

Axion-electron coupling from the RGB tip of Globular Clusters

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We present a preliminary study of the Globular Cluster RGB devoted to improve the available constraint for the axion-electron coupling. By means of multi-band IR photometry of the cluster M3 we obtain $g_{ae}/10^{-13} < 2.57$ (95% C.L.).

1 Introduction.

Shortly after the central H exhaustion, the envelope of a Globular Cluster star rapidly expands up to a few hundred solar radii. Then the star starts to climb the Red Giant Branch (RGB) and its luminosity progressively increases. Meanwhile, the He-rich core contracts, temperature and density increase, until electron degeneracy develops. Initially, the efficient conductive heat transport ensured by degenerate electrons makes the core almost isothermal. Later on, due to the central energy loss caused by plasma neutrinos, an off-center temperature maximum settle on. When the temperature rises above the threshold for the He ignition, a thermonuclear runaway occurs (He flash). This event coincides with the tip of the RGB. As firstly noted by [1] the luminosity of a RGB star essentially depends on the core mass. Then, as a consequence of the shell-H burning, which is active at the bottom of the envelope, the core mass increases and, in turn, the luminosity should increase. Therefore, the RGB tip luminosity can be used to constrain the input physics that controls the growth of the He core mass during the RGB. In this framework a discrepancy between the observed RGB tip luminosity and its theoretical prediction may be considered a hint of missed physical processes. In the following we will discuss the potential of RGB luminosity to constrain the coupling between axions and electrons. Like plasma-neutrinos, axions possibly produced in the core of a star which is climbing the red giant branch is an effective energy sink mechanism affecting the energy balance within the core and, in turn, the luminosity at the time of the off-center He ignition. The general rule is simple, the larger the production rate of weakly interactive particles produced by some thermal process the brighter the tip of the RGB. In this case the dominant axion production process is Bremsstrahlung, while Primakoff and Compton are suppressed because of the high electron degeneracy. [2] make use of I-band photometric data of M5, a well studied cluster of the Milky Way, to derive an upper bound for the strength of the axion-electron coupling: $g_{13} < 4$ (95% C.L.), or $g_{13} = 2 \pm 2$. Here we present a project we started with the aim to improve

cluster	[M/H]	N	$< \delta m_{bol} >$	M_{obs}^{tip}	σ_{stat}	σ_{obs}
M3	-1.16	125	0.045	-3.655	0.070	0.250

Table 1: Parameters used to estimate the magnitude of the RGB tip of M3. $[M/H] = \log \frac{Z}{X} - \log \left(\frac{Z}{X} \right)_{\odot}$ is the cluster metallicity and N is the number of stars within 2 mag from the tip.

this constraint. Instead of a monochromatic photometry of a single cluster, we will exploit multi-color near-IR photometric studies of a sample of galactic clusters from which bolometric magnitude can be directly derived and compared to the theoretical expectations. Brightest RGB stars are rather cool objects and their spectral energy distribution is dominated by near-IR light. In addition, to increase the statistical significance of the stellar sample our strategy is to combine high angular resolution data of the crowded central regions (with HST or ground based adaptive optic telescopes), with large field photometries to cover the external regions of the cluster. The statistical significance of the stellar sample is an important issue for a correct determination of the RGB tip luminosity, a problem often ignored in previous studies. Our statistical approach to address this problem is discussed in the following section. To illustrate the potential of the method we will present the case of M3, another well studied Cluster in the northern sky.

2 The observed brightest RGB star versus the RGB tip.

The observed brightest star on the RGB does not necessarily coincide with the brightest point on the theoretical RGB evolutionary track or isochrone. In principle, the probability to observe the brightest RGB star as close as possible to the RGB tip depends on the total number of stars in the upper portion of the RGB. To estimate this probability, we make use of synthetic color-magnitude diagrams (CMDs, see [3]). In practice, we calculate a series of synthetic CMDs having the same input parameters (age, metallicity and the like) and the same number N of RGB stars with bolometric magnitude in the range m_{bol}^{tip} and $m_{bol}^{tip} + 2$. Although all the synthetic diagrams are computed with the same set of input parameters, the m_{bol} of the brightest star varies from CMD to CMD because of statistical fluctuations. In this way, for each N we calculate the probability density function (PDF) for δm_{bol} , which is the difference between the m_{bol} of the tip and that of the brightest star. Then, for each PDF (each N) we calculate the median and the standard deviation. As N increases, the median approaches the mode, the most probable value, which is always $\delta m_{bol} = 0$. In other words, the observed brightest star approaches the RGB tip as $N \rightarrow \infty$. Then, the absolute magnitude of the RGB is given by: $M_{bol}^{tip} = m_{bol}^{brightest\ star} - < \delta m_{bol} > - (m - M)_0 - A$, where $m_{bol}^{brightest\ star}$ is the apparent bolometric magnitude of the brightest RGB star, $< \delta m_{bol} >$ is the median of the corresponding PDF, $(m - M)_0$ is the distance modulus and A is the extinction coefficient. Then, the total error budget is: $\sigma_{obs}^2 = \sigma_{stat}^2 + \sigma_d^2 + \sigma_A^2 + \sigma_{ph}^2 + \sigma_{BC}^2$, where σ_{stat} is the standard deviation of the appropriate PDF $_N$, and the other 4 uncertainties, which represent the errors on distance, extinction, photometry and bolometric corrections, are obtained according to the available measurements.

As an example, in table 2 we report the estimated value of the tip bolometric magnitude for the cluster M3. The apparent bolometric magnitude of the brightest RGB star has been derived by [4], basing on a near-IR photometric dataset obtained by combining HST and 2MASS data.

In this case the major source of uncertainty is due to the distance.

3 The theoretical RGB tip.

Models of Globular Cluster stars have been computed by means of the FUNS code (for more details, see [5] and references therein). Our theoretical predictions for the RGB tip bolometric magnitude as a function of the cluster metallicity is well represented by the following relation:

$$M_{theory}^{tip} = 0.0161[M/H]^2 - 0.1716[M/H] - 3.87 \quad (1)$$

In the case of M3 we get $M_{theory}^{tip} = -3.65$, which is very close to the observed one. In general, uncertainties of the theoretical estimation of the RGB tip luminosity may be due to the main energy sources, such as the key nuclear reaction rates, or to the energy sinks, such as the plasma neutrino rates. The shell-H burning rate is controlled by the slower reaction of the CNO cycle, i.e., the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction, whose reaction rate has been directly measured by the LUNA collaboration down to 70 KeV [6]. This limit is very close to the Gamow's peak energy for this reaction at the temperature of the shell-H burning of a RGB star. According to the STARLIB database, we assume a $\pm 10\%$ uncertainty for this reaction. The corresponding uncertainty for the theoretical tip bolometric magnitude is: $\sigma_{^{14}\text{N}(p, \gamma)^{15}\text{O}} = 0.007$ mag. On the other hand, the start of the He burning, which coincides with the RGB tip, is controlled by the 3α reaction. For $T \geq 100$ MK, the typical He ignition temperature, the uncertainty for the 3α reaction rate is $\sim \pm 10\%$ [7]. This uncertainty implies an error for the estimated tip bolometric magnitude of $\sigma_{3\alpha} = 0.0075$ mag. Note that the estimated error bars for the nuclear reaction rates do not include the uncertainty in the electron screening. The rate of plasma neutrinos production has been independently derived by several groups ([8], [9] and reference therein). This calculations commonly assume that the neutrino dipole moment, μ , is 0 (or negligible). A non-zero μ would enhance the neutrino production rate, causing a more efficient energy sink and, in turn, leading to larger core-He masses and brighter RGB tips [12]. Such an occurrence could explain or alleviate a discrepancy between stellar models and observed RGB tip luminosities, when the observed tip is brighter than the predicted one. On the other hand, the same discrepancy may be solved by introducing an additional energy sink, such as that induced by the production of non-standard weak interactive particles (e.g. axions). Keeping in mind this warning, in the following we will assume $\mu = 0$. Note that the upper bound for g_{ae} coupling constant we will obtain assuming $\mu = 0$ remains valid also in case of $\mu \neq 0$. This is not true for the hint we can get under the $\mu = 0$ hypothesis. Other model uncertainties are due to the adopted chemical composition, in particular, the metallicity and the initial He mass fraction. In the case of M3 we assume $M/H = -1.16 \pm 0.2$ and $Y = 0.25 \pm 0.01$ that corresponds to ± 0.035 mag and ± 0.015 mag on the RGB tip luminosity, respectively. Therefore, the total theoretical uncertainty is $\sigma_{theory} = 0.04$.

4 Axion-electron coupling from RGB tip

In this section we explore the hypothesis of an additional energy sink caused by the production of hypothetical bremsstrahlung axions. Therefore, we have computed models for different values of the axion-electron coupling constant, namely $0 \leq g_{13} \leq 4$. The axion production rate has been computed according to the prescriptions of [11], for low density plasma, and [10], at higher

densities. Then, the inclusion of the axion cooling rate in the energy conservation equation leads to a larger core mass at the RGB tip and, in turn, to a larger luminosity. We obtain the following equation describing the relation among the RGB tip bolometric magnitude, the metallicity and the axion-electron coupling constant:

$$M_{teory}^{tip} = 0.0161[M/H]^2 - 0.1716[M/H] - 3.87 - 0.0239g_{13}^2 - 0.078g_{13} \quad (2)$$

which reduces to Eq. 1 when $g_{13} = 0$. Then, the most probable value of g_{13} is given by the maximum of the likelihood function: $L = A \exp \left[-(M_{teory}^{tip} - M_{obs}^{tip})^2 / (\sigma_{teory}^2 + \sigma_{obs}^2) \right]$. In the case of M3 we obtain $g_{13} = 0.05$ with upper bound $g_{13} < 2.57$ at 95% C.L.. Because of the smaller difference between theory (no-axion) and observation, the upper bound we get for M3 is smaller than that obtained by [2] for M5. A more substantial improvement of this bound may be obtained by combining data of more clusters, to increase the statistical significance of the sample, and increasing the accuracy of the distance determination, which is the major source of error. In this context the final data release of the astrometric satellite GAIA will produce a big impact [13].

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