

Lawrence Berkeley National Laboratory

Recent Work

Title

HORIZONTAL BRANCH STARS AS A PROBE OF NONBARYONIC DARK MATTER

Permalink

<https://escholarship.org/uc/item/3pc0t6vn>

Author

Salati, et al. Pierre

Publication Date

1989

ca



Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Physics Division

RECEIVED
LIBRARY
BERKELEY, CALIF.

AUG 8 1989

LIBRARY AND
DOCUMENTS SECTION

Presented at the Particle Astrophysics Workshop,
Forefront Experimental Issues, Berkeley, CA,
December 8-10, 1988

Horizontal Branch Stars as a Probe of Non Baryonic Dark Matter

P. Salati, A. Bouquet, G. Raffelt, and J. Silk

January 1989



LBL-26589

ca

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

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

Pierre Salati^{1,2} †, Alain Bouquet³, Georg Raffelt^{1,4} and Joseph Silk¹

¹*Astronomy Department, University of California
Berkeley, CA 94720, U.S.A.*

²*Lawrence Berkeley Laboratory, University of California
Berkeley, CA 94720, U.S.A.*

³*Laboratoire d'Annecy le Vieux de Physique des Particules (LAPP)
BP 110, 74941 Annecy le Vieux Cedex, France*

⁴*Institute for Geophysics and Planetary Physics, LLNL
Livermore, CA 94550, U.S.A.*

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.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

†Talk presented by P. Salati at the Particle Astrophysics Workshop, Forefront Experimental Issues, held in Berkeley, CA, on December 8-10, 1988.

‡Miller Research Fellow at the University of California at Berkeley. On leave of absence from LAPP and from Université de Chambéry, 73000 Chambéry, France.

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 $\rho_c = \rho_{c4} \times 10^4 \text{ g cm}^{-3}$ is given as a function of the central temperature $T_c = T_{c8} \times 10^8 \text{ K}$, the average molecular weight μ and the mass of the core :

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

We consider specifically a $0.66 M_\odot$ star with $M_{\text{core}} = 0.475 M_\odot$ and a helium mass fraction of $Y = 0.971$ at the beginning of the HB phase. In a standard numerical model [3], this implies $T_c = 1.18 \times 10^8 \text{ K}$ and $\rho_c = 2.12 \times 10^4 \text{ g cm}^{-3}$. Using this value of T_c for our polytropic approximation yields $\rho_c = 1.34 \times 10^4 \text{ g cm}^{-3}$, in reasonable agreement with the numerical model. Moreover, in the polytropic approximation, the nuclear energy generated over the entire core is $L_{\text{core}} = 13.8 L_\odot$, 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 :

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

where the cosmion Knudsen number is $K^{-1} = r_x n_{\text{He}} \sigma_{\text{He}} 4m_x m_{\text{He}} / (m_x + m_{\text{He}})^2$ with the number density n_{He} for helium. The scale height for the cosmion cloud is $r_x = 3 \times 10^9 \text{ cm} (T_{c8}/\rho_{c4})^{1/2} (m_p/m_x)^{1/2}$ and is just intermediate between the radius of the nuclear energy producing region (80% of L_{core} originates from the inner $8 \times 10^8 \text{ cm}$) and the scale over which convection and associated semi-convection develops ($1.5 - 2 \times 10^9 \text{ cm}$). For $L_x > L_{\text{core}}$, the core adjusts itself to a radiative structure and convection is broken. In the perturbed star, one would have $L_x = L_{\text{core}} - L_{\text{rad}}$ 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_{MS} accreted during the main sequence evolution, which is found to be [5,6] :

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

The critical cross section σ_{crit} above which all cosmions impinging on the star are trapped is $\sigma_{\text{crit}} = 3 \times 10^{-36} \text{ cm}^2 (M/0.66 M_{\odot})^{0.6}$ 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 σ_{eff} relevant for cosmion trapping on the main sequence may be approximated by $\sigma_{\text{eff}} = 0.1 \sigma_{\text{He}}$. The “fudge factor” f_{MS} characterizes the progenitor and its dark matter environment by :

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

where ρ_{DM} is the dark matter density, \bar{v} its velocity dispersion, and τ_{MS} the main sequence lifetime. Our benchmark values for ρ_{DM} and \bar{v} characterize the solar neighborhood. The number N_x of cosmions in the HB star will be identical with N_{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 σ_{He} values for which convection is broken ($L_x > L_{\text{core}}$) 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 $f_{\text{MS}} = 1.5, 3, 5,$ 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_{MS} , where $f_{\text{MS}} = 1$ 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 $f_{\text{MS}} \approx 1$. 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_{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 $f_{\text{MS}} \approx 3$. 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 $\sim 0.1 M_{\odot} \text{pc}^{-3}$. 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 $f_{\text{MS}} \approx 100$. 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.

We acknowledge helpful discussions with D. Dearborn, M. Rees, A. Renzini, D. Seckel and D. Spergel. This research has been supported at Berkeley by grants from DOE, IGPP and CalSpace. At Livermore, this work was performed under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng-48. At LBL, it has been supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under contract No. DE-AC03-76SF 00098. One of us, (PS), acknowledges a fellowship from the Miller Institute for Basic Research in Science at the University of California at Berkeley and would like to thank Professor B. Sadoulet to have invited him to speak at the Particle Astrophysics Workshop, Forefront Experimental Issues, held in Berkeley, on December 8-10 1988.

References

- [1] A. Renzini, *Astron. Astrophys.* **171**, 121 (1987).
- [2] G. Steigman, C. L. Sarazin, H. Quintana, and J. Faulkner, *Astrophys. J.* **83**, 1050 (1978). R. L. Gilliland, J. Faulkner, W. H. Press, and D. N. Spergel, *Astrophys. J.* **306**, 703 (1986).
- [3] A. V. Sweigart and P. G. Gross, *Astrophys. J.* **190**, 101 (1974).
- [4] D. N. Spergel and J. Faulkner, *Astrophys. J.* **331**, L21 (1988).
- [5] W. H. Press and D. N. Spergel, *Astrophys. J.* **296**, 679 (1985).
- [6] A. Bouquet and P. Salati, Report LAPP-TH-192/87 and LPTHE 87-20, *Astron. Astrophys.*, 1988, to be published.
- [7] G. B. Gelmini, L. J. Hall and M. J. Lin, *Nucl. Phys. B* **281**, 726 (1987).
- [8] For a review see I. Iben Jr. and A. Renzini, *Phys. Rep.* **105**, 329 (1984).
- [9] M. Aaronson, in C. Norman, A. Renzini, M. Tosi (eds.), *Stellar Populations* (Cambridge University Press, 1986).

- [10] E. W. Olszewski and M. Aaronson, *Astron. J.* **90**, 2221 (1985). G. S. DaCosta, *Astrophys. J.* **285**, 483 (1984). J. Mould and M. Aaronson, *Astrophys. J.* **273**, 530 (1983).

Figure caption

Figure 1 : Neutrino-like WIMPs. Range of masses m_x and scattering cross sections on helium σ_{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_{MS} value, convection is broken inside the corresponding island. The environmental factors $f_{\text{MS}} = 1.5, 3, 5$ and 10 are displayed. The dashed rectangle delimits the approximate regime for which cosmions would solve the solar neutrino problem.

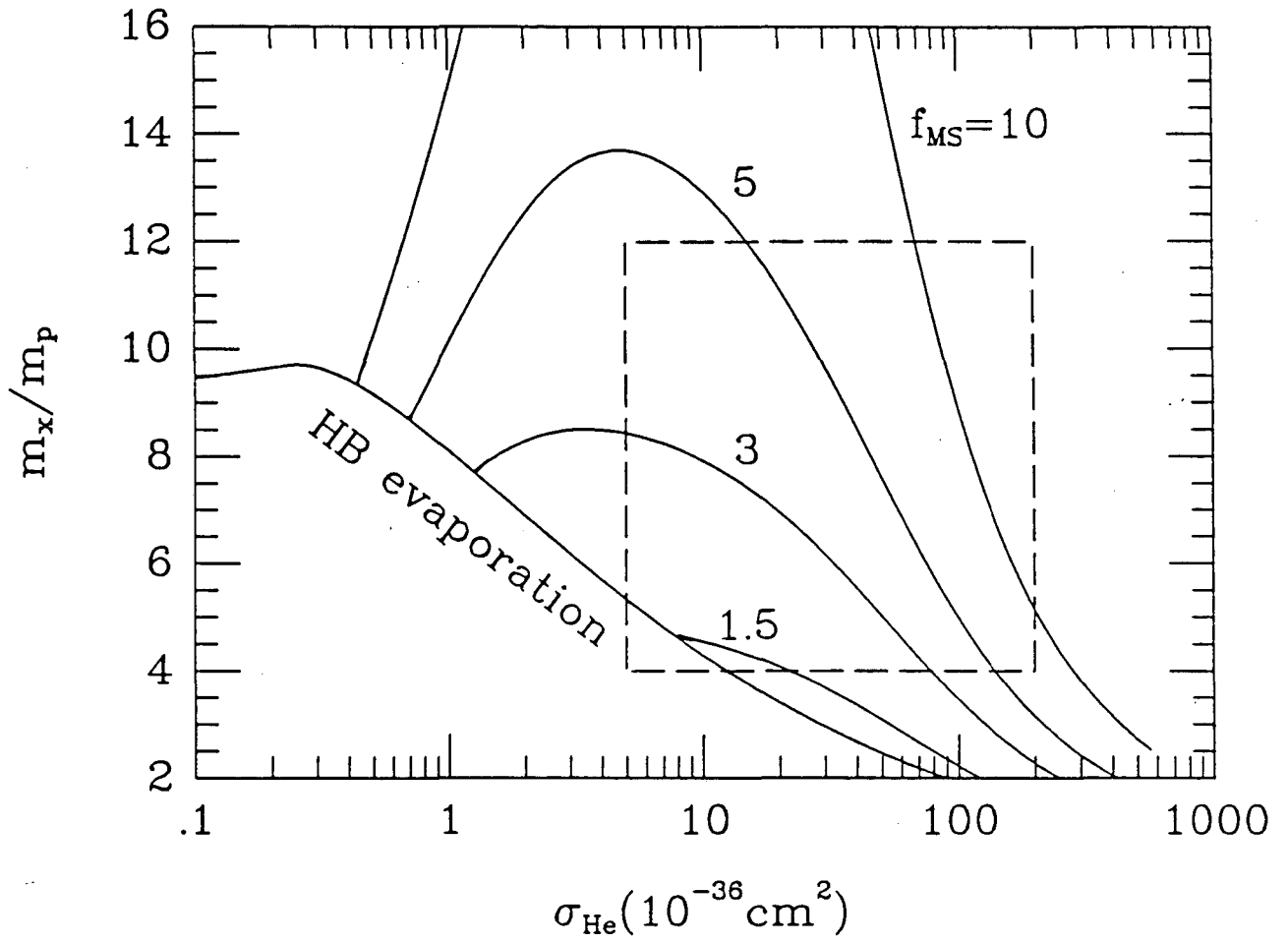


Figure 1

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720