Neutrino and Axion Bounds from the Globular Cluster M5 (NGC 5904)

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The red-giant branch (RGB) in globular clusters is extended to larger brightness if the degenerate helium core loses too much energy in "dark channels." Based on a large set of archival observations, we provide high-precision photometry for the Galactic globular cluster M5 (NGC 5904), allowing for a detailed comparison between the observed tip of the RGB with predictions based on contemporary stellar evolution theory. In particular, we derive 95% confidence limits of $g_{ae} < 4.3 \times 10^{-13}$ on the axion-electron coupling and $\mu_\nu < 4.5 \times 10^{-12} \mu_B$ (Bohr magneton $\mu_B = e/2m_e$) on a neutrino dipole moment, based on a detailed analysis of statistical and systematic uncertainties. The cluster distance is the single largest source of uncertainty and can be improved in the future.

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Astrophysics and cosmology provide us with powerful arguments to constrain the properties of elementary particles. The "heavenly laboratories" are complementary to terrestrial experiments, notably at the low-energy frontier of particle physics, which includes the physics of neutrinos and other weakly interacting low-mass particles such as the hypothetical axion. In particular, stars would lose energy by emitting such particles in addition to standard neutrinos, leading to potentially observable modifications of the properties of individual stars or of entire stellar populations [1–4].

Different types of stars provide information on different particles or interaction channels, because the energy-loss rate of the hot stellar medium depends on temperature and density in ways determined by the emission process. For example, low-mass hidden photons are most significantly constrained by properties of the Sun [5]. On the other extreme, the neutrino burst duration of supernova 1987A provides the most restrictive limit on the axion-nucleon interaction [6]. In many other cases, evolved low-mass stars—red giants and horizontal branch (HB) stars in globular clusters (GCs) or white dwarfs (WDs)—supply the most interesting information [7–11].

One particularly sensitive observable is the brightness of the tip of the red-giant branch (TRGB) in GCs [7,9,11,11]. Together with other observables such as the HB brightness, it was found that the core mass at helium ignition should not exceed its standard value by about 5% [10,11]. This constraint means that the energy-loss rate should not exceed standard neutrino emission by more than about a factor of 3.

The helium core before ignition is highly degenerate [12], and neutrinos are primarily emitted by plasmon decay $\gamma \to \bar{\nu}\nu$. A sizable magnetic dipole moment μ_ν would enhance this process [1], and the TRGB brightness provides the most restrictive μ_ν limit to date [11]. Another important constraint is on the axion-electron coupling g_{ae}, where the most relevant emission reaction is axio-bremsstrahlung $e + Ze \to Ze + e + a$. It is these cases that we will reexamine here.

The main motivation for returning to this subject is the enormous observational progress and especially the newly available, exquisite GC color-magnitude diagrams (CMDs) that have become available only recently, based on both ground- and space-based observations (e.g., [13,14]). Likewise, stellar evolution theory has seen revolutionary progress, for example, by new opacity and equation-of-state tables. Moreover, in previous studies, systematic and statistical errors were not analyzed in sufficient detail to assign clear quantitative confidence levels, preventing a simple comparison with laboratory results. Our new constraints are similar to previous astrophysical limits [8–11] if the latter are interpreted as 1σ results. However, we have used homogeneous observations of a single GC and provide a detailed error budget.

Technical details, with a focus on the μ_ν case, are reported in [15]. We here communicate the main points and extend the analysis to the axion-electron interaction which is of topical interest in view of some indications for enhanced WD cooling, which we comment on in more detail below.

Cluster selection and photometry.—Among the fully resolved Milky Way GCs, we consider those with an integrated absolute magnitude $M_V < -8.0$ mag to ensure a well-populated CMD. We restrict foreground reddening to $E(B-V) \leq 0.1$ mag, also reducing the possibility of differential reddening. We ensure that the metallicity is neither too high nor too low, leading to a fairly uniformly populated HB. Candidates must be sufficiently close that deep, high-quality photometric data exist. We avoid GCs which seem to have multiple CMD sequences. These criteria leave us with a short list of candidates with M5 (NGC 5904) at the top. It is a well-studied, fairly massive GC, with $M_V = -8.81$ mag, a moderate metallicity of $[\mathrm{Fe/H}] = -1.29$, and a foreground reddening of only $E(B-V) = 0.03$ mag. The distance is only a modest 7.5 kpc from the Sun.

We have carried out crowded-field, point-spread function photometry of M5 using the DAOPHOT II/ALLFRAME suite of programs [16]. Our database was compiled from many sources, including public archives, following previous works on different GCs [17]. Current observations consist of 2840 CCD images obtained during 40 observing runs on 12 telescopes over a span of 27 years (see [15] for details). The resulting CMD is decontaminated from field stars with a statistical procedure [18].

The cleaned upper CMD is shown in Fig. 1 together with an empirical RGB fit function $I = 10.289 + 3.83[1.95 - (V-I)_0]^{2.5}$. We identify stars as belonging to the RGB if their distance from this line is less than 0.03 mag. Most of the brightest stars are found to be on the RGB, in agreement with purely statistical expectations. Another way of discrimination is based on chemical abundance variation. Other authors also assign the three brightest stars to the RGB [19,20], except for the second brightest that could be on the asymptotic giant branch (AGB) [19].

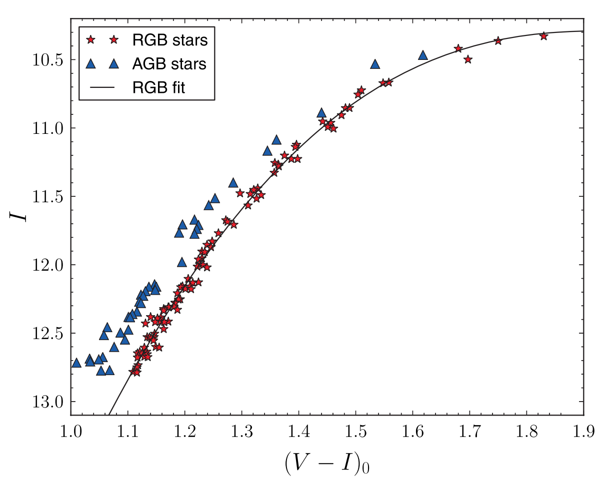

FIG. 1 (color online). Upper CMD for the GC M5, with our RGB and AGB identification according to color. We also show our empirical RGB fit function.

The I-band magnitudes of the brightest stars are 10.329, 10.363, and 10.420 mag, respectively. These stars are located near the cluster center, yet the combined error from crowding, completeness, and saturation is probably less than ± 0.01 mag. The photometric error for the brightest star is ± 0.0057 mag, whereas the calibration error of the I-band photometry is not larger than ± 0.02 mag (see Fig. 1 of Ref. [21]). Combining these errors in quadrature provides a photometric uncertainty of $\sigma_I = 0.023$ mag for the brightest star.

Observed TRGB brightness.—The brightest star, whose I-band magnitude we shall denote I_1, has not yet ignited helium; it will brighten further, and therefore its current CMD position provides a lower limit to the TRGB. Using Monte Carlo realizations of the upper CMD of M5, based on the population shown in Fig. 1, we find a statistical TRGB distribution relative to I_1 which has nearly exponential form. On average, the TRGB is $\langle \Delta_{\mathrm{tip}} \rangle = 0.048$ mag brighter than I_1 with an rms deviation of $\sigma_{\mathrm{tip}} = 0.058$ mag.

One key ingredient to compare the TRGB brightness with theoretical predictions is the distance modulus to M5. Different methods lead to estimations falling in the range $14.32 \leq (m-M)_0 \leq 14.67$ (see Table 4 of Ref. [22]), but several of them depend on HB and RR Lyrae stars whose properties depend on additional cooling in their RGB progenitors. Therefore, to avoid circular reasoning, we use only $(m-M)_0 = 14.45 \pm 0.11$ derived via main-sequence fitting [23], which is unaffected by the exotic energy-loss channels we discuss here. It is also in excellent agreement with other distance indicators and already takes into account interstellar extinction.

We estimate the absolute I-band TRGB brightness as $M_{I,\mathrm{TRGB}}^{\mathrm{obs}} = I_1 - \langle \Delta_{\mathrm{tip}} \rangle - (m-M)_0$, i.e.,

$$M_{I,\mathrm{TRGB}}^{\mathrm{obs}} = -4.17 \pm 0.13 \text{ mag}, \tag{1}$$

where we have added the errors in quadrature. The uncertainty derives almost entirely from the distance.

Predicted TRGB brightness.—To predict $M_{I,\mathrm{TRGB}}$ we use the Princeton-Goddard-PUC (PGPUC) code [24] to calculate evolutionary sequences up to the point of He ignition, implementing varying amounts of μ_ν or axion energy losses. Our benchmark tracks use $M = 0.82 M_\odot$ without mass loss on the RGB, $Y = 0.245$, $Z = 0.00136$, and $[\alpha/\mathrm{Fe}] = +0.30$ to capture the best estimates for the stellar properties in M5. To compare with observational data, we transform the luminosity into I-band absolute brightness by using the bolometric correction (BC) of Worthey and Lee [25].

The dominant neutrino emission process on the RGB evolution is plasmon decay for which PGPUC uses the analytic approximation formulas of Haft, Raffelt, and Weiss [26]. To incorporate μ_ν effects, we scale this rate by the prescription given in Eqs. (9) and (10) of Ref. [8]. The axion-electron interaction, to be discussed in more detail below, allows for photoproduction (Compton scattering) $\gamma + e \rightarrow e + a$ and bremsstrahlung $e + (Z, A) \rightarrow (Z, A) + e + a$ and $e + e \rightarrow e + e + a$. We take the energy-loss rate from Ref. [9] but extend their calculation to include all chemical elements as scattering targets, not helium alone.

The simulated TRGB brightness for the neutrino case can be expressed in terms of simple analytic fit formulas as $M^0_{I,\mathrm{TRGB}} = -4.03 - 0.23[(\mu_{12}^2 + 0.64)^{0.5} - 0.80 - 0.18\mu_{12}^{1.5}]$, where $\mu_{12} = \mu_\nu/10^{-12}\mu_B$. For axions the corresponding result is $-4.03 - 0.25[(g_{13}^2 + 0.93)^{0.5} - 0.96 - 0.17g_{13}^{1.5}]$, where $g_{13} = g_{ae}/10^{-13}$ and g_{ae} is the dimensionless axion-electron Yukawa coupling constant.

These predictions are affected by a number of systematic uncertainties of stellar evolution theory detailed in [15]. Many of them influence $M_{I,\mathrm{TRGB}}$ by less than ± 0.01 mag and deserve no further mention here. Larger uncertainties derive from the helium abundance ($\pm$ 0.010 mag), conductive opacity ($\pm$ 0.016 mag), nuclear reaction rates ($\pm$ 0.019 mag), screening effects ($\pm$ 0.011 mag), and standard neutrino emission rates ($\pm$ 0.013 mag).

More important is the question of mass loss on the RGB. Based on the HB properties in M5, we argue in [15] that stars lose between 0.12 and $0.28 M_\odot$. The impact on $M_{I,\mathrm{TRGB}}$ is not monotonic in this interval, leading to a shift relative to the no-mass-loss baseline case of between +0.022 and +0.035 mag.

The uncertainty of the equation of state (EoS) has a similar impact. PGPUC uses FreeEOS (see Table 2 of Ref. [24]), while other codes use other prescriptions. To study the impact of EoS variations we use the GARSTEC stellar evolution code [27] with eight different EoS prescriptions. For FreeEOS and all other parameters identical to our PGPUC baseline case, the TRGB is found 0.05 mag brighter. The internal GARSTEC spread of EoS cases is -0.0045 to $+0.0242$ mag in $M_{I,\mathrm{TRGB}}$.

The largest theoretical uncertainty derives from the treatment of convection. PGPUC uses the mixing-length theory (MLT) where the mixing-length parameter α_{MLT} of convection theory is chosen to reproduce the Sun. In this way, one achieves a quite satisfactory match of the CMDs of GCs over a wide range of metallicities, suggesting an uncertainty of ± 0.1 in α_{MLT}. In addition, an uncertainty due to the calibration of α_{MLT} arises. Depending on the inclusion of atomic diffusion, another shift of ± 0.1 in α_{MLT} is conceivable. Overall, we adopt an uncertainty of ± 0.2 in α_{MLT}, corresponding to a brightness uncertainty of ∓ 0.056 mag.

The largest uncertainty in the comparison between theory and observations comes from the color transformations and BC. Worthey and Lee [25] provide explicit error estimates for their BC which depends on the luminosity and temperature of the star and hence on the TRGB locus. For the neutrino case, these results suggest an error of $\sigma_{\mathrm{BC}} = (0.08 + 0.013\mu_{12})$ mag. This uncertainty is considerably larger than the spread of BC values derived from the prescriptions of other authors. The corresponding axion result is $\sigma_{\mathrm{BC}} = (0.08 + 0.02g_{13})$ mag.

All of these uncertainties are systematic (not statistical) and are our best estimates of the maximum error. The associated probability distributions are in most cases completely unknown, so we make the simplest possible choice and use top-hat, flat probability distributions in the given ranges of $M_{I,\mathrm{TRGB}}$ modifications. Convolving all of these distributions leads to a Gaussian distribution with mean 0.039 mag, i.e., $M^{\mathrm{theory}}_{I,\mathrm{TRGB}} = M^0_{I,\mathrm{TRGB}} + 0.039$, and standard deviation $\sigma_{\mathrm{theory}} = [0.039^2 + (0.046 + 0.0075\mu_{12})^2]^{0.5}$ mag. For axions, this result is $\sigma_{\mathrm{theory}} = [0.039^2 + (0.046 + 0.012g_{13})^2]^{0.5}$ mag shown as a green band in Fig. 2. (A similar figure for the μ_ν case is shown in [15].)

Within the uncertainties, the observed and predicted TRGB brightness agrees without novel cooling effects. To derive bounds on μ_ν and g_{ae}, we combine the observational and theoretical errors in quadrature. Integrating the combined probability distribution from $\mu_{12} = 0$ or $g_{ae} = 0$ to the limiting value, we find

$$\mu_\nu < 2.6(4.5) \times 10^{-12}\mu_B, \qquad g_{ae} < 2.6(4.3) \times 10^{-13} \quad (2)$$

at the 68% (95%) C.L., respectively.

The axion-electron coupling.—Axions are hypothetical pseudoscalar particles that must exist if the Peccei-Quinn mechanism is the correct explanation for *CP* conservation in QCD [28–30]. Their properties are governed primarily by an energy scale f_a, the Peccei-Quinn scale, or an axion decay constant. Their mass arises from mixing with the π^0, η, and η' mesons and is found to be $m_a = (m_\pi f_\pi/f_a)\sqrt{z}/(1+z) \sim 6$ meV$(10^9\ \mathrm{GeV}/f_a)$ in terms of the pion mass $m_\pi = 135$ MeV, pion decay constant

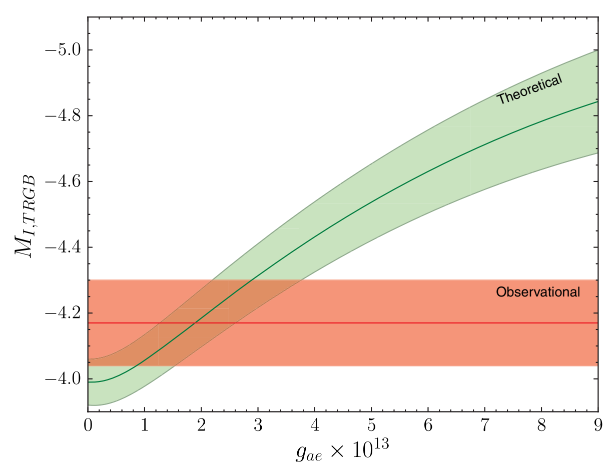

FIG. 2 (color online). Absolute *I*-band brightness of TRGB in cluster M5. Red band: Observations with 1σ error, dominated by distance. Green band: Theoretical prediction, depending on the axion-electron coupling, with 1σ systematic error, dominated by the bolometric correction.

$f_\pi = 93$ MeV, and up or down quark mass ratio $z = m_u/m_d = 0.38$–0.58 [31]. One generic axion property is its two-photon vertex that allows for production in stars by the Primakoff process [3,32] and for solar axion searches by the reverse process [33–37]. The helium-burning lifetime of HB stars in GCs [38] as well as the existence of the blue-loop phase in massive stars [39] provide a limit for typical axion models, corresponding to $m_a \lesssim 0.3$ eV, which is more stringent than constraints based on the helium flash in low-mass stars, as discussed, for instance, in Refs. [11,40].

In addition, axions can interact with electrons with a vertex of the form $C_e \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e \partial_\mu a/2f_a$, where C_e is a model-dependent coefficient and one usually defines the dimensionless Yukawa coupling $g_{ae} = C_e m_e/f_a$. A benchmark case is the DFSZ (Dine-Fischler-Srednicki, 1981, Zhitnitskii, 1981) model [41], where explicitly $g_{ae} = \frac{1}{3}\cos^2(\beta) m_e/f_a$ and $\tan\beta$ is the ratio between two Higgs-field expectation values. Conversely, this implies $\tilde{m}_a/\mathrm{meV} = g_{ae}/2.8 \times 10^{-14}$, where we have defined $\tilde{m}_a = m_a \cos^2\beta$. Our limit on g_{ae} from the TRGB in M5 then implies $\tilde{m}_a < 9.3$ (15.4) meV at the 68% (95%) C.L., respectively.

WDs also emit axions efficiently by bremsstrahlung, and the WD luminosity function allows one to set restrictive limits [42–45]. In particular, Isern *et al.* [43] find that a small amount of axion cooling, corresponding to $\tilde{m}_a \sim 5$ meV, slightly improves the overall fit. On the other hand, a more consistent implementation of axion cooling reveals $\tilde{m}_a < 8$ meV at 95% C.L. [44].

The WD cooling speed can also be tested by the period decrease of pulsating WDs (ZZ Ceti stars). The well-studied case of G117-B15A shows a decrease of its 215 s period at a rate of $(4.19 \pm 0.73) \times 10^{-15}$ s/s and requires additional cooling corresponding to $\tilde{m}_a$ of 15–20 meV [45–47]. The star R548 shows a similar effect where additional cooling is required at about 95% C.L. [48]. The axion limits from the WD luminosity function and TRGB brightness exclude strong axion cooling of pulsating WDs—the apparent period decrease may be caused by other effects or systematic uncertainties.

Still, the tantalizing possibility remains that axions with meV-range masses could exist and then play an important role for the cooling of WDs and neutron stars. If so, core-collapse SNe would emit a significant fraction of their energy in axions and produce a cosmic diffuse supernova axion background [49].

Conclusions.—The observed and predicted I-band brightness of the TRGB in M5 agree reasonably well within uncertainties, although the agreement would improve with a small amount of extra cooling that slightly postpones helium ignition. We have implemented additional cooling by plasmon decay which is enhanced by a neutrino magnetic dipole moment μ_ν and by axion emission in terms of the axion-electron Yukawa coupling g_{ae}. After adding statistical and systematic uncertainties in quadrature, we find the 95% C.L. constraints $\mu_\nu < 4.5 \times 10^{-12} \mu_B$ and $g_{ae} < 4.3 \times 10^{-13}$. These are comparable to similar astrophysical bounds in the literature but are now based on a single GC and a detailed error budget that has allowed for a reasonably quantified confidence level. Both limits correspond to $\Delta M_c < 0.047 M_\odot$ for the nonstandard core-mass increase at helium ignition.

Our limits have not improved as much as one might have hoped, because observations and predictions would agree better with a small amount of extra cooling, although this effect is not significant within the uncertainties. Still, it is noteworthy that the WD luminosity function and period decrease of ZZ Ceti stars also mildly point to extra cooling. None of these cases have fluctuated in the opposite direction of suggesting reduced standard cooling. So perhaps there is an unrecognized common systematic issue with all of these cases.

Our new TRGB comparison between theory and observations can be improved in the future, because our single largest source of uncertainty is the cluster distance, which should be improved by the upcoming GAIA (Global Astrometric Interferometer for Astrophysics) mission. Repeating our analysis for more GCs would also help to check for overall consistency, although the distance from main-sequence fitting would suffer from common uncertainties caused by the limited number of Hipparcos subdwarfs that can be used.

The stellar energy-loss limit remains the most restrictive constraint on μ_ν. The most restrictive laboratory limit uses the $\bar{\nu}_e$ flux from reactors and studies the electron recoil spectrum upon $\bar{\nu}_e$ scattering, leading to the constraint $\mu_{\bar{\nu}_e} < 32 \times 10^{-12} \mu_B$ (90% C.L.) on neutrino magnetic or transition moments that are connected to $\bar{\nu}_e$ [50]. This quantity is different from our μ_ν, which effectively sums over all direct and transition moments between all flavors, and therefore is more general. It also applies to transition moments between ordinary active and putative sterile neutrinos, provided the latter are light enough to be emitted from the degenerate helium core near the TRGB; i.e., the mass is safely below the relevant plasma frequency of about 10–20 keV.

Globular clusters remain powerful—and in some cases leading—particle physics laboratories. Their potential should be fully exploited with contemporary observations and modern stellar evolution theory.

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