NEUTRON STARS IN THE EARLY UNIVERSE

CALLEGARI GIMMI
Physics Institute, University of Ferrara, Ferrara, Italy
Sez. INFN Bologna, Italy

and

BREGOLA MAURO
Physics Institute, University of Ferrara, Ferrara, Italy
Sez. INFN Padova, Padova, Italy

(Received in revised form 12 September 1985)

It is known that most part of neutron stars consist of supernovae remnants and that also a small part of them can be made from white dwarfs that, with suitable accretion conditions, overcame the Chandrashekar limit becoming neutron stars. In this paper we study a further possibility of neutron stars formation that could have taken place in the early stages of the universe. We show that at about $10^{-3}$ s after the Big-Bang conditions were such to allow for matter condensations of the size of a neutron star.

In the Standard Model at this time of $\approx 10^{-3}$ s, during the so-called leptonic era, the hot plasma temperature was $T \approx 10^{12}$ K and the plasma itself was made by $e^+, e^-$, neutrinos, antineutrinos, photons, neutrons and protons in thermal equilibrium [1].

At the temperature under consideration electrons, positrons, neutrinos and antineutrinos were able to induce very rapid transformations from neutrons to protons and vice versa [2]. After thermal equilibrium was reached, at a temperature $T \approx 10^{12}$ K the neutron density was about one half of the proton density. When, during the expansion, the temperature drops below $10^{10}$ K the neutrons begin to decay. We consider that the law of expansion of the very early universe is given by the law of expansion of the Friedmann Universe:

$$P = \frac{3}{32\pi G} = \frac{4.5 \times 10^5}{t^2} \text{9/cm}^3,$$

where $\rho$ is the matter density, $G$ is the gravitational constant and $t$ is the cosmological time in seconds.

The temperature in terms of the cosmological time is:

$$T (\text{MeV}) = t^{-1/2} \chi^{-1/4} \times 1.3 ,$$

where $\chi$ is a dimensionless coefficient greater than one that accounts for the existence of many kinds of particles at thermal equilibrium.
The density of all types of particles is [1]:
\[ n = t^{-3/2} \chi^{1/4} 5 \cdot 10^{31} \text{ cm}^{-3} \]
so for \( t \approx 10^{-3} \text{s} \) we have a temperature \( T \approx 30 \text{ MeV} \) and a neutron density \( \rho_0 \approx 10^{12} \text{ g/cm}^3 \).

The modern theory of galaxy formation is based on the fact that small density perturbation in the early universe must have been transformed into the observed structure of inhomogeneities. The nature of perturbations may be considered to be of two kinds: Adiabatic and Entropic [1].

However, in both cases the evolution of the inhomogeneities is closely related to the initial spectrum of perturbations. The long-wave part of the spectrum is supported by astronomical observations made on stellar cluster, galaxies and cluster of galaxies but it is obvious that also the short-wave part of the spectrum of inhomogeneities is important in order to explain the evolution of the universe. Indeed, the existence of a density fluctuation on a small scale in the early universe may have been separated from the cosmological expansion forming, as we suppose, neutron stars. In the thermodynamical conditions considered above we have the Yeans length \( \lambda_y \approx 100 \text{ km} \) so we consider the condensation of a neutron system with a radius \( R \approx 100 \text{ km} \) and we study the dynamical evolution by means of the temperature dependent gravitational Thomas–Fermi equation [3].

We outline briefly the method: the gravitational temperature-dependent Thomas–Fermi equation is
\[
\Delta U(r) = \frac{\sqrt{32}}{\pi} \int_0^\infty d\epsilon \epsilon^{1/2} \left[ 1 + \exp \left( \frac{\epsilon + U(r) - \mu}{T} \right) \right]^{-1},
\]
where \( U(r) \) is the gravitational potential \( U(r) = -\int d^3r' \rho(r')|r-r'|^{-1} \) which satisfies \( \Delta U(r) = 4\pi \rho(r) \);
\( \epsilon \) is the one-particle kinetic energy;
\( \mu \) is the chemical potential, which has to be determined by the total particle number of the system;
\( T \) is the temperature.

Here we assume that:
\[
\hbar = k = G = m_n = 1;
\]
\( k \) is the Boltzmann constant;
\( G \) is the gravitational constant;
\( m_n \) is the neutron mass.

We assume further that our system is spherically symmetric and enclosed in a radius of