QUARK DECONFINEMENT IN PROTONEUTRON STARS CORES: ANALYSIS WITHIN THE MIT BAG MODEL

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I. INTRODUCTION

It is currently a matter of speculation the actual occurrence of quark matter during protoneutron star (PNS) evolution. The standard scenario for the birth of neutron stars indicates that these objects are formed as consequence of the gravitational collapse and supernova explosion of a massive star. Initially, PNSs are very hot and lepton rich objects, where neutrinos are temporarily trapped. During the first tens of seconds of evolution the PNS evolves to form a cold ($T < 10^{10}$ K) catalyzed neutron star. As neutrinos are radiated, the lepton - per - baryon content of matter goes down and the neutrino chemical potential tends to essentially zero in 50 seconds. Deleptonization is fundamental for quark matter formation inside neutron stars, since it has been shown that the presence of trapped neutrinos in hadronic matter strongly disfavors the deconfinement transition. In fact, neutrino trapping makes the density for the deconfinement transition to be higher than in the case of neutrino-free hadronic matter. As a consequence, the transition could be delayed several seconds after the bounce of the stellar core. When color superconductivity is included together with flavor conservation, the most likely configuration of the just deconfined phase is 2SC provided the pairing gap is large enough. The relevance of this 2SC intermediate phase (a kind of activation barrier) has been analyzed for deleptonized neutron stars but not for hot and lepton-rich objects like PNSs. In the present paper we shall analyze the deconfinement transition in protoneutron star conditions employing the MIT Bag model in the description of quark matter. For simplicity, the analysis will be made in bulk, i.e. without taking into account the energy cost due to finite size effects in creating a drop of deconfined quark matter in the hadronic environment.

II. THE HADRONIC PHASE

For the hadronic phase we shall use a model based on a relativistic Lagrangian of hadrons interacting via the exchange of σ, ρ, and ω mesons: a non-linear Walecka model (NLWM) which includes the whole baryon octet, electrons and electron neutrinos in equilibrium under weak interactions.

❑ The Lagrangian of the model is given by: $\mathcal{L} = \mathcal{L}_B + \mathcal{L}_M + \mathcal{L}_L$

$$\mathcal{L} = \sum_B \bar{\psi}_B \left[i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - \frac{1}{2} g_{\rho B}\gamma_\mu \vec{\tau}\cdot\vec{\rho}^\mu \right]\psi_B + \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma{}^2\sigma^2\right)$$
$$-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega{}^2\omega_\mu\omega^\nu - \frac{1}{4}\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} + \frac{1}{2}m_\rho{}^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{b}{3}m_n(g_\sigma\sigma)^3 - \frac{c}{4}(g_\sigma\sigma)^4 \quad (1)$$
$$+\sum_L \bar{\psi}_L\left(i\gamma_\mu\partial^\mu - m_L\right)\psi_L,$$

where the indices *B*, *M* and *L* refer to baryons, mesons and leptons respectively, with $B = n, p, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^-$, and Ξ^0. The coupling constants are $g_{\sigma B} = x_{\sigma B}\, g_\sigma$, $g_{\omega B} = x_{\omega B}\, g_\omega$ and $g_{\rho B} = x_{\rho B}\, g_\rho$. The ratios $x_{\sigma B}$, $x_{\omega B}$ and $x_{\rho B}$ are equal to 1 for the nucleons and acquire different values for the other baryons depending on the parametrization (TABLE I).

Label	$(g_\sigma/m_\sigma)^2$	$(g_\omega/m_\omega)^2$	$(g_\rho/m_\rho)^2$	b	c	M_{max}
GM1	11.79 fm^2	7.149 fm^2	4.411 fm^2	0.002947	-0.001070	1.78 $M_\odot$
GM1nh	11.79 fm^2	7.149 fm^2	4.411 fm^2	0.002947	-0.001070	2.32 $M_\odot$
NL3	15.8 fm^2	10.51 fm^2	5.35 fm^2	0.002052	-0.002651	1.95 $M_\odot$

TABLE I. Parameters of the hadronic equation of state. For each parametrization we give the maximum mass M_{max} *of a* hadronic star.

III. THE QUARK MATTER PHASE

The quark phase is composed by *u*, *d*, and *s* quarks, electrons, electron neutrinos and the corresponding antiparticles. We describe this phase by means of the MIT bag model at finite temperature with zero strong coupling constant, zero *u* and *d* quark masses and strange quark mass m_s = 150 MeV.

❑ The ***total thermodynamic potential*** can be written as: $\Omega = \Omega_Q + \Omega_L + B$ (2)

where the indexes *Q* and *L* refer respectively to quarks and leptons. The contribution of quarks is given by $\Omega_Q = \sum \Omega_{cf}$, being *f* = *u*, *d*, *s* the flavor index and *c* = *r*; *g*, *b* the color index.

❑ For ***free unpaired quarks*** we employ:

$$\Omega_{cf} = -\frac{\gamma T}{2\pi^2}\int_0^\infty k^2 \ln\left[1 + e^{-\frac{(E_{cf}-\mu_{cf})}{T}}\right]dk \quad (3)$$

where $E_{cf} = \sqrt{k^2 + m^2}$.

❑ For ***paired quarks*** we use the expression:

$$\Omega_{cf} = -\frac{\gamma T}{2\pi^2}\int_0^\infty k^2 \ln\left[1 + e^{-\frac{\varepsilon_{cf}}{T}}\right]dk \quad (4)$$

being $\varepsilon_{cf} = \pm\sqrt{(E_{cf} - \mu_{cf})^2 + \Delta^2}$ the single-particle energy dispersion relation when it acquires an energy gap Δ.

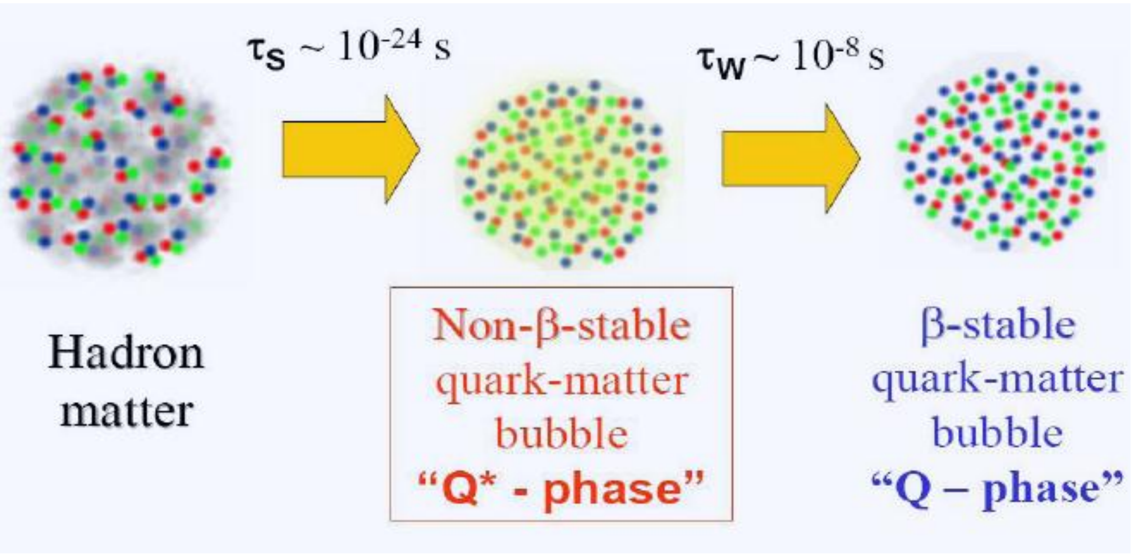
The temperature dependence of the gap parameter is given by:

$$\Delta(T) = \Delta_0\sqrt{1 - \left(\frac{T}{T_c}\right)^2}, \quad (5)$$

where the critical temperature for the 2SC phase is: $T_c = 0.57\Delta_0$. (6)

IV. DECONFINEMENT TRANSITION IN PROTONEUTRON STARS

The flavor composition of hadronic matter in β-equilibrium is different from that of a β-stable quark-matter drop. Roughly speaking, the direct formation of a β-stable quark-drop with N quarks will need the almost simultaneous conversion of N/3 up and down quarks into strange quarks, a process which is strongly suppressed with respect to the formation of a non β-stable drop by a factor $\sim G^{2N/3}_{\mathrm{Fermi}}$. For typical values of the critical-size β-stable drop (N ~100 - 1000) the suppression factor is actually tiny. Thus, quark flavor must be conserved during the deconfinement transition.



In order to determine the transition conditions, we apply the Gibbs criteria, i.e. we assume that deconfinement will occur when the pressure and Gibbs energy per baryon are the same for both hadronic matter and quark matter at a given common temperature. Thus, we have,

Pressure equilibrium:

$$P^H(T^H, \mu_p, \mu^H_{\nu_e}) = P^Q(T^Q, \{\mu_{fc}\}, \mu^Q_e, \mu^Q_{\nu_e})$$

Chemical equilibrium

$$g^H(T^H, \mu_p, \mu^H_{\nu_e}) = g^Q(T^Q, \{\mu_{fc}\}, \mu^Q_e, \mu^Q_{\nu_e})$$

Thermal equilibrium:

$$T^H = T^Q$$

Flavor conservation:

$$Y^H_f(T^H, \mu_p, \mu^H_{\nu_e}) = Y^Q_f(T^Q, \{\mu_{fc}\}, \mu^Q_e, \mu^Q_{\nu_e})$$

Pairing condition:

$$n_{ur}(T^Q, \mu_{ur}) = n_{dg}(T^Q, \mu_{dg}),$$
$$n_{dr}(T^Q, \mu_{dr}) = n_{ug}(T^Q, \mu_{ug})$$

Color neutrality:

$$n_r(T^Q, \{\mu_{fr}\}) = n_g(T^Q, \{\mu_{fg}\})$$
$$n_r(T^Q, \{\mu_{fr}\}) = n_b(T^Q, \{\mu_{fb}\})$$

IV. RESULTS

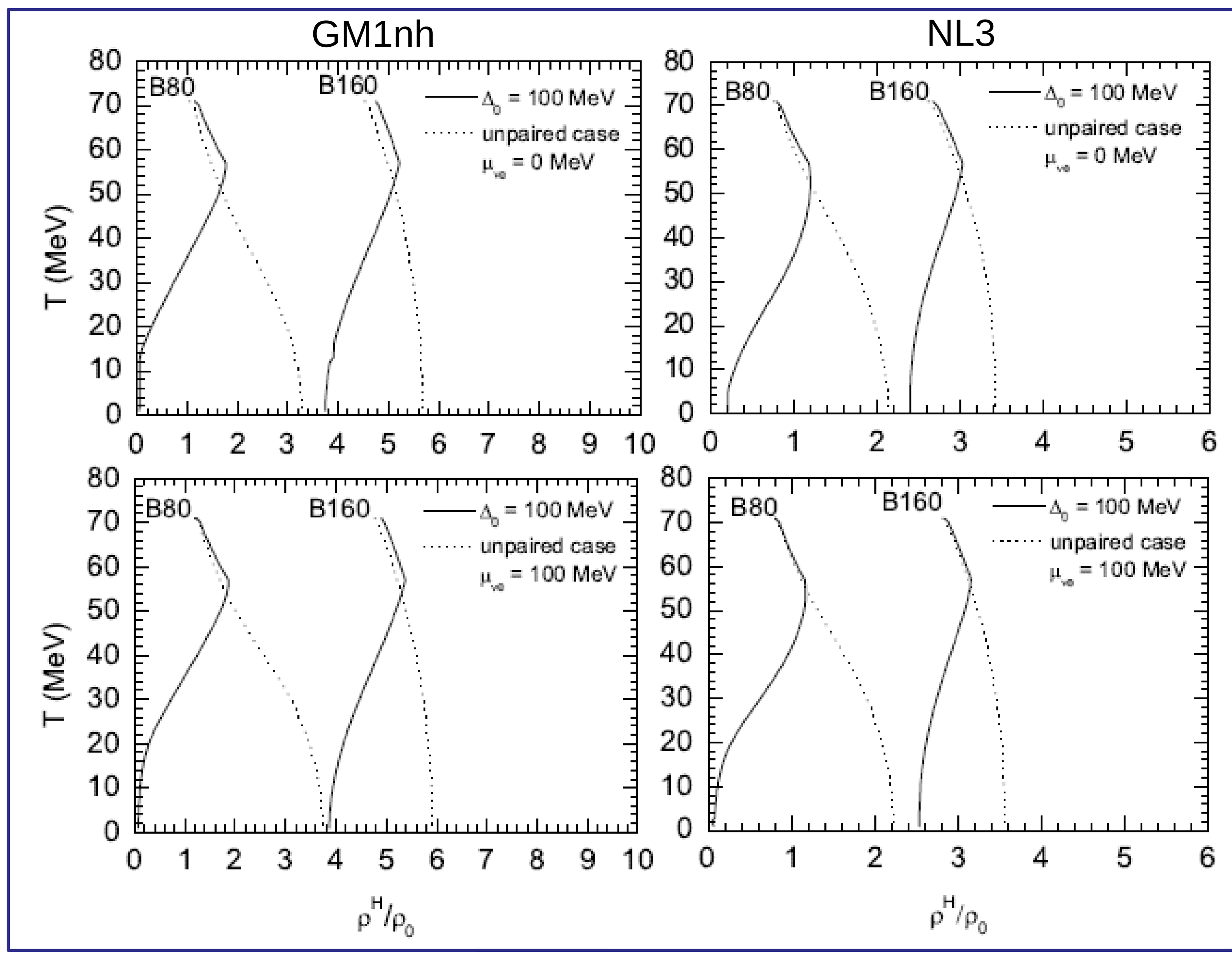


FIG. 1. The hadron-matter mass-energy density at which the deconfinement phase transition occurs as a function of the temperature T. Density is given in units of the nuclear saturation density ρ_0 (~ 2.7 x10^{14} g/cm^3). The results are shown for quark matter without pairing (dotted lines) and for color superconducting quark matter with Δ_0 = 100 MeV (full lines). The adopted values for the bag constant are B = 80 MeV/fm^3 (B80) and B = 160 MeV/fm^3 (B160). We employed different values for the chemical potential of the trapped neutrinos in the hadronic phase: $\mu_{\nu e}$ = 0; 100 MeV. Notice that in general electron neutrinos push the transition density upwards, but in the case of color superconducting matter the effect is very slight. The decrease of the transition density due to color superconductivity is clearly seen in solid lines for T < T_c.

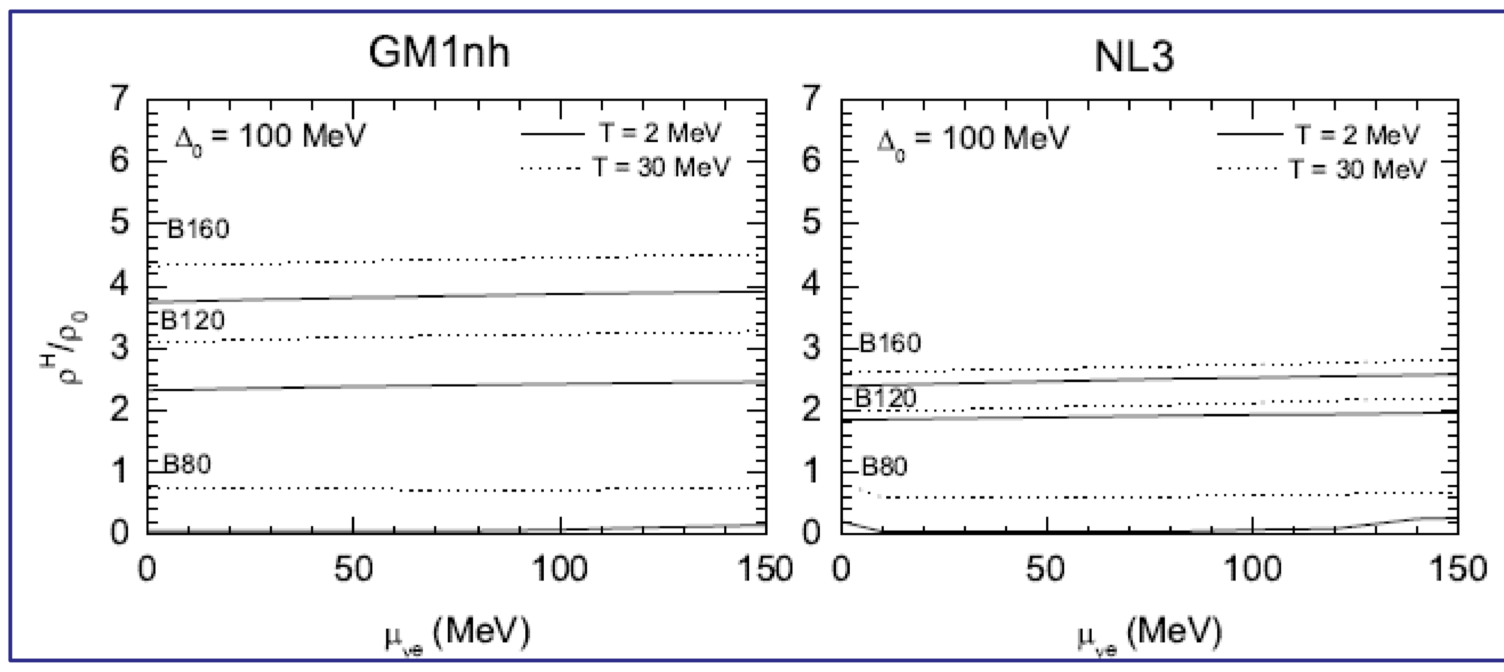


FIG. 2. Mass-energy density of hadronic matter at which deconfinement occurs versus the chemical potential of trapped electron neutrinos $\mu_{\nu e}{}^H$ in the hadronic phase for the GM1nh and the NL3 parametrizations.

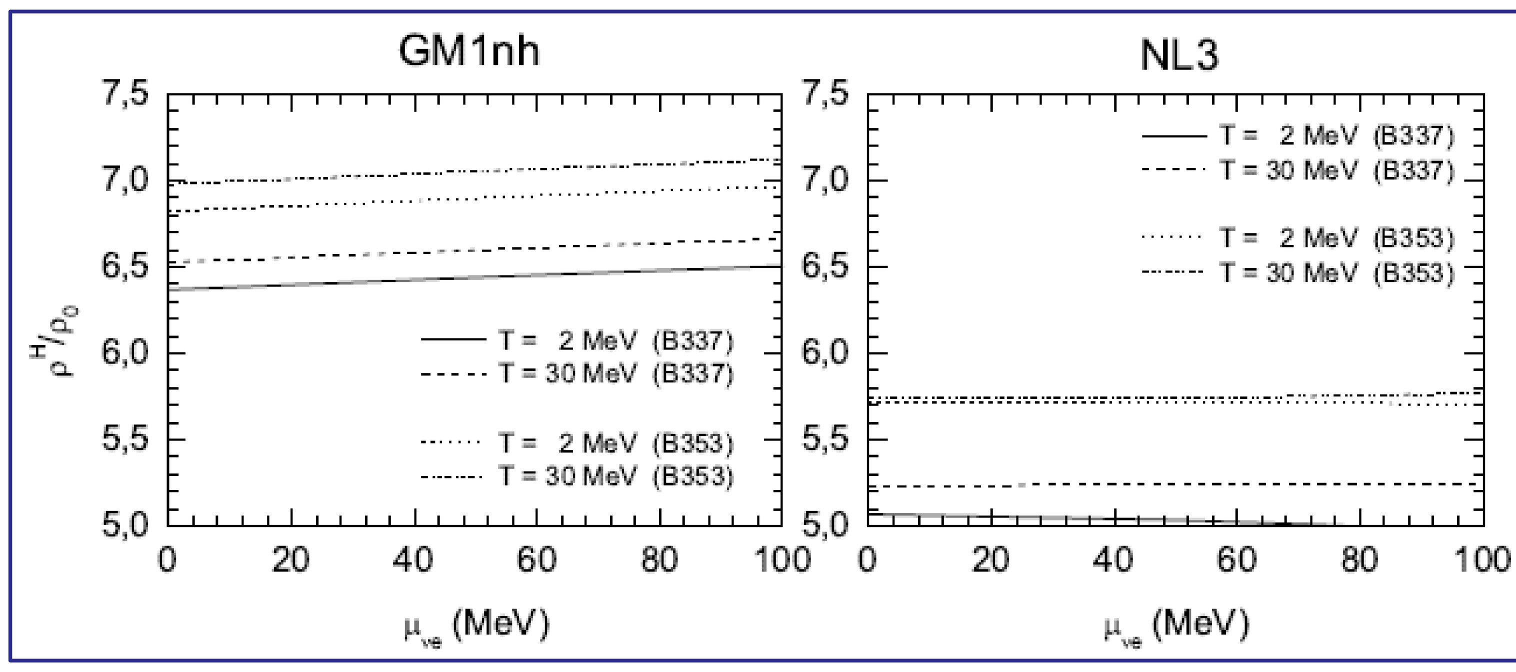


FIG. 3. Same as Fig. 2 but for *B* = 353 MeV/fm^3 (*B*353) and *B* = 337 MeV/fm^3 (*B*337). These values of *B* correspond to the *set 1* and *set 2* parametrizations of the Nambu-Jona-Lasinio model respectively

V. CONCLUSIONS

❑ The expected effects on protoneutron star evolution are as follows:

- when a PNS is formed it is hot and it has a large amount of trapped neutrinos. If color superconductivity were not considered, cooling will increase the transition density while deleptonization will decrease it [1]. Since both effects compete which each other it is possible that the transition is inhibited in the initial moments of the evolution of neutron stars [2];
- when color superconductivity is taken into account, the decrease of temperature decreases the transition density (due to the increase of the pairing gap). Therefore, both cooling and deleptonization of the PNS increase the probability of deconfinement as the PNS evolves.

❑ The *set 1* and *set 2* parametrizations of the NJL model employed in Ref. [3] correspond to *B* = 353 MeV/fm^3 and 337 MeV/fm^3 respectively. The behavior of the transition density ρ^H as a function of *T* is similar for both models. The results between MIT and NJL models are coincident within a 5%, i.e. very similar in spite of the very different equations of state [4].

VI. REFERENCES

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[4] do Carmo, T. A. S., Lugones, G. *submitted* (2012).