Constraints on superdense preon stars and their formation scenarios

J. E. Horvath
Instituto de Astronomia, Geofísica e Ciencias Atmosféricas
Rua do Matão 1226, 05508-900 São Paulo SP, Brazil
foton@astro.iag.usp.br

February 5, 2020

Abstract We address in this work the general features of a possible compact stars composed by elementary fermions beyond the quark level. The locus of these hypothetic objects in the mass-radius plane is constructed for the maximum mass (minimum radius) of the sequence of models in terms of a compositeness scale only, and in fact this approach applies for any composite model postulating fermions at or beyond the preon level. We point out a constraint on the preon mass arising from the applicability of the General Relativity structure equations, leading to the questioning of the hypothesis of light preons if the preon scale is high, provided classical compact objects are enforced. Some remarks on the existence of superdense stars of astrophysical and primordial origin are made and discussed.

keywords: preons, compact stars, cosmology.
PACS Nos.: 12.60.Rc, 98.80.-k

1 Introduction

Relativistic astrophysics and particle physics seem to have merged completely in modern science. Starting from the pioneer works, the developed interplay between both disciplines is far-reaching and long-lasting. As a prime example, the quest for the internal composition of actual “neutron” stars, as discovered in 1967 (Hewish et al. 1967) is still ongoing after several decades of research. Landau’s (1932) insight preceded this discovery by more than 30 years, and Baade and Zwicky (1934) were among the first to postulate an actual astrophysical site to produce these objects, namely type II supernova thought to arise after gravitational collapse of a massive star. Later in the ’60s the emergence of the quark model (that is, the acknowledgement that nucleons are composed of more elementary fermions, confined in bubbles of the order $\sim 1 \text{fm}$ at low energies) raised the possibility of having deconfined matter inside neutron stars (Ivanenko and Kurdygaidze 1969; Itoh 1970; Collins and Perry 1975). A radical version of this idea was put forward
later, namely, that a form of cold quark matter could be the true ground state of hadronic interactions (Bodmer 1971; Terazawa 1979; Chin and Kerman 1979; Witten 1984) and thus “neutron” stars should be rather giant quark balls, properly renamed as strange stars. Stars may be the only place in the universe for the latter to form.

In spite of its success, the well-known incompleteness of the Standard Model, needing at least 19 parameters of unknown origin to work, prompted unification ideas based on the gauge theory concepts extended to higher energies. Following the historical examples of the atomic nucleus and the subnuclear partons, the idea of seeking another compositeness scale and construct the known hadrons and leptons out of a small set of more elementary components (termed preons hereafter) raised in the ’70s. Examples of this approach were discussed by Pati and Salam (1983) and Pati (1989), among many others (see D’Souza and Kalman 1992 for a more complete account). This “bottom-up” strategy to understand nature building blocks is now somewhat superseded by Theories of Everything starting from a whole symbiosis of particles and forces and trying to understand how to go down in energy to match the observations and experiments accessible today. However, and despite of the attractive features of TOEs, it is not obvious that they can successfully explain the physics of the Standard Model and beyond, disconnected of the natural unification scale by many orders of magnitude in energy, and it is entirely possible that unification schemes can be derived from them instead of the Standard Model gauge structure (Pati 2006).

Several theoretical expectations to strike the next interesting scale in physics rely on the existence of supersymmetry, relating known bosons and fermions, broken below some scale $\Lambda_{SUSY}$. Supersymmetry (SUSY) is very important for TOEs as well, and in fact many of the preon models required supersymmetry to work (Pati 1989). It is expected that supersymmetry can be observed in colliders at an energy scale of around $\approx 1 \, TeV$. In fact, experimental limits to the compositeness of electrons have shown (Sabetfakhri 2000) that preons are not needed down to $\ell \sim 10^{-17} \, cm$, a value consistent with some SUSY preon models, which should show up well above the present accelerator energies. Based on all these expectations, we shall always adopt $1 \, TeV$ as a minimal scale for compositeness below, keeping in mind that a viable scheme could require a much higher value.

The very existence of compositeness of quarks and leptons would merit a consideration related to the compact star problem. Recently Hansson and Sandin (2005) and Sandin (2005) have discussed the general features of hypothetic preon stars, including their possible role in avoiding black hole formation (Hansson 2006). Given that almost nothing is known of detailed preon physics (i.e. masses, interactions, etc.), we limit ourselves to the most general features, which are quite model-independent, and show below the room left in the mass-radius plane and related issues. Finally we point out the serious difficulties encountered to form preon stars in the contemporary and primordial universe.

2 How much room for preon stars?

With just minimal assumptions about a fermionic character of preons, their lightness (they should compose light known particles, like neutrinos), and an assumed minimal compositeness scale, it is still possible to address the features of putative preon stars. As
a suitable framework for this task, Narain, Schaffner-Bielich and Mishustin (2006) recently analyzed the general features of stars made of fermions by integrating a dimensionless form of the Tolman-Oppenheimer-Volkoff equations for scaled equations of state valid for free fermions and also for model interactions. The masses of preons (Pati 1989; Hansson and Sandin 2005), are expected to be light or zero, certainly much smaller than the mass of the composites (which include the neutrinos in most models, Pati and Salam 1983). This means that most of the composite states masses are probably from interactions. This is why a "bag model" approach has been employed in Sandin (2006) to represent the main features of the preon matter. Adapting the results of Narain, Schaffner-Bielich and Mishustin (2006), we may write for the maximum mass and (minimum) radius of the spherically symmetric models the general expressions

\[ M_{\text{max}} = 2.16 \times 10^2 \frac{1}{\sqrt{\lambda/10^5 \text{TeV} m^{-3}}} M_{\odot} \]  

(1)

\[ R_{\text{min}} = 8.5 \times 10^2 \frac{1}{\sqrt{\lambda/10^5 \text{TeV} m^{-3}}} \text{cm} \]  

(2)

where \( \lambda \) is proportional to the energy density needed to fit the electron mass in this bagged approach. The maximum mass model sets the scale for the masses expected in nature, being the most compact ones, even though the stellar sequences contain larger and less massive stars. The work of Narain, Schaffner-Bielich and Mishustin (2006) has also shown that the integration of a dimensionless TOV equation allows a universal description of the maximum mass-minimum radii relation, both scaling as \( \lambda^{-1/2} \), which reads

\[ \frac{M_{\text{max}}}{M_{\odot}} = 0.22 \frac{R_{\text{min}}}{\text{cm}} \]  

(3)

Another obvious constraint is that the stars can not become black holes, that is to say, that no matter how important the (repulsive) interactions other than the “bag constant” are, the compactness of the stellar models is bound from above. These unaccounted repulsive interactions can presumably be parametrized by an effective shift in \( \lambda \), resulting in an increase of the maximum mass. If causality is ignored (that is, \( \rho = \text{constant} \)), it is well-known (Shapiro and Teukolsky 1983) that the maximum compactness parameter satisfies \( 2GM_{\text{max}}/R_{\text{min}}c^2 = 8/9 \). For any causal equation of state, calculations by Haensel, Lasota and Zdunik (1999) give instead a factor 0.7 for the r.h.s, allowing one to write down the boundary separating compact stars from black holes, in the same units, as

\[ \frac{M_{\text{max}}}{M_{\odot}} = 0.83 \frac{R_{\text{min}}}{\text{cm}} \]  

(4)

The parameter space allowed for preon stars is shown in Fig. 1 under these assumptions.

As stated, a minimum compositeness lengthscale \( \ell \sim 10^{-17} \text{cm} \) has been assumed, according to the present experimental limits. The preon “stars” must necessarily be carsized objects or smaller, as already noticed by Hansson and Sandin 2005. This region encompasses any stellar model made from composite fermions, and the whole hierarchy of composed objects down to a minimal scale discussed in Hansson (2006).
It is clear from these considerations that allowed region can extend all the way down to microscopic values of $M_{\text{max}}$ and $R_{\text{min}}$. However, the structure calculations do not make sense unless the pressure, density and other quantities can be defined as classical quantities. This would be possible in turn if preons are not too light, because otherwise their Compton wavelength $\lambda_{C}$ would be bigger than the radius of the "star" $R_{\text{min}}$. From this condition, $\lambda_{C} \ll R_{\text{min}}$ we obtain the following bound

$$m_{p} \gg 2 \times 10^{-5} \sqrt{\lambda/10^{5} \text{TeV} \text{fm}^{-3}} \text{eV}. \quad (5)$$

For the adopted minimum scale $\lambda$ we find that the preon mass $m_{p}$ starts to conflict with the determinations (Goobar et al. 2006) of the neutrino mass $m_{\nu} \leq 0.3 \text{eV}$, for a very high energy density $\lambda \sim 10^{13} \text{TeV} \text{fm}^{-3}$, or $\lambda^{1/4}$ around $10^{6}$ times the natural QCD bag scale $B^{1/4} \sim 150 \text{MeV}$. It is not presently known whether this scale is too high for the next level of compositeness. The compact star description would be correct below this scale. However, if the compositeness produces a value above $\sim 10^{13} \text{TeV} \text{fm}^{-3}$, we may still employ it if we abandon the idea that preons must be lighter than their bound states. On the other hand, we do not have any reliable description for preon stars if they should be considered as quantum objects.

3 Formation of preon stars and preon nuggets

The mismatch between the maximum compact star mass made of preons $\sim 100 M_{\odot}$ and the neutron (or quark) scale can not be overemphasized: the latter is found to lie around $1 M_{\odot}$ because the hadronic scale is controlled by $B \sim 60 \text{MeV} \text{fm}^{-3}$, whereas the correspondingly larger $\lambda$ energy density gives rise to a factor $\sqrt{(B_{\text{QCD}}/\lambda) \sim 10^{-4}}$, leading to earth-like masses for the preon stars. Therefore, if an actual hadron (or quark) star is made to collapse, for example, being pushed over its maximum mass by accretion from a companion, the scale at which a preon region can form at the center must be much smaller than the Schwarzschild radius of the whole collapsing object. The falling of a mass $\gg M_{\text{max}}$ onto the center suggests that preon stars, with an average static density $< \rho > = 3.7 \times 10^{26} (R_{\text{min}}/\text{cm})^{-2}$ can not form in the contemporary universe, rather becoming black holes of stellar mass size. A solution would be to couple preons to some kind of massless particle that can be extremely efficiently radiated during collapse, as already pointed out by Hansson and Sandin (2005). This would keep the Schwarzschild radius smaller than the actual radius of the collapsing configuration, thus avoiding the formation of a black hole, but its realization remains to be convincingly demonstrated.

An alternative would be to form the preon objects when they bind forming quarks and leptons, in the early universe, hereafter named preon nuggets. They could cool and become self-gravitating eventually, leaving light preon stars, provided they form and survive. The naive temperature at which this happens can be found by assuming a radiation gas for the preon matter and demanding its pressure to be positive (that is, its kinetic term should remain larger than the energy density associated with $\lambda$). Using the same values as above, this estimate yields

$$T_{p} \sim 12 \times (10/g_{p})^{1/4} \text{GeV}$$

(6)
where \( g_p = n_b + (7/8)n_f \) counts the number of relativistic bosonic and fermionic degrees of freedom \( n_b \) and \( n_f \). A preon to quark-lepton phase transition seems to require \( g_p > g_{q-l} \) as well (Nishimura and Hayashi 1987), a condition which is not realized for the most economic description (Harari 1979) of substructure, but poses no problems for more elaborated schemes (Harari and Seiberg 1981). Note that all quark flavors, with exception of the top, and all lepton types would contribute to \( g_{q-l} \) at a temperature \( \sim T_p \), thus tightening the bound \( g_p > g_{q-l} \) which is non-trivial and must be studied on a case-by-case basis.

The horizon at the onset of the quark-lepton era is \( H^{-1} \sim 3 \times 10^2 (g_p/10)^{3/2} \) cm, a factor of 3 below the radius of the maximum mass model. Thus only preon structures around \( \leq 1 M_\odot \) could be formed, if at all, in the cosmological setting (Hansson and Sandin 2005). This should be considered as an absolute upper limit for primordial objects originated in the limits on compositeness as discussed above.

Given that \( m_p \ll m_l \), with \( m_l \) any lepton mass, and quite possibly zero, we may think analogously to the QCD phase transition and ask whether the preons would like to stay as such (forming “preon nuggets”), doubling the celebrated “Witten effect” (Witten 1984) at higher energies. In such a scenario, when the cosmological temperature falls below \( T_p \), the universe remains mostly in the preon phase with some supercooling, until nucleation of quarks and leptons proceeds through bubble nucleation (first order transition). Quark-lepton bubbles release latent heat and expand, heating the surrounding preon matter, until the latter pushed into small regions can provide enough pressure to stop its contraction. The number of particles trapped in nuggets would depend on the degree of supercooling and transport properties in the process. However, analogously to the discussed strange quark nugget scenario (and technicolor matter as well, Frieman and Giudice 1991) it is important that nuggets can loss energy without necessarily loosing the conserved charge that stabilizes them as non-topological solitons, as baryon number or technibaryon number are. It is not clear whether a preon model possessing such a conserved charged (e.g. preon number) can be constructed. For instance, in ordinary QCD global symmetries like baryon number or isospin can not be broken (Vafa and Witten 1984), and also that massless states do not form from massive constituents. These restrictions do not apply, for example, to massless preon theories with gauge Yukawa interactions as discussed in Pati (1989). The point here is that the formation or absence of preon nuggets depends on the specific model assumptions (see Das and Laperashvili 2006; Dugne, Fredriksson and Hansson 2002 and Burdyuzha et al. 1999 for very recent models) to a point which is not possible to state anything firm today. However, a large class of models are ruled out from the scratch, independently of other conditions.

In any case, if formed, these concentrations should be fragile against evaporation into quarks and hadrons at intermediate temperatures. The gravitational potential is initially unimportant, and does not help much either because of the limit given by the horizon. Clearly, the situation is much worse if the compositeness scale happens to be higher. This arguments cast doubts on the very formation of preon nuggets, but in any case, this issue remains to be thoroughly investigated.
4 Conclusions

Are there “preon stars” in the present universe? The answer is not simple, but the payoff potentially large. We have discussed the region in the mass-radius plane available in a one-parameter approach (just an energy density $\lambda$) and found results consistent with more detailed calculations (Hansson and Sandin 2005) suggesting robust predictions for them. An important clue for the problem of preon masses related to these objects has been pointed out, namely the validity of a classical description suggesting a lower limit on $m_p$. The formation of these superdense objects, separated by “ordinary” neutron/quark stars by a jump of 12 orders of magnitude in the average density, is problematic not only in contemporary scenarios but in the early universe as well. These arguments should be further reexamined before a reasonable answer to the existence question can be given.

5 Acknowledgments:

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo and the CNPq Agency (Brazil).

References

[1] Hewish, A., Bell, S.J, Pilkington, J.D, Scott, P.F.F. and Collins, R.A.: 1967 Nature 217 709

[2] Landau, L.D.: 1932. Phys. Z. Sowjetunion 1 285

[3] Baade, W. and Zwicky, F.: 1934. Phys. Rev. 45 138

[4] Collins, J.C. and Perry, M.J.: 1975. Phys. Rev. Lett.30 1353

[5] Ivanenko, D. and Kurdgelaidze, D.G.: 1969. Nuovo Cim. Lett.2 13

[6] Itoh, N.: 1970. Prog. Theor. Phys.44 291

[7] Bodmer, A.R.: 1971. Phys. Rev. D 4 1601

[8] Terazawa, H.: 1979. INS Report 336 (unpublished)

[9] Chin, S.A and Kerman, A.: 1979. Phys. Rev. Lett.43 1292

[10] Witten, E.: 1984. Phys. Rev. D30 272

[11] Pati, J.C and Salam, A.: 1983. Nucl.Phys.B214 109

[12] Pati, J.C.: 1989. Phys. Lett. B228 228, see also Pati, J.C.: 1995. hep-ph/9505227 and references therein.

[13] D’Souza, I.A. and Kalman, C.S. Preons (World Scientific, Sinagapore, 1992)
[14] Pati, J.C.: 2006. *hep-ph/0606089* (unpublished)

[15] Sabetfakhri, A.: 2000. DESY-THESIS-2000-039 (unpublished)

[16] Hansson, J. and Sandin, F.: 2005. *Phys.Lett.B* 616 1

[17] Sandin, F.: 2005. *Eur.Phys.Jour.C* 40 15

[18] Hansson, J.: 2006. *astro-ph/0603342* (unpublished)

[19] Narain, G., Schaffner-Bielich, J. and Mishustin, I.N.: 2006. *Phys.Rev.D* 74 063003

[20] Shapiro, S.L. and Teukolsky, S.A. *Black Holes, White Dwarfs and Neutron Stars: the physics of compact objects* (J. Wiley & Sons, NY 1983)

[21] Haensel, P., Lasota, J.P. and Zdunik, J.: 1999. *Astron. Astrophys.* 344 151

[22] Goobar, A., Hannestad, S., Mörtsell, E. and Tu, H.: 2006. *JCAP* 6 019

[23] Nishimura, H. and Hayashi, Y.: 1987. *Phys.Rev.D* 35 3151

[24] Harari, H.: 1979. *Phys. Lett. B* 86 83

[25] Harari, H. and Seiberg, N.: 1981. *Phys. Lett. B* 98 269

[26] Frieman, J.A. and Giudice, Gian F.: 1991. *Nucl. Phys. B* 355 162

[27] Vafa, C. and Witten, E.: 1984. *Nucl. Phys. B* 234 173

[28] Das, C.R. and Laperaashvili, L.: 2006. *Phys.Rev. D* 74 035007

[29] Dugne, J-J., Fredriksson, S. and Hansson, J.: 2002. *Europhys.Lett.* 57 188

[30] Burdyuzha, V.V., Vereshkov, G., Lalakulich, O. and Ponomarev, Y.: 1999. *astro-ph/9912555* (unpublished)
Fig. 1. The *locus* of preon stars (and higher level of compositeness fermion objects) in the M-R plane. The allowed trapezoidal region is limited on the right by the minimum compositeness scale, on the bottom by the maximum mass- minimum radius given by eq.(3) and atop by the black hole boundary eq.(4). Two possible sequences of models are sketched, both without interactions (solid line) and with some repulsive interaction (dashed line) driving the models closer to the black hole limit.
