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Horizontal Branch Stars as a Probe of Non Baryonic Dark Matter

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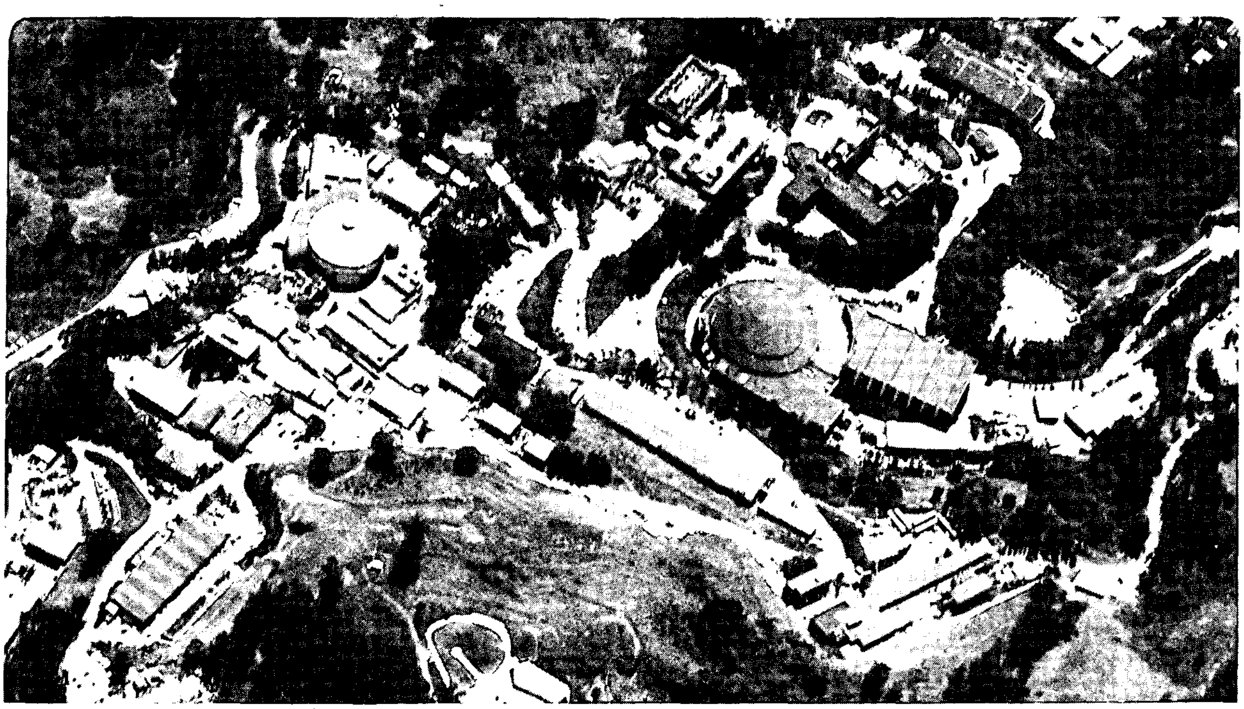

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Horizontal Branch Stars as a Probe of Non Baryonic Dark Matter *†

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ABSTRACT

The solar neutrino problem can be interpreted as a signature for the existence and properties of certain dark matter candidate particles ("cosmions"). We investigate the breaking of convection by neutrino-like cosmions in horizontal branch (HB) stars. These particles may affect globular clusters in the inner galaxy or in dwarf spheroidals where the dark matter density is larger than in the solar neighborhood, leading to an observable reduction of the HB lifetime.

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As pointed out by Renzini [1], the weakly interacting massive particles which may solve the solar neutrino puzzle (cosmions) [2] may also break convection inside horizontal branch (HB) stars and lead to anomalies in the stellar counts of globular clusters. We have reconsidered this exciting possibility, taking possible variations of the dark matter (DM) environment into account.

We approximate the helium core of a typical HB star of a globular cluster with a polytrope of index n = 1.5. In such a model, the central density $\rho_c = \rho_{c4} \times 10^4\,\mathrm{g\,cm^{-3}}$ is given as a function of the central temperature $T_c = T_{c8} \times 10^8\,K$, the average molecular weight μ and the mass of the core :

$$\rho_{c4} = 0.1894\, T_{c8}^3\, (M_\odot / M_{\mathrm{core}})^2\, (4/3\mu)^3 \ . \qquad (1)$$

We consider specifically a $0.66\,M_\odot$ star with $M_{\mathrm{core}} = 0.475\,M_\odot$ and a helium mass fraction of $Y = 0.971$ at the beginning of the HB phase. In a standard numerical model [3], this implies $T_c = 1.18 \times 10^8\,\mathrm{K}$ and $\rho_c = 2.12 \times 10^4\,\mathrm{g\,cm^{-3}}$. Using this value of T_c for our polytropic approximation yields $\rho_c = 1.34 \times 10^4\,\mathrm{g\,cm^{-3}}$, in reasonable agreement with the numerical model. Moreover, in the polytropic approximation, the nuclear energy generated over the entire core is $L_{\mathrm{core}} = 13.8\,L_\odot$, to be compared with $15\,L_\odot$ of the numerical model [3]. This excellent agreement encouraged us to trust our relatively simple analytical approach and to use it in order to quantify the effects of cosmions on convection breaking inside HB stars.

In the core of an HB star, the total energy flux L_{core} is too large to be carried by radiative transfer, and so convection develops. However, if the star has been steadily accreting cosmions since its birth, and if the maximum energy transfer L_x carried by these particles approaches L_{core}, the remaining energy can be carried out by radiation, and convection consequently is broken. Following Ref. [4], we have used the analytical approximation :

$$L_x = 1.1 \times 10^4\, L_\odot\, T_{c8}\, \rho_{c4}^{1/2} \left(\frac{N_x}{10^{47}}\right) \left(1 - \frac{T(r_x)}{T_c}\right) \frac{K}{1+K^2}\,, \qquad (2)$$

where the cosmion Knudsen number is $K^{-1} = r_x\, n_{\mathrm{He}}\, \sigma_{\mathrm{He}}\, 4 m_x m_{\mathrm{He}} / (m_x + m_{\mathrm{He}})^2$ with the number density n_{He} for helium. The scale height for the cosmion cloud is $r_x = 3 \times 10^9\,\mathrm{cm}\,(T_{c8}/\rho_{c4})^{1/2}\,(m_p/m_x)^{1/2}$ and is just intermediate between the radius of the nuclear energy producing region (80% of L_{core} originates from the inner 8×10^8 cm) and the scale over which convection and associated semi-convection develops ($1.5 - 2 \times 10^9$ cm). For $L_x > L_{\mathrm{core}}$, the core adjusts itself to a radiative structure and convection is broken. In the perturbed star, one would have $L_x = L_{\mathrm{core}} - L_{\mathrm{rad}}$ so that for a self-consistent structure L_x never exceeds the nuclear energy production.

If evaporation during the helium flash or at the beginning of the HB phase is not important, the number N_x of cosmions in an HB star is given by the number $N_{\rm MS}$ accreted during the main sequence evolution, which is found to be [5,6] :

$$N_{\rm MS} \approx 1.8 \times 10^{47} f_{\rm MS} \, (m_p/m_x) \, [1 - exp(\sigma_{\rm eff}/\sigma_{\rm crit})] \, . \tag{3}$$

The critical cross section $\sigma_{\rm crit}$ above which all cosmions impinging on the star are trapped is $\sigma_{\rm crit} = 3 \times 10^{-36} \, {\rm cm}^2 \ (M/0.66 \, M_\odot)^{0.6}$ where M is the progenitor mass, and we have assumed that its radius varies as $M^{0.8}$. For neutrino-like WIMPs [7], the cross section $\sigma_{\rm eff}$ relevant for cosmion trapping on the main sequence may be approximated by $\sigma_{\rm eff} = 0.1 \, \sigma_{\rm He}$. The "fudge factor" $f_{\rm MS}$ characterizes the progenitor and its dark matter environment by :

$$f_{\rm MS} = \left(\frac{\rho_{\rm DM}}{0.01 \, M_\odot/{\rm pc}^3} \right) \left(\frac{300 \, {\rm km/s}}{\overline{v}} \right) \left(\frac{M}{0.66 \, M_\odot} \right)^{1.8} \left(\frac{\tau_{\rm MS}}{10^{10} \, {\rm yr}} \right) , \tag{4}$$

where $\rho_{\rm DM}$ is the dark matter density, $\overline{v}$ its velocity dispersion, and $\tau_{\rm MS}$ the main sequence lifetime. Our benchmark values for $\rho_{\rm DM}$ and $\overline{v}$ characterize the solar neighborhood. The number N_x of cosmions in the HB star will be identical with $N_{\rm MS}$ unless cosmions are ejected during the helium flash (a possibility which we estimate to be fairly unrealistic), or unless they evaporate from the HB star [4].

Fig. 1 shows the range of m_x and $\sigma_{\rm He}$ values for which convection is broken ($L_x > L_{\rm core}$) in the case of neutrino-like WIMPs. Below the "evaporation line", the cosmion population is depleted by HB evaporation and, as pointed out by Spergel and Faulkner [4], no effect on HB stars occurs. Above this line, different contours for the values $f_{\rm MS} = 1.5$, 3, 5, and 10 delimit the regime where convection is broken. The dashed rectangle delimits the approximate range of parameters for which the solar neutrino puzzle is solved. Thus it is clear that the regime of cosmion parameters to which HB stars are sensitive depends strongly on the "environmental factor" $f_{\rm MS}$, where $f_{\rm MS} = 1$ characterizes the solar neighborhood.

Number counts of HB stars in 15 well studied globular clusters clearly indicate that convection is not broken in these systems [8]. All of these globular clusters are at relatively large distances from the inner galaxy so that presumably $f_{\rm MS} \approx 1$. These observations do not preclude an interpretation of the solar neutrino deficiency as a signature of neutrino-like cosmions. However, one may expect to observe an anomalous paucity of HB stars in systems where the "environmental factor" $f_{\rm MS}$ is only slightly enhanced over the solar values. An example would be globular clusters in the inner galaxy, where the dark matter density is enhanced by a factor of at least 2 and the one-dimensional velocity dispersion in the inner halo, inferred from the spheroidal component of the galaxy, is about 120 km/sec, whence $f_{\rm MS} \approx 3$. An even stronger test may come from examining HB stars in nearby dwarf spheroidal galaxies. Several of these are inferred to contain substantial amounts of dark matter [9] with a density $\sim 0.1\,M_{\odot}\,\mathrm{pc}^{-3}$. Even though the dark matter core radius is not measured directly, the velocity dispersion in the luminous cores (around 200 pc) is 10 − 20 km/sec, so that we infer $f_{\mathrm{MS}} \approx 100$. While a significant population of HB stars is seen in these systems [10], the data have not been analyzed to determine the HB lifetimes. A detailed analysis of the color magnitude diagrams could either yield a signature for DM cosmions or, less interestingly, allow for the exclusion of a large range of cosmion parameters.

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Figure caption

Figure 1 : Neutrino-like WIMPs. Range of masses m_x and scattering cross sections on helium $\sigma_{\rm He}$ for which convection is broken. Below the curve "HB evaporation", cosmions evaporate quickly during the HB phase, and their equilibrium number is too small to break convection. Above this curve, their number is determined by the main sequence accretion as given in Eq. (3) and (4). For a given $f_{\rm MS}$ value, convection is broken inside the corresponding island. The environmental factors $f_{\rm MS} = 1.5, 3, 5$ and 10 are displayed. The dashed rectangle delimits the approximate regime for which cosmions would solve the solar neutrino problem.

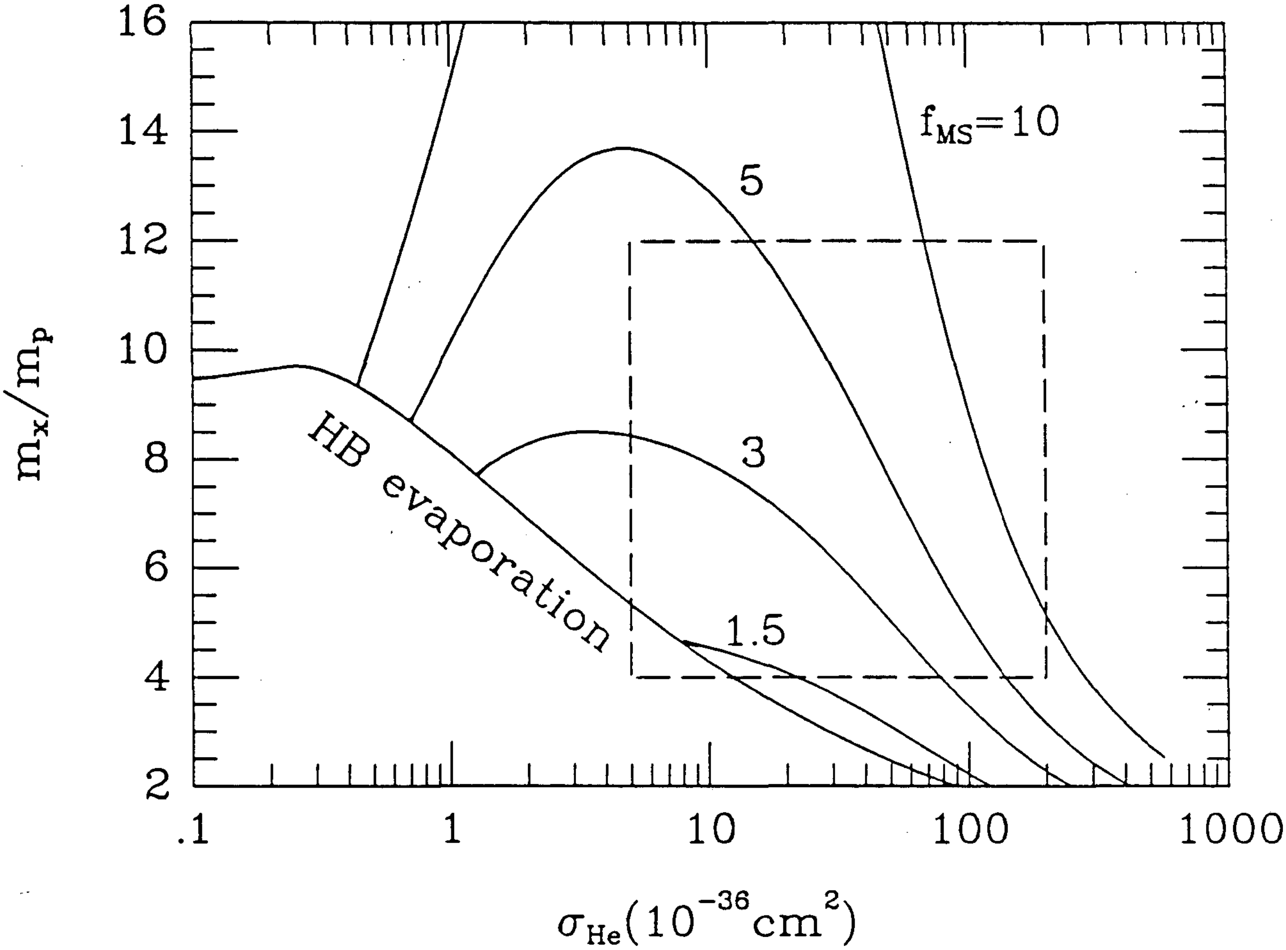
16
14
12
10
8
6
4
2
.1
1
10
100
1000
m_x/m_p
$\sigma_{He}(10^{-36}cm^2)$
$f_{MS}=10$
5
3
1.5
HB evaporation

Figure 1

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