). It is worthwhile to mention here that axions with $m_a \approx 5$ meV would change the expected period drift of variable DB white dwarfs — which have values between $\dot{P} \sim 10^{-13}$ and 10^{-14} s s^{-1} (Córsico & Althaus 2004) — by a factor 2, the exact value depending on the adopted temperature of the stellar core and that the detection of such a drift would provide a strong additional argument in favor of the existence of axions.

The results presented here are not a definite proof of the existence of axions, since there are still some observational and theoretical uncertainties. However, the calculations reported here show that the hot branch of the white dwarf luminosity function is a powerful tool to test the existence of weakly interacting massive particles because it is only sensitive to the averaged cooling rate of white dwarfs and not to the details of the star formation rate or the initial mass function, as shown in §2. Moreover, our results are problably the first evidence that the shape of the white dwarf luminosity function could be affected by the emission of axions and that this change can be measured. If this is indeed the case the mass of the axion would be of about 5 meV. In addition, we have derived an upper bound to the mass of the axions of 10 meV, which is compatible with other recent determinations (Bischoff-Kim et al. 2008). It is worth mentioning that this result is relevant for other research fields and, in particular, for cosmology. Specifically, assuming $\cos^2\beta = 1$, the contribution of axions to dark matter would be of the order of 0.2% (Raffelt 2007). In view of this, we consider it of the largest importance to improve the observational determination of the white dwarf luminosity function, especially in the region of the hottest white dwarfs (see Fig. 3). Thus, the extension of the SDSS is of the maximum interest not only for astronomers and cosmologists, but also for particle physicists. However, not only observational efforts are needed, since in order to obtain a reliable determination of the mass of the axion it is also important to decrease the uncertainties in the plasmon neutrino emission rates at the relevant temperature range. Furthermore, it would be also convenient to intensify the study of the drift of the pulsational periods of variable white dwarfs in order to obtain additional independent evidence.

Part of this work was supported by the MEC grants AYA05-08013-C03-01 and 02, and ESP2007-61593 by the European Union FEDER funds and by the AGAUR. We thank M. Salaris for providing us with the neutrino emission files corresponding to the models of Salaris et al. (2000).

REFERENCES

Bischoff-Kim, A., Montgomery, M. H., & Winget, D. E. 2008, ApJ, 675, 1512

Catalán, S., Isern, J., García-Berro, E., & Ribas, I. 2008, MNRAS, 387, 1693

Córsico, A. H., Benvenuto, O. G., Althaus, L. G., Isern, & García-Berro, E. 2001, New Astronomy, 6, 197

Córsico, A. H., & Althaus, L. G. 2004, A&A, 428, 159

D'Antonna, F., & Mazzitelli, K. 1989, ApJ, 347, 934

DeGennaro, S., von Hippel, T., Winget, D. E., Kepler, S. O., Nitta, A., Koester, D., & Althaus, L. 2008, AJ, 135, 1

Dine, M., Fischler, W., & Srednicki, M. 1981, Phys. Let. B, 104, 199

García–Berro, E., Hernanz, M., Mochkovitch, R., & Isern, 1988a, A&A, 193, 141

García–Berro, E., Hernanz, M., Isern, J., & Mochkovitch, R., Nature, 333, 642

Harris, H. C., et al. 2006, AJ, 131, 571

Isern, J., Hernanz, M., & García-Berro, E. 1992, ApJ, 392, L23

Isern, J., Mochkovitch, R., García-Berro, E., & Hernanz, M. 1997, ApJ, 485, 308

Isern, J., García-Berro, W., Hernanz, M., & Mochkovitch, R. 1998, Journal of Physics Condensed Matter, 10, 11263

Isern, J., García-Berro, E., Hernanz, M., & Chabrier, G. 2000, ApJ, 528, 397

Itoh, N., Hayashi, H., Nishikawa, & Kohyama, Y. 1996, ApJ, 102, 411

Kim, J. E. 1979, Phys. Rev. Let., 43, 103

Nakagawa, M., Kohyama, Y., & Itoh, N. 1987, ApJ, 322, 291

Nakagawa, M., Adachi, T., Kohyama, Y., & Itoh, N. 1988, ApJS, 326, 241

Peccei, R. D., & Quinn, H. R. 1977a, Phys. Rev. D, 16, 1791

Peccei, R. D., & Quinn, H. R. 1977b, Phys. Rev. Let., 38, 1440

Raffelt, G. G. 1986, Phys. Let. B, 166, 402

Raffelt, G. G. 2007, Journal of Physics A: Mathematical and Theoretical, 40, 6607

Salaris, M., Domínguez, I., García-Berro, E., Hernanz, M., Isern, J., & Mochkovitch, R. 1997, ApJ, 486, 413

Salaris, M., García-Berro, E., Hernanz, M., Isern, J., & Saumon, D. 2000, ApJ, 544, 1036

Shifman, M. A., Vainshtein, A. I., & Zakharov, V. I. 1980, Nucl. Phys. B, 166, 493

Weidemann, V. 1968, ARA&A, 6, 351

Weinberg, S. 1978, Phys. Rev. Let., 40, 223

Wilczek, F. 1978, Phys. Rev. Let., 40, 279

Wood, M. A., 1992, ApJ, 386, 539

Zhitnitskii, A. P. 1980, Sov. J. Nucl., 31, 260