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EVIDENCE FOR WHITE DWARFS WITH STRANGE-MATTER CORES*

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We summarize masses and radii for a number of white dwarfs as deduced from a combination of proper motion studies, *Hipparcos* parallax distances, effective temperatures, and binary or spectroscopic masses. A puzzling feature of these data, however, is that some stars appear to have radii which are significantly smaller than that expected for a standard electron-degenerate white-dwarf equations of state. We construct a projection of white-dwarf radii for fixed effective mass and conclude that there is at least marginal evidence for bimodality in the radius distribution for white dwarfs. We argue that if such compact white dwarfs exist it is unlikely that they contain an iron core. We propose an alternative of strange-quark matter within the white-dwarf core. We also discuss the impact of the so-called color-flavor locked (CFL) state in strange-matter core associated with color superconductivity. We show that the data exhibit several features consistent with the expected mass-radius relation of strange dwarfs. We identify eight nearby white dwarfs which are possible candidates for strange matter cores and suggest observational tests of this hypothesis.

We explore[1] the possible existence of white dwarfs with strange-matter cores. Such *strange dwarfs* could gradually form[2–4] during the progenitor main-sequence by the accretion of a strange-matter nugget which pre-exists either as a relic of the early universe or as an ejected fragment from the merger/coalescence of strange-matter neutron stars. Once captured by a star, strange-matter nuggets would gravitationally settle to the center and begin to convert normal matter to strange matter. This would eventually lead to the formation of an extended strange-quark-matter core

2

in the white dwarf remnant.

The additional degrees of freedom for strange-quark matter lower the degeneracy pressure and Fermi energy and allow the matter to be more compact. A strange white dwarf is expected[1–3] to consist of three distinct regions, a crust, a core-crust boundary, and a core.

The crust of the star is composed of normal degenerate matter[5] taken here to be ^{12}C. Within the crust the density increases until the neutron drip density, $\rho_{drip} = 4.3 \times 10^{11}$ g cm^{-3}, above which free neutrons are released which gravitate to the core where they are absorbed and converted into strange matter.[2–4] A sharp boundary between the inner core and the outer crust develops[6] due to a Coulombic repulsion. The finite mass of the strange quark prevents the achievement of neutral strange matter. Degenerate electrons are unable to fully neutralize the positive charge of the inner strange-matter core because they are not bound by the strong interaction. Hence, a dipole layer of very high voltage develops between the crust and the core which isolates the core. This gap prevents the further growth of the core beyond the radius associated with the neutron drip density and defines the size to which the strange-quark core can grow.

The core of the star is taken to be comprised of noninteracting $\approx$ massless u and d quarks and gluons plus s quarks with $m \approx 150$ MeV. The *MIT* bag model equation of state is adequate for our purposes whereby, $P = (\rho - 4B)/3$, with ρ the mass-energy density and B the bag constant constrained from hadronic properties to be, $B^{1/4} \sim 145$ to 160 MeV. Within the quark core, the density reaches $\sim 2 - 3$ times nuclear matter density ($\sim 4 - 6 \times 10^{14}$ g cm^{-3}. Although the density jumps discontinuously at the boundary, the star maintains pressure equilibrium and the pressure varies continuously through the star.

Adopted masses and radii for 22 nearby white dwarfs[7,8] are shown in Fig. 1. The astrometric mass was taken[1] to be better than the spectroscopic or gravitational mass. Radii are based upon the Stefan-Boltzmann radius inferred from the observed luminosity and *Hipparcos* distances or the gravitational redshift.

The curves for strange dwarfs agree surprisingly well with several of the best determined data points. Of particular importance are *G238-44, EG 50* and *GD 140*. These stars have well determined masses and they lie very close to the strange dwarf mass radius relation. The other stars which minimize χ^2 by identification as a strange-dwarf are *G156-64, EG21, G181-B5B, GD 279* and *WD2007-303*. The total χ^2 if all stars are associated with a normal carbon white-dwarf EOS is 119 (reduced $\chi_r^2 = 5.2$ for 23 degrees of freedom). If we allow an iron-core population with members chosen to minimize χ^2 we obtain 105 ($\chi_r^2 = 4.4$ with 24 degrees of freedom). This is to be compared with a value of 78 ($\chi_r^2 = 3.2$) when these eight stars are identified with a strange-matter EOS. Hence, we have a $\Delta\chi^2 = 41$ ($\sim 6\sigma$) preference for the presence of a strange-dwarf population over a normal EOS versus a $\Delta\chi^2 = 14$ ($\sim 4\sigma$) improvement by identifying these stars with an iron-core population.

We also note[1] that two of the stars *G181-B5B* and *GD279* have temperatures

($T \approx 13,500$ K) which are tantalizingly close the the DAV ($ZZCeti$) pulsation instability at $T \approx 12,000$ K. We have estimated[1] that the buoyancy frequency will be affected by the steep density gradient of the core. This will lead to mode filtering and easier excitation of those pulsation modes which probe the inner strange-matter core. Preliminary observations have begun to search for the relevant pulsations and determine the cooling rate in these stars.
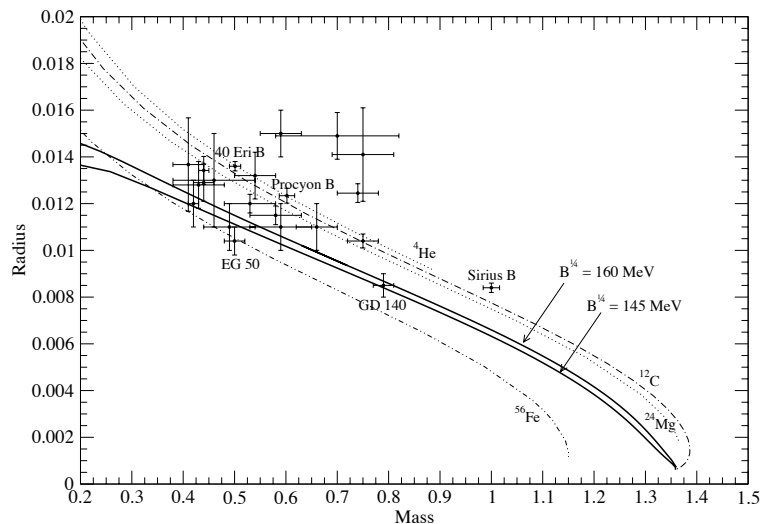

Fig. 1.   Comparison of the theoretical mass-radius relationships for strange dwarfs (solid curves) and normal white dwarfs with the data of.[7,8]

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