Neutron Star Crustal Mass Fractions

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Abstract. We are investigating mass fractions on the crust of a neutron star which would remain after one year of cooling. We use cooling curves corresponding with various densities, or depths, of the neutron star just after its formation. We assume the modified Urca process dominates the energy budget of the outer layers of the star in order to calculate the temperature of the neutron star as a function of time. Using a nuclear reaction network up to technetium, we calculate how the distribution of nuclei quenches at various depths of the neutron star crust. The initial results indicate that \(^{28}\)Si is the lightest isotope to be optically thick on the surface after one year of cooling.

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INTRODUCTION

The observed emission from a neutron star passes through a crustal layer of the neutron star. In order to fully interpret the observed emission from a neutron star, we need to understand what comprises this crustal layer of the neutron star \([1, 2]\). Here, the mass fractions on the surface are calculated for what would exist on the crust after one year of cooling of the neutron star. These mass fractions are calculated using a 489 isotope reaction network which burns up to technetium written by F.X. Timmes \([3]\) and is available on Timmes’s webpage \(^3\).

COOLING CURVE AND INPUT TEMPERATURE

The neutron star cools for one year starting from a central temperature of \(10^{10}\)K and after one year the central temperature is \(9.5 \times 10^8\)K. During this first year of the neutron star the energy budget is assumed to be dominated by the modified Urca process. Using the Urca process the cooling steps are determined\([4]\):

\[
\Delta t = 1\text{yr} T_9^{-6}(f) \left\{ 1 - \left[ \frac{T_9(f)}{T_9(1)} \right]^6 \right\}
\] (1)

where \(T_9(f)\) is the temperature of the outer core \((T_c)\) in units of \(10^9\)K. The temperature used for each of the time steps depends on the density. For the densities above \(10^7\)g/cm\(^3\), the temperature is given by \(T = T_c\); whereas for the densities below \(10^7\)g/cm\(^3\) the temperature is interpolated between the surface \((T_s)\) and the core temperatures by

\[
\log(T) = \left[ \frac{\log(T_c) - \log(T_s)}{7} \right] \log(\rho) + \log(T_c)
\] (2)

where the surface temperature is given by \([4]\)

\[
T_s = \left(10 \times T_c\right)^{2/3}
\] (3)

where both temperatures are given in Kelvin. The relationship, in equation 2, between the initial temperature of various densities is shown in Fig. 1, for a central temperature of \(10^{10}\)K of the neutron star.

The cooling curves of the first year of the neutron star are displayed in figure 2. These cooling curves are representative of the various densities at which the nuclear reactions were calculated. The temperature for each of these curves is the temperature at the specified density, as opposed to the central temperature of the neutron star. For the densities above \(10^7\)g/cm\(^3\) the cooling curves have the same relationship and thus overlap in the figure.

In order to calculate the nuclear mass fractions the system is initially set to nuclear statistical equilibrium with an initial core temperature of \(T_c = 10^{10}\)K. As the star cools the mass fractions of the isotopes at the various densities are calculated. Pressure arguments are used in order to calculate a minimum initial abundance required for the isotope to be optically thick on the neutron star surface. The total column density of a particular isotope depends on its partial pressure. The total pressure at a
assuming that the star is in the regime of relativistic electrons and the dominant species, $^{56}\text{Ni}$, is fully ionized ($\mu_e = 2$). By dividing the partial pressure of a particular isotope by the surface gravity of the neutron star its column density can be found. The surface gravity ($g_{ns}$) used in this analysis assumes a neutron star with a mass of 1.4$M_\odot$ and a radius of 10 km: $g_{ns} = 2.43 \times 10^{14}$cm/s$^2$. The minimum mass fraction abundance for which enough of the isotope would have risen to the surface for the isotope to have a surface density of 1 g/cm$^2$ and be optically thick is found by dividing the minimum surface density by the column density of the layer.

**INITIAL RESULTS**

We have calculated the mass fractions for two densities within the neutron-star crust, $10^{12}$ g/cm$^3$ and $10^{7}$ g/cm$^3$. At each of these densities the neutron star cool for a year starting at a central temperature of $10^{10}$K. For the case of the higher density, $10^{12}$ g/cm$^3$, the corresponding pressure is $4.9 \times 10^{30}$dyne, which results in a column density of $2.0 \times 10^{16}$g/cm$^2$. For any mass fraction abundance above $4.9 \times 10^{-17}$ enough of the isotope will rise the the neutron star surface to have at least a surface density of 1g/cm$^2$. We find that at a density of $10^{12}$ g/cm$^3$ the lightest elements to rise to the surface and be optically thick are $^{28}\text{Si}$, $^{30}\text{Si}$, $^{31}\text{P}$, $^{33}\text{S}$, and $^{34}\text{S}$. This is shown in figure 3, where the horizontal line indicates the minimum mass fraction abundance required for the surface density to be 1g/cm$^2$.

Likewise, for the case of the neutron star density of $10^{7}$ g/cm$^3$ we find the corresponding pressure to be $1.1 \times 10^{24}$ dyne and the column density to be $4.4 \times 10^{9}$g/cm$^2$. A minimum mass fraction abundance of $2.3 \times 10^{-10}$ at a density of $10^{7}$g/cm$^3$ is required for an isotope to have a surface density of 1g/cm$^2$ and be optically thick. The isotopes $^{28}\text{Si}$, $^{32}\text{S}$, $^{34}\text{S}$, and $^{36}\text{Ar}$ are the lightest isotopes found to have large enough abundances to be optically thick after rising to the surface. Figure 4 displays the mass fraction abundances with a horizontal line indication the minimum abundance of the mass fractions required.

**CONCLUSIONS AND FUTURE WORK**

We have examined the mass fractions that will result in an optically thick surface layer by looking at two cases: a density of $10^{12}$ g/cm$^3$ and another of $10^{7}$ g/cm$^3$. The mass fractions at these densities are calculated using a 489 isotope reaction network which burns up to technetium. The neutron star is cooled for a year, starting with a temperature of $10^{10}$K, assuming the modified Urca process dominates. Upon calculating the mass frac-
FIGURE 3. Mass fractions for the density of $10^{12} \text{g/cm}^3$, this has a corresponding pressure of $4.9 \times 10^{30} \text{dyne}$ and a column density of $2.0 \times 10^{16} \text{g/cm}^2$. The horizontal line indicates the minimum mass fraction abundance required in order for there to be a surface density of an isotope of $1\text{g/cm}^2$. The mass fractions included in this plot are the lightest isotopes for which the isotope would be optically thick on the surface.

FIGURE 4. Lightest isotopes for which the mass fraction abundance would be great enough that the isotope will be optically thick on the neutron star surface. These are the mass fractions for the density of $10^7 \text{g/cm}^3$. The horizontal line indicates the minimum abundance required for an isotope to have a surface density of $1\text{g/cm}^2$. The corresponding pressure and column density for this neutron star density are $1.1 \times 10^{29} \text{dyne}$ and $4.4 \times 10^9 \text{g/cm}^2$, respectively.

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