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D.E. Winget[*], M.H. Montgomery[*], S.O. Kepler[†], F. Campos[†] and P. Bergeron[**]

[*]Department of Astronomy, McDonald Observatory and the Texas Cosmology Center, University of Texas at Austin, Austin, TX, USA
[†] Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS - Brasil
[**]Département de Physique, Université de Montréal, C. P. 6128, Succ. Centre-Ville, Montréal, Québec H3C 3J7, Canada

Abstract. We explore the physics of crystallization in the dense Coulomb plasma of the deep interiors of white dwarf stars using the color-magnitude diagram and luminosity function constructed from Hubble Space Telescope photometry of the globular cluster M 4 and compare it with our results for proper motion cleaned Hubble Space Telescope photometry of the globular cluster NGC 6397. We demonstrate that the data are consistent with a binary mixture of carbon and oxygen crystallizing at a value of Γ higher than the theoretical value for a One Component Plasma (OCP). We show that this result is in line with the latest Molecular Dynamics simulations for binary mixtures of C/O. We discuss implications for future work.

Keywords: white dwarfs, astrophysical plasma, stellar evolution
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ASTROPHYSICAL CONTEXT

In [9] we showed that the HST observations of the globular cluster NGC 6397 could be used to constrain the physics of crystallization in a dense Coulomb plasma. In particular, we suggested that either there was very little oxygen in the interiors of globular cluster white dwarf stars, or the binary mixture of carbon and oxygen must crystallize at a much higher value of Γ than that for a one component plasma (OCP). This work created renewed interest in the crystallization of a binary mixture of carbon and oxygen; several groups have since investigated this question and published their findings, these include Medin & Cumming (2010) [4], Horowitz, Schneider & Berry (2010) [3], and H. DeWitt and collaborators (2010) [2].

The melting curve from Figure 2 in Horowitz, Schneider & Berry (2010) [3] is shown, with permission, in our Figure 1. The key result from this work and that of Medin & Cumming (2010) [4] is that for oxygen mass fractions less than about 60%, the melting temperature is very close to that for pure carbon. This has profound consequences for our understanding of the interiors of globular cluster white dwarfs. In this paper we use this melting curve to recalculate the theoretical luminosity function for NGC 6397 using models with equal mass fractions of carbon and oxygen using the constraints and techniques described in [9] to compare with the observed luminosity function from HST data using a proper motion cleaned sample obtained by Richer et al. (2008) [6]. We perform a similar calculation of the theoretical luminosity function for the globular
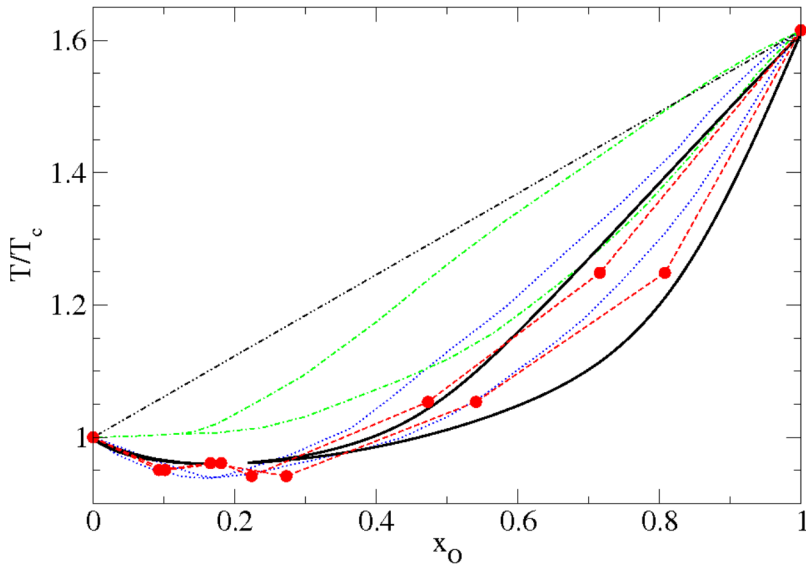
FIGURE 1. Theoretical phase diagram taken from Figure 2 of Horowitz, Schneider & Berry (2010) [3], with permission. The plot shows the excellent agreement between the results of [4], the solid black lines, and the filled red circles of the molecular dynamics simulations of [3]. The liquid and solid phase are shown as two separate lines. The additional calculations shown are density functional calculations of Segretain (1996) [7], the dot-dashed green lines, and Ogata et al. (1993) [5], the dotted blue line; the dot dashed grey lines represent the value of $\Gamma = 178$ connecting the pure carbon point with pure oxygen.

cluster M4 and compare with the HST observations of Bedin et al. (2009) [1].

NGC 6397 REVISITED WITH THE NEW MELTING CURVE

We used the same theoretical colors from model atmosphere grid computed by one of us (PB) and the same values of distance and reddening as our earlier work [9]. These last are obtained by fitting the main sequence and the white dwarf cooling sequence simulataneously; this serves to anchor the cooling tracks in the observed color-magnitude diagram, thereby constraining the white dwarf masses. In Figure 2 we plot the observed luminosity function in the F814W filter against a set of theoretical models. All models are computed with 50/50 carbon and oxygen and include phase separation. The models labeled PSSC use the old Segretain and Chabrier [8] phase diagram, and the models labeled PSHB use the new [3] phase diagram. This verifies the conclusions of [3] and illustrates that evolutionary models computed with the new phase diagram, computed
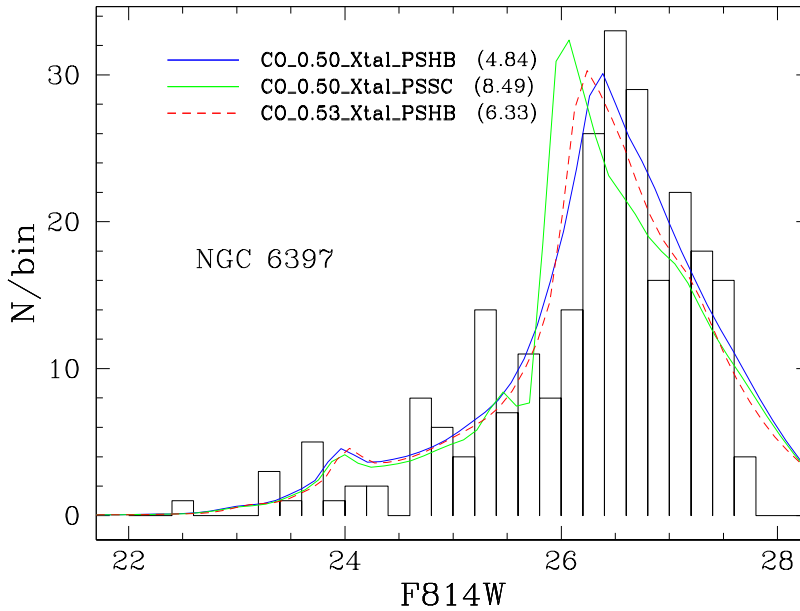
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FIGURE 2. Theoretical Luminosity Functions plotted with the observed Luminosity Function for NGC 6397.

for a binary (50/50) mixture of carbon and oxygen using new molecular dynamics calculations, provide a comparable fit to that obtained with the old pure carbon models.

We stand to gain considerable confidence in these new phase diagram results if we can use them successfully for another cluster. In the next section we examine this question.

A COLOR-MAGNITUDE DIAGRAM FOR M4

In figure 3 we see the color magnitude diagram for the white dwarf stars created from the HST observations of M4 by Bedin et al. (2009). We obtained reddening and distance parameters to place the models in the color-magnitude plane by again simulatneously fitting both the main sequence and the white dwarf cooling sequence as in [9]. i Note that presence of a blue hook, presumably the result of low temperature opacity effects from collisionally induced absorption, necessitates the division of the color-magnitude diagram into color regions as shown in the figure in red and blue boxes. The inclusion of the stars in red boxes in the luminosity function results in a piling-up of stars that is only an artifact of the blue hook on the left-hand side and possible DB stars on the right-hand side. We also note that M4 may be less well characterized by a single mass through the region of the luminosity function maximum than was the case for NGC 6397.
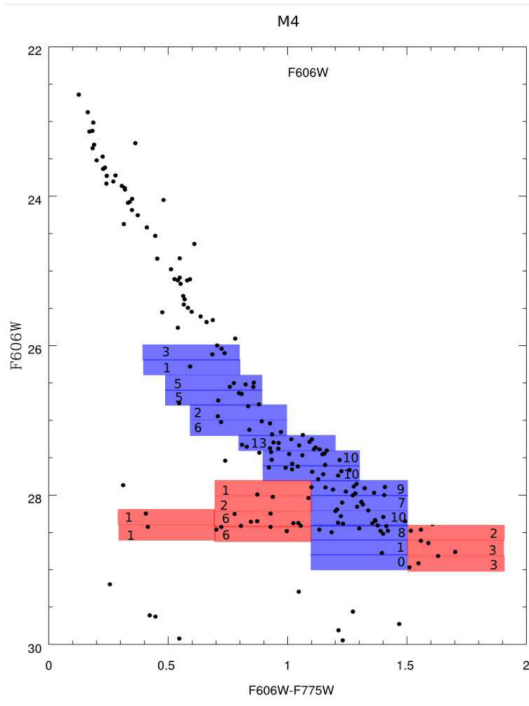
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FIGURE 3. We plot the observed color-magnitude diagram for M4. The results of summing the stars in each of the quarter-magnitude bins are shown as a number printed inside each shaded rectangle.

APPLICATION OF THE NEW MELTING CURVES TO M4

We construct the luminosity function for the white dwarfs in M4 by plotting the numbers in each of the central, blue-shaded, boxes shown in figure 3 as a function of magnitude. We then apply the same tools and techniques to construct the theoretical luminostity functions to compare with M4. Although the same model atmospheres were used, there is a difference in the filters used on HST for the observations as noted in the axes. In figure 4 we present the results of the theoretical luminosity functions with the old and new phase diagrams to the observed luminosity function constructed as described above. Our results are very consistent with those for NGC 6397 as the figure clearly shows. Although we have only plotted the lower mass models in the figure for the M4 cluster, We do note that these models are likely the best-fitting mass for both clusters.

CONCLUSIONS AND DISCUSSION

We find that our results from fitting the observed luminsity functions in the globular clusters NGC 6397 and M4 with models constructed using the phase diagram of Horowitz, Schneider, and Berry (2010) [3] allow us to draw two important conclusions. First, and
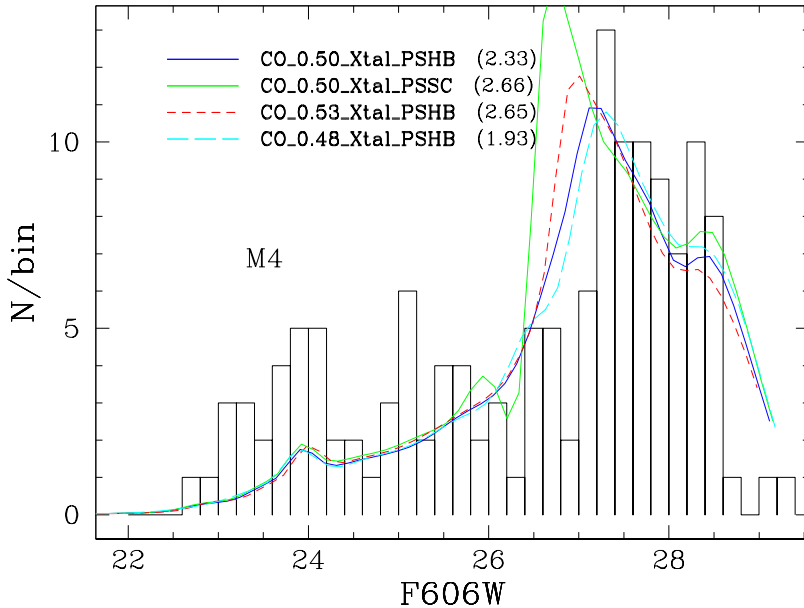
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FIGURE 4. Theorecital Luminosity Functions plotted with the observed Luminosity Function for M4.

perhaps least surprising, the internal composition of the white dwarf stars in globular clusters are consistent with the conclusions of asteroseismology for the internal abuncances of disk white dwarfs: roughly equal parts carbon and oxygen in the core. This is not surprising as there was no a priori reason to suspect that the metallicity of the star on the main sequence would affect the results of helium burning in the core. Second, the ratio of the Coulomb to the thermal energy of the ions at crystallization in a dense Coulomb plasma is substantially higher for a binary C/O mixture than for a one component plasma (OCP).

What might be less obvious, is that the two conclusions above may be strongly linked. The deep interior is not a pure binary mixture, but contains trace elements in proportion to the parent metallicity, as well as those resulting from by-products of helium burning. Does this alter the Γ of crystallization relative to a pure binary mixture? The effect may be significantly enhanced near the centers by the settling of heavier elements in the core–this is more fully described by Garcia-Berro et al. in a paper in these proceedings. As they point out, this releases additional graviational energy, slowing cooling. This raises an interesting question. Does increasing the fractional abundance in the core of elements heavier than carbon and oxygen, beyond trace levels associated with the parent metallicity, have the potential to further affect the value of Γ at crystallization? This remains to be investigated.

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