COMPARING P-STARS WITH OBSERVATIONS

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ABSTRACT

P-stars are compact stars made of up and down quarks in β-equilibrium with electrons in a chromatomagnetic condensate. P-stars are able to account for compact stars as well as stars with radii comparable with canonical neutron stars. We compare p-stars with different available observations. Our results indicate that p-stars are able to reproduce several observations from isolated and binary pulsars in a natural manner.

Subject heading: pulsars: general

1. INTRODUCTION

In the years since their discovery (Hewish et al. 1968) pulsars have been identified with rotating neutron stars, first predicted theoretically by Baade & Zwicky (1934a, 1934b, 1934c), endowed with a strong magnetic field (Pacini 1968; Gold 1968).

It is widely believed that there are no alternative models able to provide as satisfactory an explanation for the wide variety of pulsar phenomena as those built around the rotating neutron star model. Nevertheless, recently we have proposed (Cea 2004a, 2004b) a new class of compact stars, p-stars, which is challenging the standard paradigm.

P-stars are compact stars made of up and down quarks in β-equilibrium with electrons in a chromatomagnetic condensate. In our previous studies (Cea 2004a, 2004b), we found that p-stars are able to account for compact stars and stars with radii comparable with those of canonical neutron stars, as well as supermassive compact objects. Moreover, we showed that p-stars, once formed, are absolutely stable. The cooling curves of p-stars compare rather well with observations. We also suggested that p-matter produced at the cosmological deconfinement phase transition could be a viable candidate for baryonic cold dark matter.

In addition, in Cea (2006) we discussed p-stars endowed with a superstrong dipolar magnetic field. We found that soft gamma-ray repeaters and anomalous X-ray pulsars can be understood within our theory. In particular, we pointed out that within our p-star model there is a quite natural mechanism to account for the generation of dipolar surface magnetic fields up to $10^{16}$ G. We succeed in obtaining a well-defined criterion to distinguish rotation-powered pulsars from magnetic-powered pulsars. We showed that glitches, which in our theory are triggered by magnetic dissipative effects in the inner core, explain both the quiescent emission and burst activity in soft gamma-ray repeaters and anomalous X-ray pulsars. We are able to account for braking and normal glitches observed in soft gamma-ray repeaters and anomalous X-ray pulsars. We discussed and explained the observed anticorrelation between hardness ratio and burst intensity. Within our p-star theory we are able to account quantitatively for light curves from both gamma-ray repeaters and anomalous X-ray pulsars.

It is worthwhile to briefly discuss the theoretical foundation of our proposal. Indeed, quite recently, the QCD vacuum was probed by means of an external constant abelian chromatomagnetic field on the lattice (Cea & Cosmai 2003, 2005). We found that increasing the strength of the applied external field causes the deconfinement temperature to decrease toward zero. In other words, there is a critical field $gH_c$ such that for $gH > gH_c$ (where $g$ is the color gauge coupling and $H$ is the strength of the chromatomagnetic field directed along the third direction in color space) the gauge system is in the deconfined phase (the color Meissner effect). As a consequence, we see that there is an intimate connection between abelian chromatomagnetic fields and color confinement. The existence of a critical chromatomagnetic field is compatible with the QCD vacuum behaving like a disordered chromatomagnetic condensate, for strong enough chromatomagnetic field strengths enforce long-range color order thereby destroying confinement. In a seminal paper, Feynman (1981) argued that in QCD in two spatial dimensions the confining vacuum at large distances is a chromatomagnetic condensate disordered by the gauge invariance. The confinement of colors comes from the existence of a mass gap and the absence of color long-range order. As a matter of fact, we were able to show that, indeed, the QCD vacuum in three spatial dimensions does display, at large distances, a mass gap and no color long-range order and that the vacuum displays the color Meissner effect. We find that chiral symmetry breaking for quarks in the fundamental color representation is an inevitable consequence of the disordered chromatomagnetic condensate. Finally, we argue that the deconfined vacuum behaves more like a correlated liquid than an ideal gas, in accordance with recent results from heavy ion experiments. This, in turn, leads us to the conclusion that the deconfined QCD vacuum is characterized by long-range chromatomagnetic correlations, and whence p-matter, namely, almost massless up and down quarks immersed in a chromatomagnetic condensate, must be quite close to the true QCD deconfined state. In absence of strong gravity effects, the chromatomagnetic condensate in p-matter is of the order of the critical field strength, which turns out to be $(gH)^{1/2} \approx 1.0$ GeV (Cea & Cosmai 2003, 2005).\footnote{Note that we are using natural units where $\hbar = c = 1$. In these units $g$ is dimensionless and $(gH)^{1/2}$ has the dimension of energy. To switch to cgs units it suffices to replace $gH$ with $\hbar c g H$.}

On the other hand, when including the effects of gravity it turns out that p-matter gives rise to compact stars (p-stars), which are more stable than neutron stars (Cea 2004a) whatever the value of $(gH)^{1/2}$. Therefore, we find, in general, that in p-stars the chromatomagnetic condensate must satisfy the constraint

$$\sqrt{gH} \leq \sqrt{gH_c} \approx 1.0 \, \text{GeV}. \quad (1)$$
We see, then, that the chromomagnetic condensate in p-stars acts like a dynamical effective bag constant which can be varied according to equation (1). The actual value of the chromomagnetic condensate depends only on the central density of the compact star. In this way, p-stars are able to overcome gravitational collapse irrespective of the stellar mass. Indeed, as discussed in Cea (2004a), our p-stars do not admit the existence of an upper limit lapse irrespective of the stellar mass. Indeed, as discussed in Cea et al. (2004a), p-stars are able to overcome gravitational collapse irrespective of the stellar mass.

It turns out (Cea 2004a) that the function $\tilde{F}$ acts as a constraint on the mass-radius p-star curves. Indeed, clear observational evidence in favor of p-stars would be the detection of pulsars with mass above $3 M_\odot$.

In the present paper we focus on a few selected topics with the aim of furnishing further compelling evidence in support of our proposal. In §2 we compare recent determinations of masses and radii of isolated and binary pulsars with our p-star model. In §3, after a brief review of cooling in p-stars, we compare our theoretical cooling curves with observational data. Finally, we draw our conclusions in §4.

2. MASSES AND RADII

In a recent analysis of the low-mass X-ray binary pulsar EXO 0748–676 observational data Özel (2006) concluded that the determination of the mass and radius of this pulsar appears to rule out all the soft equations of state of neutron star matter. Indeed, multiple phenomena have been observed from this low-mass X-ray binary that can be used to determine uniquely the mass and radius.

The three quantities used in Özel (2006) are the Eddington limit $F_{\text{Edd}}$, the gravitational redshift $z$, and the ratio $F_{\text{cool}}/\sigma T_c^4$. Following Özel (2006), we have

$$ F_{\text{Edd}} = \frac{1}{4\pi D} \frac{GM}{\kappa_e} \left(1 - \frac{2GM}{R}\right)^{1/2}, \quad (6) $$

$$ z = \left(1 - \frac{2GM}{R}\right)^{-1/2}, \quad (7) $$

$$ \frac{F_{\text{cool}}}{\sigma T_c^4} = f_\infty \frac{R^2}{D^2} \left(1 - \frac{2GM}{R}\right)^{-1}. \quad (8) $$

Here and in the following we adopt natural units where $h = c = k_B = 1$.

In equations (6), (7), and (8) $G$ is the gravitational constant, $M$ and $R$ are the stellar mass and radius, respectively, $D$ the distance to the source, and $\kappa_e$ is the electron scattering opacity:

$$ \kappa_e \simeq 0.2(1 + X) \text{ cm}^2 \text{ g}^{-1}, \quad (9) $$

where $X$ is the hydrogen mass fraction of the accreted material. Finally, $f_\infty$ is the color correction factor, which relates the color temperature $T_c$ to the effective temperature $T_{\text{eff}}$ of the star.

Özel pointed out that the following parameterization of the color correction factor,

$$ f_\infty \simeq 1.34 + \left(1 + \frac{X}{1.7}\right)^{2.2} \left\{ \frac{T_{\text{eff}}/(10^7 \text{ K})}{g/(10^{13} \text{ cm s}^{-2})} \right\}^{2.2}, \quad (10) $$

leads to an accurate description of the results from model atmosphere calculations (Madej et al. 2004).

Remarkably, equations (6), (7), and (8) can be solved to uniquely determine the stellar mass, radius, and distance (Özel 2006):

$$ M = \frac{h^{1/2} c^5/2}{G^{3/2} h^2} \frac{1}{f(\tilde{\rho}_c)} \tilde{F}_{\text{Edd}}, \quad (11) $$

$$ R = \frac{h^{1/2} c^5/2}{G^{3/2} h^2} \frac{1}{f(\tilde{\rho}_c)} \tilde{F}_{\text{Edd}}, \quad (12) $$

$$ D = \frac{h^{1/2} c^5/2}{G^{3/2} h^2} \frac{1}{f(\tilde{\rho}_c)} \tilde{F}_{\text{Edd}}. \quad (13) $$

The value of the redshift has been reported in Cottam et al. (2002):

$$ z = 0.35. \quad (14) $$

Moreover, the Eddington limit luminosity $F_{\text{Edd}}$ has been obtained in Özel (2006) by averaging the values determined with RXTE (Wolf et al. 2005) and EXOSAT (Gottwald et al. 1986):

$$ F_{\text{Edd}} = (2.25 \pm 0.23) \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}. \quad (15) $$

Finally, the ratio $F_{\text{cool}}/\sigma T_c^4$ has been inferred from the RXTE data (Wolf et al. 2005):

$$ \frac{F_{\text{cool}}}{\sigma T_c^4} = (1.14 \pm 0.10) (\text{km kpc}^{-1})^2. \quad (16) $$
Using the values in equations (14), (15), and (16) we easily obtain from equations (11), (12), and (13)

\[ \frac{M}{M_\odot} = (0.2009 \pm 0.0271) f_\infty^4 \kappa_c, \]

\[ R = (1.315 \pm 0.177) \text{ km} f_\infty^{4/3} \kappa_c, \]

\[ D = (1.232 \pm 0.137) \text{ kpc} f_\infty^{2} \kappa_c. \]

The main uncertainty that affects the mass, radius, and distance of the binary pulsar resides in the hydrogen mass fraction \( X \) of the accreting material and the color correction factor \( f_\infty \).

Following Özel (2006), if we assume for the color correction factor

\[ f_\infty \simeq 1.37 \]

and use the extreme value of hydrogen mass fraction \( X \simeq 0.70 \), we get

\[ \frac{M}{M_\odot} = 2.10 \pm 0.28, \]

\[ R = 13.62 \pm 1.84 \text{ km}. \]

On the other hand, for binary systems such as EXO 0748—676 a helium-rich companion should be expected (see, e.g., Lewin et al. 1993). In this case the value \( X \simeq 0.30 \) seems to be more appropriate. If this is the case, we get

\[ \frac{M}{M_\odot} = 2.72 \pm 0.37, \]

\[ R = 17.82 \pm 2.40 \text{ km}. \]

In Figure 1 we compare equations (21)–(24) with the mass-radius relation obtained within our p-star theory (Cea 2004a). We can see that for both hydrogen abundances our model is able to account for the inferred values, equations (21)–(24), together with the constraint equation (14). On the contrary, the mass-radius curve for neutron stars is consistent with the determinations in equations (21) and (22) only by assuming the stiffest equation of state (labeled MS0 in Fig. 1; see Lattimer & Prakash 2001), which corresponds to high-density neutron matter without nonlinear vector and isovector interactions (Mueller & Serot 1996). Note, however, that even the stiffest high-density neutron matter equation of state is ruled out if we consider the more realistic hydrogen mass fraction \( X \simeq 0.30 \).

Interestingly enough, we find that regardless of the actual value of the hydrogen mass fraction the distance of the binary system is quite tightly constrained:

\[ 8.87 \pm 0.99 \text{ kpc} \leq D \leq 12.38 \pm 1.39 \text{ kpc}. \]

We see that Figure 1 shows that EXO 0748—676 can be accounted for by our p-star model irrespective of the assumed value of the hydrogen mass fraction.

We see that the stiffest equation of state for neutron star matter is marginally compatible with observations from EXO 0748—676. However, we argue below that there is some tension with several pulsar data points which would require a softer equation of state.

It was proposed a long time ago that the compact accreting object in the famous X-ray binary Hercules X-1 is a strange star (Li et al. 1995). This proposal was based on the comparison of a phenomenological mass-radius relation for Hercules X-1 (see, e.g., Shapiro & Teukolsky 1983) with theoretical M-R curves for neutron and strange stars. The analysis in Li et al. (1995) has, however, been criticized by Reynolds et al. (1997). These authors, using a new mass estimate together with a revised distance, which leads to a somewhat higher X-ray luminosity, argued that the hypothesis that Hercules X-1 is a neutron star is not disproved. As a matter of fact, Reynolds et al. (1997) found that there is marginal consistency with observations if one adopts for neutron stars a very soft equation of state. At the same time, these authors pointed out that the hypothesis of a strange star can be ruled out since the theoretical curves no longer intercept the observational relations within the permitted mass range. However, it is evident from Figure 1 in Reynolds et al. (1997) that the mass-radius constraints for Hercules X-1 seem to be incompatible with the stiffest equation of state displayed in our Figure 1, where we display the semiempirical M-R curve for Hercules X-1 discussed in Reynolds et al. (1997) corresponding to the luminosity \( L_X = 3.5 \times 10^{37} \text{ erg s}^{-1} \). On the other hand, the phenomenological mass-radius relation for Hercules X-1 could be compatible with a softer equation of state such as that labeled AP4 in Figure 1 (for the nomenclature on the equations of state see Lattimer & Prakash 2001).

The millisecond pulsar SAX J1808—3658 (hereafter J1808) is one of the most studied accreting pulsars (see, e.g., van der Klis 1995). Recently, Poutanen & Gierlinski (2003) studied the pulse profile of J1808 at different energies. In particular, they derived simple analytical formulae for the light curves. By fitting the observed pulse profiles in the 3—4 and 12—18 keV energy bands, Poutanen & Gierlinski (2003) constrained the compact star mass and radius. The best-fitting parameters for two different
models are presented in Table 1 of Poutanen & Gierlinski (2003). It turns out that the results from the two adopted models are quite consistent (Poutanen & Gierlinski 2003). In Figure 1 we report the results from model 2 in Poutanen & Gierlinski (2003). Again, we see that the mass-radius constraints for J1808 are more consistent with a soft equation of state for high-density neutron matter. On the other hand, our p-star model can easily account for the observed mass-radius values for the accreting X-ray millisecond pulsar J1808.

Remarkably, our previous conclusion is confirmed by the recent analysis of the light curves of J1808 during its 1998 and 2002 outbursts (Leahy et al. 2007). Indeed, Leahy et al. (2007) obtain that at the 3σ level the radius must satisfy \( R < 11.9 \) km and the mass \( M < 1.56 \, M_\odot \).

RX J1856.5−3754 (hereafter RX J1856) is the nearest and brightest of a class of isolated radio-quiet compact stars. RX J1856 has been observed with *Chandra* and *XMM-Newton* (Burwitz et al. 2003), showing an X-ray spectrum that is accurately fitted by a blackbody law. By assuming that the X-ray thermal emission is due to the surface of the star, Burwitz et al. (2003) found for the effective radius and surface temperature:

\[
R^\infty \approx 4.4 \frac{d}{120 \, \text{pc}}, \quad T^\infty \approx 63 \, \text{eV},
\]

where

\[
R^\infty = R \left( \sqrt{1 - \frac{2GM}{R}} \right)^{-1}, \quad T^\infty = T \sqrt{1 - \frac{2GM}{R}}. \quad (27)
\]

It should be stressed, however, that in the observed spectrum there is also optical emission in excess over the extrapolated X-ray blackbody. By interpreting the optical emission as the Rayleigh-Jeans tail of the thermal blackbody emission, one finds that the optical and X-ray data can also be fitted by the two-blackbody model. In this case, the spectral fit yields an effective radius (Burwitz et al. 2003)

\[
R^\infty \approx (16 \, \text{km}) \frac{d}{120 \, \text{pc}}. \quad (28)
\]

The two-blackbody model, however, does not furnish an acceptable description of the observed spectrum. Indeed, quite recently the distance measurement of RX J1856 has been reassessed and is now estimated to be at about 180 pc (Kaplan 2003). Moreover, from recent parallax measurements (Kaplan 2003; van Kerkwijk & Kaplan 2007) we infer that there is a lower limit to the distance of RX J1856:

\[
d \geq 160 \, \text{pc}. \quad (29)
\]

In fact, equation (29) excludes the two-blackbody interpretation, for in this case from equation (28) we should obtain

\[
R^\infty > 21 \, \text{km}, \quad (30)
\]

which is too large for a neutron star. In addition, if we consider the second nearest isolated compact star, RX J0720.4−3125 (hereafter RX J0720), which has been detected by *ROSAT* (Haberl et al. 1997; Motch & Haberl 1998) and observed with *XMM-Newton* (Cropper et al. 2001; Paerels et al. 2001), then we see that the spectrum of RX J0720 is almost identical to that of RX J1856. Indeed, RX J0720 exhibits a blackbody X-ray spectrum, a large X-ray–to–optical flux ratio, and optical emission in excess of the extrapolated X-ray blackbody. In this case, however, the recent analysis of the optical, ultraviolet, and X-ray data (Kaplan et al. 2003) showed that the optical spectrum of RX J0720 is not well fitted by a Rayleigh-Jeans tail, but it is best fitted by a non-thermal power law. This strongly suggests that the pulsar surface emission cannot account for the observed soft emission spectra, and that this last emission must be magnetospheric in origin. For instance, in Cea (2004b) we suggested that the soft spectrum originates from synchrotron radiation (Wallace 1977) emitted by electrons with a power-law energy spectrum. In this case, the radiation in the soft spectrum should display a rather large linear polarization.

Our previous conclusion led to the conclusion that the most realistic interpretation of the X-ray spectrum is thermal emission due to the whole surface of the star. Now, assuming \( d \approx 180 \) pc, from equation (26) we get \( R^\infty \approx 6.6 \) km. From this value of \( R^\infty \) we can solve equation (27) to constrain the mass and radius of RX J1856 (Cea 2004b). The result of this analysis, displayed in Figure 1, indicates that there are stable p-star configurations which agree with observational data. However, it should be kept in mind that \( R^\infty \) is a lower limit of the true stellar radius. Nevertheless, from Figure 1 we see that the mass-radius curve for RX J1856 is more consistent with a soft equation of state.

Finally, from Figure 1, assuming that the observed compact objects are p-stars, we infer that the chromomagnetic condensate is constrained within the rather narrow interval

\[
0.35 \, \text{GeV} \leq \sqrt{gH} \leq 0.6 \, \text{GeV}. \quad (31)
\]

As a consequence, the allowed region for p-stars is the region in Figure 1 bounded by the two dot-dashed lines and the \( M-R \) curves with \((gH)^{1/2} = 0.6 \) and 0.35 GeV.

### 3. COOLING

The thermal evolution of compact stars is an important tool to investigate the state of dense matter at supranuclear densities. In fact, observations of the thermal photon flux emitted from the surface of the stars provide valuable information about the physical processes operating in the interior of these objects.

The cooling in p-stars has been discussed for the first time in Cea (2004a). As for neutron stars, the predominant cooling mechanism of newly formed p-stars is neutrino emission. In p-stars neutrino cooling dominates for about \( 10^7 - 10^9 \) yr. Subsequently, after the internal temperature has sufficiently dropped, the photon emission overtakes neutrinos.

Let us briefly review the cooling in p-stars (Cea 2004a). Assuming stars of uniform density and that are isothermal, the cooling equation is

\[
C_T \frac{dT}{dt} = -(L_\nu + L_\gamma), \quad (32)
\]

where \( L_\nu \) is the neutrino luminosity, \( L_\gamma \) is the photon luminosity, and \( C_T \) is the specific heat. If we assume blackbody photon emission from the surface at an effective surface temperature \( T_S \) we get

\[
L_\gamma = 4\pi R^2 \sigma_{SB} T_S^4, \quad (33)
\]

where \( \sigma_{SB} \) is the Stefan-Boltzmann constant. Following Shapiro & Teukolsky (1983), in Cea (2004a) we assumed that the surface and interior temperature were related by

\[
\frac{T_S}{T} = 10^{-2} a, \quad 0.1 \leq a \leq 1.0. \quad (34)
\]
Equation (34) is relevant for a p-star which is not bare, namely, for p-stars which are endowed with a thin crust. The result (Cea 2004b) is that p-stars have a sharp edge of thickness of the order of about 1 fermi. On the other hand, electrons, which are bound by the Coulomb attraction, extend several hundred fermis beyond the edge. It follows, then, that on the surface of the star there is a positively charged layer which is able to support a thin crust of ordinary matter. The vacuum gap between the core and the crust of the order of several hundred fermis leads to a strong suppression of the surface temperature with respect to the core temperature. In principle, the actual relation between $T_S$ and $T$ can be obtained by studying the crust and core thermal interactions. In any case, our phenomenological relation equation (34) allows a wide variation in $T_S$, which encompasses the neutron star relation (see, e.g., Gundmundsson et al. 1983). Moreover, as we discuss below, our cooling curves display a rather weak dependence on the parameter $a$ in equation (34).

In Cea (2004a) we showed that the dominant cooling processes by neutrino emission are the direct $\beta$-decay quark reactions (Iwamoto 1980; Burrows 1980):

$$d \rightarrow u + e + \nu_e, \quad u + e \rightarrow d + \nu_e.$$  \hspace{1cm} (35)

We find the following neutrino luminosity (Cea 2004a):

$$\epsilon_\nu \simeq \left(3.18 \times 10^{36} \text{ erg s}^{-1}\right) T_9^8 \frac{M}{M_0} \frac{\sqrt{gH}}{1 \text{ GeV}},$$  \hspace{1cm} (36)

where $T_9$ is the temperature in units of $10^9$ K, and $\epsilon_0 \simeq 2.51 \times 10^{14} \text{ g cm}^{-3}$ is the nuclear density. So for typical values of the parameters we have

$$L_\nu \simeq \left(10^{36} \text{ erg s}^{-1}\right) T_9^8,$$  \hspace{1cm} (37)

Note that the neutrino luminosity $L_\nu$ has the same temperature dependence as the neutrino luminosity by modified Urca reactions in neutron stars (see, e.g., Shapiro & Teukolsky 1983), but it is more than 2 orders of magnitude smaller. This peculiar dependence on the core temperature is due to the presence of the strong chromomagnetic condensate, which strongly constrains the quark transverse motion.

It is worthwhile to stress that since our neutrino luminosity is reduced by more than 2 orders of magnitude with respect to neutron stars, the maximum allowed quiescent luminosity of isolated pulsars is about 2 orders of magnitude greater than the maximum allowed surface luminosity in neutron stars (Van Riper 1991). Thus, while our theory accounts for luminosities up to $10^{36}$ erg s$^{-1}$ as observed in magnetars (Cea 2006), the standard model based on neutron stars is in striking contradiction with observations.

Further support for our neutrino luminosity equation (37) comes from superbursts, namely, rare, extremely energetic, and long-duration type I X-ray bursts, from low-mass X-ray binaries (see Kuulkers 2004). Indeed, it has been pointed out that to account for the observed ignition depths in superbursts one needs slow neutrino emission processes with emissivity (Page & Cumming 2005; Stejner & Madsen 2006):

$$\epsilon_\nu = Q_\nu T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}, \quad Q_\nu \sim 10^{18} - 10^{22}.$$  \hspace{1cm} (38)

It is evident that the phenomenological neutrino emissivity in equation (38) needed to explain observed superbursts from low-mass X-ray binaries cannot be accounted for within the standard neutron star model. On the contrary, from our equation (37) we infer for the neutrino emissivity in p-stars

$$\epsilon_\nu \sim 10^{18} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1},$$  \hspace{1cm} (39)
which naturally fits in the phenomenological allowed range of values.

Finally, to determine the thermal evolution of p-stars we need the specific heat (Cea 2004a),

$$C_V \simeq 0.92 \times 10^{35} T_9 \frac{M}{M_0} \varepsilon \left(\frac{\sqrt{gH}}{1 \text{ GeV}}\right)^2,$$  \hspace{1cm} (40)

which, for typical parameter values, in physical units reads

$$C_V \sim (10^{59} \text{ erg K}^{-1}) T_9.$$  \hspace{1cm} (41)

Note that from equation (41) it follows that the p-star specific heat is of the same order of the neutron star specific heat (Shapiro & Teukolsky 1983). To obtain the thermal history of a p-star we integrate equation (32) by assuming the initial temperature $T_0 = 1.4$ (Cea 2004a). We stress, however, that the thermal history is almost independent on the assumed initial temperature as long as $T_0 \lesssim 10^{10}$ K.

In Figure 2 we report our cooling curves for three different values of the parameter $a$ in equation (34). It is worthwhile to note that the cooling curves are almost independent on the p-star mass. Moreover, there is a weak dependence on $a$ up to age $\tau \sim 10^3$ yr. We compare our theoretical cooling curves with data on several pulsars taken from the literature.

In any case we see that the agreement between theoretical cooling curves and observational data is quite satisfying. In particular, we see that, at variance with neutron stars, our peculiar neutrino luminosity allows sizeable surface effective temperatures, up to $10^5$ K, for compact stars with age $\tau > 10^9$ yr. Indeed, Figure 2 suggests that this distinguishable feature of the p-star model is corroborated by observations.

4. CONCLUSIONS

The proposal for p-stars originated in our nonperturbative investigations of QCD (Cea & Cosmai 2003, 2005), which suggested that quarks and gluons get deconfined in strong enough chromomagnetic fields. This, in turns, led us to argue that the deconfined QCD vacuum is characterized by long-range chromomagnetic correlations and that p-matter, namely, almost massless up and down quarks immersed in a chromomagnetic condensate, is formed in the collapse of the core of an evolved massive star (Cea 2004a). In addition, we have already argued that p-stars are more stable than neutron stars whatever the value of the chromomagnetic condensate. As a consequence, the true ground state of QCD in strong gravitational fields is not hadronic matter, but p-matter. In other words, the final collapse of massive stars leads inevitably to the formation of p-stars.

The results discussed in the present paper indeed indicate that p-stars are able to reproduce in a natural manner several observations from pulsars. On the other hand, we have seen that within the standard model based on neutron stars there is some tension in the determination of the equation of state for high-density neutron matter. However, we would stress that mass-radius constraints are affected by important systematic errors and are therefore not so constraining. Thus, we need more precise mass-radius determinations to reach a firm conclusion.

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