A peculiarity of nuclear flow in the stellar CNO cycle with energetic particles

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Abstract

A peculiarity of the stellar carbon-nitrogen-oxygen (CNO) cycle caused by MeV α-particles and protons generated in exoergic nuclear processes is analyzed. The main parameters of these particles and suprathermal reactions induced by them in a stellar core are calculated. It is shown that these reactions can trigger an abnormal nuclear flow in the second branch of the stellar CNO cycle. A conjecture is made that the phenomenon is of a general nature and can manifest in various stars at non-exploding stages of their evolution. The influence of the abnormal flow on some CNO characteristics is demonstrated.

1. Introduction

It is known that most models of stellar nucleosynthesis rely on nuclear reaction networks operating with thermal processes between Maxwellian particles. In some cases, however, energetic non-Maxwellian particles of various origins are also invoked to account for element abundances in certain stars (see, e.g. [1] and references therein). For example, this concerns characteristics of the surface composition of P-rich stars [2], metal-poor halo stars [3], and a chemically-peculiar magnetic star [4]. The nuclear interaction of solar energetic particles with the surface of the early Sun is also considered [5] as a mechanism for the origin of some short-lived nuclides.

Characteristics of the inner part of stars can also be influenced by energetic particles naturally produced in thermonuclear reactions and released in the decay of unstable nuclei. These fast projectiles slow down in stellar core plasmas and with some probability undergo suprathermal nuclear reactions before being thermalized. While these reactions are omitted in thermal reaction networks, they can significantly enhance endoergic processes that do not proceed at low energies below their thresholds. A possibility of such effects in some stellar reactions induced by fast charged particles and neutrons was demonstrated, e.g. in Refs. [6–8]. The reaction enhancement can particularly appear in reverse and breakup processes, as they are all endoergic (for breakup reactions in the Sun, see [9]).

In this context, the stellar carbon-nitrogen-oxygen (CNO) cycle presents a sequence of processes suitable for the suprathermal effects to manifest. This cycle involves various reverse processes like \( \alpha + B \rightarrow p + A \) that can be induced by fast \( \alpha \)-particles generated in stellar reactions.

Among the interesting processes, we can find:

\[ \alpha + ^{14}\text{N} \rightarrow p + ^{17}\text{O} \quad (E_{\alpha,\text{thr}} = 1.531 \text{ MeV}) \]  

having a moderate value of threshold \( E_{\alpha,\text{thr}} \) accessible for MeV \( \alpha \)-particles. The balance between this process and the corresponding forward \((p, \alpha)\) reaction

\[ p + ^{17}\text{O} \rightarrow \alpha + ^{14}\text{N} \quad (Q = 1.191 \text{ MeV}) \]  

controls nuclear flow in the \( ^{14}\text{N} - ^{17}\text{O} \) pair. An important point is that the \((p, \alpha)\) reaction closes the second branch of the CNO cycle (the CNO-II cycle) and is one of three processes primarily determining the CNO burning rate [10].

Some features of the solar CNO cycle irradiated by MeV \( \alpha \)-particles born in the pp chain processes were demonstrated in Refs. [11, 12]. In particular, it was shown that the reverse \( ^{14}\text{N}(\alpha, p)^{17}\text{O} \) reaction rate can exceed
the forward $^{17}\text{O}(p, \alpha)^{14}\text{N}$ one, causing the redirection of nuclear flow between $^{14}\text{N}$ and $^{17}\text{O}$. It was also obtained that this phenomenon can affect some characteristics of the CNO cycle, e.g. the $^{17}\text{O}$ abundance and the emission rate of $^{16}\text{F}$ neutrinos in the solar outer core [13].

In view of these findings, an interesting question arises whether the CNO-II flow peculiarity demonstrated for the Sun is of a general nature, creating conditions for its manifestation in other stars at non-exploding stages of their evolution.

The purpose of the present paper is to provide arguments in favor of such a scenario.

2. Fast-particle-induced nuclear flow in a stellar core

Several factors determine the rates of suprathermal reactions in a stellar plasma. One of them is the flux of fast particles $f$ generated in the stellar core. In the Sun, most of these particles are produced in the $pp$ chain processes being the predominant mechanism of solar burning. Given this, in order to explore the question posed in section 1, it seems reasonable to examine suprathermal processes in objects other than the Sun, in which not the $pp$ chain but the CNO cycle plays an important role in stellar burning.

Such an object—a star with a mass of five solar masses and a metallicity $Z = 0.02$ having radial temperature and density profiles found [14] by running a code [15]—is chosen for the present analysis. It is worth noting that the plasma condition in this star essentially differs from that in the Sun. For example, in the star’s center the plasma temperature $T = 2.5$ keV (versus the solar core temperature $T_{\odot} \sim 1.4$ keV) and density $\rho = 20$ g/cm$^3$ (versus $\rho_{\odot} \sim 150$ g/cm$^3$).

2.1. Calculation model

The formalism of in-flight reaction probability was used to calculate the rate $R_{f \rightarrow xy, \text{st}}$ of a suprathermal $f + b \rightarrow x + y$ reaction induced by fast charged particle $f$ in the stellar core plasma. According to it

$$R_{f \rightarrow xy, \text{st}} = R_f \times W_{f \rightarrow xy},$$

where $R_f$ is the emission rate of particles $f$ and $W_{f \rightarrow xy}$ is the probability that they undergo the in-flight $f + b$ reaction with bulk ions $b$ while slowing down in the plasma. The particle emission rate in a $i + j$ process is

$$R_f = N_f (1 + \delta_{ij})^{-1} n_i n_j \langle \sigma v \rangle_{ij},$$

where $N_f$ is the number of particles $f$ produced per pair of $(ij)$, $n_i$ and $n_j$ are the number densities of plasma species $i$ and $j$, and $\langle \sigma v \rangle_{ij}$ is the thermal (Maxwellian) $i + j$ reactivity. If fast particles are released in the decay of an unstable nucleus $Y$, then

$$R_f = N_f n_Y / \tau,$$

where $\tau$ is the nucleus mean lifetime.

The expression for $W_{f \rightarrow xy}$ has a different form for monoenergetic particles $f$ and those with some source energy spectrum. In the former case

$$W_{f \rightarrow xy}(E_f, 0 \rightarrow E_{f, i}) = 1 - \exp \left[ \int_{E_{f, i}}^{E_{f, 0}} \left( \frac{2E_f}{m_f} \right)^{1/2} n_b \sigma_{f \rightarrow xy}(E_f) (dE_f / dt) \ dE_f \right].$$

In equation (6), $E_{f, 0}$ and $E_{f, i}$ are the initial and final particle energy, respectively, $\sigma_{f \rightarrow xy}$ is the reaction cross section, and $(dE_f / dt)$ is the particle energy loss rate in the plasma. In turn, for fast particles having a source energy spectrum $S(E_f')$ with $0 \leq E_f' \leq E_{f, \text{max}}$

$$W_{f \rightarrow xy} = \frac{\int_{E_{f, i}}^{E_{f, \text{max}}} W_{f \rightarrow xy}(E_f' \rightarrow E_{f, i}) S(E_f') \ dE_f'}{\int_{E_{f, i}}^{E_{f, \text{max}}} S(E_f') \ dE_f'}.$$

One of the key parameters determining the probability $W_{f \rightarrow xy}$ is the particle energy loss rate $(dE_f / dt)$. In the stellar plasma, most of $(dE_f / dt)$ comes from Coulomb (Coul) scattering of particles $f$ by bulk electrons ($e$) and ions ($i$), that is

$$(dE_f / dt) \simeq (dE_f / dt)_e^{\text{Coul}} + (dE_f / dt)_i^{\text{Coul}}.$$  

The terms $(dE_f / dt)_s^{\text{Coul}}$ ($s = e, i$) can be described using a model [16] based on the Fokker-Planck collision theory. They are given by
The temperature $T$ in the stellar core varies within 0.9–2.5 keV and, accordingly, $R_{\alpha^{14N} \rightarrow p^{15}O, th}$ is fully negligible. Indeed, it follows from the relation between thermal reverse and forward reactions [21] that

$$R_{\alpha^{14N} \rightarrow p^{15}O, th} \simeq 0.7 \frac{N_{\text{He}}}{n_{\text{H}}} n_{\text{H}}^{14N} R_{p^{15}O \rightarrow \alpha^{14N}, th} \times \exp \left( \frac{-1191}{T} \right).$$

The temperature $T$ in the stellar core varies within 0.9–2.5 keV and, accordingly, $R_{\alpha^{14N} \rightarrow p^{15}O, th} \simeq 0$. 

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**Figure 1.** The emission rates of fast protons $R_p$ and $\alpha$-particles $R_\alpha$ as a function of distance $R/R_\odot$ from the center of the star.
The total reverse $^{14}$N($\alpha$, $p$) $^{17}$O rate is compared with the forward $^{17}$O($p$, $\alpha$) $^{14}$N rate in figure 5. Both thermal and suprathermal contributions to these rates are shown. The results were found with the $^{14}$N($\alpha$, $p$) $^{17}$O and $^{17}$O($p$, $\alpha$) $^{14}$N cross sections [22–24] and the thermal reactivity $\langle \sigma v \rangle_{^{17}O \rightarrow ^{14}N}$ taken from [18].

The balance of these rates determines the nuclear flow between $^{14}$N and $^{17}$O. Figure 5 shows that in the outer core region the reverse ($\alpha$, $p$) rate is twice as high as the forward ($p$, $\alpha$) one. This causes the flow redirection in the CNO-II cycle illustrated in figure 6(a)–6(c). The normal flow $^{14}$N$\rightarrow$ $^{17}$O (figure 6(a)) is observed in the inner

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**Table 1.** A list of processes generating fast particles ($f(=p, \alpha)$) in the stellar core. The right column shows the particle energy $E_f$. For the process No. 3, the $\alpha$-particle energy may change within the half-width of the $^{8}$Be* [16.626] state [19].

| No. | Reaction | $E_f$(MeV) |
|-----|----------|------------|
| 1   | $^3$He($^3$He, 2$p$)$\alpha$ | $< 10.7$ (for $p$) $< 4.3$ (for $\alpha$) |
| 2   | $^7$Li($p$, $\alpha$)$\alpha$ | 8.674 |
| 3   | $^8$B($\beta^+$)$^{8}$Be* [16.626] $\rightarrow 2\alpha$ | 8.359 |
| 4   | $^{15}$N($p$, $\alpha$)$^{12}$C | 3.724 |
| 5   | $^{17}$O($p$, $\alpha$)$^{14}$N | 3.142 |
core. However, at the radius $R/R_\odot \gtrsim 0.7$ the situation changes. At $R/R_\odot \approx 0.7$ the competing $(p, \alpha)$ and $(\alpha, p)$ rates become equal (that is schematically demonstrated in figure 6(b)) and at the larger radii the abnormal clockwise flow $^{14}\text{N} \rightarrow ^{17}\text{O}$ appears (figure 6(c)). This flow is formed in the outer core region constituting $\sim 70\%$ of the total core volume.

To better realize the level of the abnormal flow as a channel of $^{17}\text{O}$ built-up, it is useful to compare its rate with the rate of $^{17}\text{O}$ burn-up. It is known that $^{17}\text{O}$ burns up predominantly in $^{17}\text{O}(p, \alpha)^{14}\text{N}$ and $^{17}\text{O}(p, \gamma)^{18}\text{F}$ reactions. Their rates are compared with the $^{14}\text{N}(\alpha, p)^{17}\text{O}$ rate in figure 7. It is seen that in the outer core the suprathermal channel of $^{17}\text{O}$ synthesis fully compensates both $^{17}\text{O}$ burn-up processes.

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![Figure 3](image1.png)

**Figure 3.** The probabilities of the reverse (a) and forward (b) processes induced by fast $\alpha$-particles and protons.

![Figure 4](image2.png)

**Figure 4.** The total suprathermal $^{14}\text{N}(\alpha, p)^{17}\text{O}$ rate together with partial contributions provided by fast $\alpha$-particles born in different processes.
Figure 5. The thermal (th) and suprathermal (sth) rates for the forward $^{17}$O($p, \alpha$)$^{14}$N and reverse $^{14}$N($\alpha, p$)$^{17}$O reactions in the stellar plasma.

Figure 6. The diagram of the CNO-II cycle (see explanations in the text).

Figure 7. The rates of competing reactions of $^{17}$O built-up and burn-up in the stellar core.
The results in figures 5 and 7 suggest that the suprathermal reactions can affect the total energy released in the pair of $^{17}\text{O} + p \rightarrow \alpha + ^{14}\text{N}$ processes and also change the $^{17}\text{O}$ abundance in the outer core. The total power density $P$ for these processes is determined by a superposition of thermal and suprathermal components

$$P = P_{\text{th}} + P_{\text{sh}},$$

where

$$P_{\text{th}} = R_{p^2}^{17}\text{O} \rightarrow ^{14}\text{N}_{\text{th}} \times Q,$$

$$P_{\text{sh}} = R_{f} \times \mathcal{E}.$$  

For an expression for the energy $\mathcal{E}$ released per fast particle $f = (\alpha, p)$, the reader is referred to [13]. The calculated power densities are compared in figure 8(a). One can see that at $R/R_0 > 0.5$ the suprathermal component increases the total power density up to 15 times.

Figure 8(b) presents the suprathermal enhancement for the mass fraction $X$ of $^{17}\text{O}$ and also $^{18}\text{F}$ that follows $^{17}\text{O}$ in the CNO cycle diagram (see, e.g. [25]). It is seen that in the outer core the suprathermal reactions increase the abundance of these elements by about 10\%–30\%. Furthermore, since the $^{18}\text{F}$ decay rate $R_{\nu} = n_{\nu} / \tau$, the curve marked with triangles in figure 8(b) also shows the enhancement of $^{18}\text{F}$ neutrino emission. One should note, however, that at $R/R_0 > 1.2$ the suprathermal effect was found to be rapidly weakening. The results in figure 8(b) were obtained by running a stellar reaction network allowing for the suprathermal processes using a code [26]. The code was run at constant temperature and density corresponding to the selected radii $R/R_0$.

In closing, the abnormal flow does not decrease the $^{14}\text{N}$ number density, because its value is almost completely controlled by the main (first) branch of the CNO cycle. This is a reason why in the outer core the $^{17}\text{O}$ abundance still remains lower than the $^{14}\text{N}$ abundance by about two orders of magnitude.
Plasma electrons are the main stopping agents for fast particles.

The data that support the findings of this study are available upon reasonable request from the authors.

Plasma characteristics

| Object | Present | Sun |
|--------|---------|-----|
| predominant burning mechanism | the CNO cycle | the pp chain |
| temperature $T_T = T_i = T$(keV) | 2.5–0.9 | 1.4–0.7 |
| density $\rho$(g/cm$^3$) | 20–2 | 154–21 |
| electron number density $n_e$(cm$^{-3}$) | $8 \times 10^{20}$–$9 \times 10^{23}$ | $6 \times 10^{22}$–$1 \times 10^{25}$ |
| particle emission rate $R_{\text{Fi}}$(cm$^{-3}$s$^{-1}$) | $8 \times 10^{9}$–$6 \times 10^{12}$ | $6 \times 10^{7}$–$3 \times 10^{9}$ |
| degeneracy parameter $\Theta^a$ | 17–26 | 2–4 |
| coupling parameter $\Gamma^b$ | 0.02–0.03 | 0.07–0.07 |

Suprathermal impact

(i) abnormal flow region:
- redirection radius $R_r/R_i$: 0.7 vs. 0.08
- fraction of the core volume (%): ~70 vs. ~90

(ii) enhancement factor:
- $^{17}$O + $p \rightarrow ^{14}$N power density: 1–15 vs. 1–254
- $^{17}$O mass fraction: 1–1.3 vs. 1–4.1
- $^{14}$F mass fraction: 1–1.27 vs. 1–4.2
- $^{18}$F neutrino emission: 1–1.27 vs. 1–4.2

References:

$^a$ $\Theta = T_e/E_F$, where the Fermi energy $E_F = (\hbar^2/2m_e)(3\pi^2 n_e)^{2/3}$.

$^b$ $\Gamma = E_e/T_e$, where the Coulomb energy $E_C = e^2/(4\pi\varepsilon_0)^{3/2}(4\pi n_e/3)^{1/3}$.

3. Conclusions

Thus, the irradiation of the stellar core plasma by reaction-produced MeV particles gives rise to the appearance of the abnormal nuclear flow between $^{14}$N and $^{17}$O capable of enhancing some CNO parameters in the outer core. These are the energy released in the $^{17}$O + $p \rightarrow ^{14}$N reactions closing the CNO-II cycle, the abundances of $^{17}$O and $^{18}$F isotopes, and the $^{18}$F neutrino emission rate.

Some characteristics of the plasma are summarized in table 2. Shown are the predominant mechanism of plasma burning and several parameters for the inner and outer core region. The respective characteristics for the Sun are also given for comparison. Table 2 indicates that the physical conditions of these plasmas differ significantly. In particular, this concerns the parameters $R_i$ and $n_e$, essentially affecting the strength of the suprathermal processes.

In spite of this, however, a comparison of the present results with those for the Sun (see table 2) reveals that both objects demonstrate a qualitatively similar picture of suprathermal impact on the CNO-II cycle, such as the redirection of nuclear flow and the enhancement of some parameters. This serves as an argument in favor of a conjecture that the phenomenon is of a general nature and can manifest to a greater or lesser extent in various stars at non-exploding stages of their evolution. At least it seems likely that the effect can appear in the objects with keV temperatures and densities of a few tens g/cm$^3$ to a few hundreds g/cm$^3$.

A possible application of the conjecture may concern studies of presolar grains originated in low or intermediate mass stars (see Refs. [27, 28] and references therein). In these stars, suprathermal ($\alpha$, $p$) processes can increase $^{17}$O and $^{18}$O abundances in external layers of the core. The abundance enhancement for both elements is expected to be nearly the same, so the $^{17}$O/$^{18}$O ratio will remain almost unchanged. However, the abundance of another oxygen isotope, $^{16}$O, is rather weakly affected by the suprathermal reactions, and, therefore, the $^{17}$O/$^{18}$O and $^{18}$O/$^{16}$O ratio should increase in proportion to the $^{17}$O and $^{18}$O enhancement. The latter can be calculated if radial profiles of the temperature and element number densities in the stellar core are known with good accuracy.

It is hardly possible to provide a universal rule by which one can accurately predict the strength of suprathermal effects is stars. It depends on the stellar plasma condition and may differ significantly for different objects. Therefore, each particular case should be studied individually.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

1 Plasma electrons are the main stopping agents for fast particles.
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