Effect of uncertainty in the $^{12}C(\alpha,\gamma)$ reaction rate on the predicted $^{12}C/^{16}O$ abundance ratio in the Sun

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Introduction

The Sun is a main sequence star that is presently generating energy by burning hydrogen through pp chain and CNO cycle reactions. In this hydrogen burning process four hydrogen nuclei fuse to produce one ^{4}He nucleus thereby releasing energy [1]. This process keeps the sun shining as we see it today. The density of the core during burning is about 150 gm/cc and the core temperature is about 1.5×10^{7} K. As the hydrogen burning continues the inward gravitational pull is balanced by the radiation pressure (appearing from capture reactions) thereby keeping the star in a hydrostatic equilibrium. Using reaction network calculations [2] one can predict the approximate time when all the hydrogen at the core of the Sun is expended and is converted to a helium core. As the hydrogen in the core is completely spent the photon pressure is unable to counteract the gravitational contraction. As a result the density and temperature of the core increases and a stage is reached when helium burning sets in. Helium burning does not start immediately after hydrogen burning because of the higher Coulomb barrier involved in helium burning reactions. One of the most important helium burning reactions is the $^{12}C(\alpha,\gamma)$ reaction [3]. This reaction is important since it determines the ratio of ^{12}C to ^{16}O abundance. However, the rate of this reaction has a large uncertainty even in the most recent measurements. Many recent theoretical works [3,4] have addressed the $^{12}C(\alpha,\gamma)$ reaction mainly from view point of studying the reaction rate or astrophysical S-factor. However, in this paper we study the uncertainty in ^{12}C to ^{16}O abundance ratio in Sun due to the large uncertainty in the measured rate of $^{12}C(\alpha,\gamma)$ reaction. We use a stellar evolution code [5] for main sequence stars and reaction network calculation to investigate this aspect.

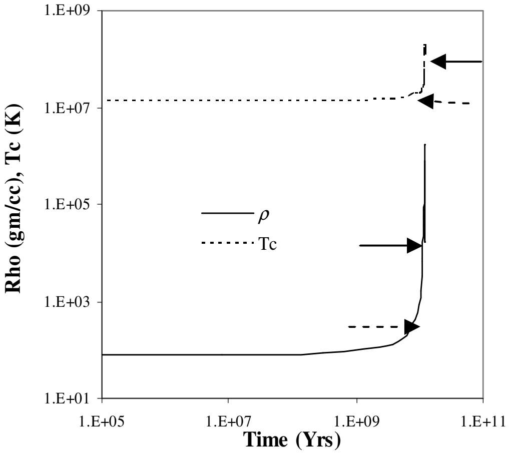

Fig. 1 Time evolution of density and temperature for Sun calculated from *EZ*. The dotted arrows indicate the end of hydrogen burning and the solid arrows indicate the beginning of helium burning.

Calculations

The calculation of the ^{12}C to ^{16}O abundance ratio in the Sun at the end of the helium burning can be done using reaction network calculations. Some basic aspects of the reaction network calculations are described for pp chain reactions in an earlier report [6]. However, for helium burning several options of the network code is available in the literature. In this work we have used the seven isotope helium burning network of Timmes [7]. The program requires besides other parameters, the density and temperature of the Sun. In order to know a reliable value of density and temperature of the Sun at the beginning of helium burning we have used a stellar evolution code for main sequence stars, *EZ* [5]. This code tracks the evolution of the density and temperature with the age of the star. In the fig.1 we show a time evolution of the density and core temperature from the hydrogen burning to the end of helium burning phase. The arrows in the figure indicate the end of hydrogen burning and the onset of helium burning. This calculation has been done using CF88 compilation of reaction rates. The reaction network code also calculates the value with the CF88 compilation of reaction rates. We have modified this code and used the latest measured reaction rate by Kunz et al [8] for the $^{12}C(\alpha,\gamma)$ reaction. We also plot in fig.2 the abundance of ^{12}C and ^{16}O with time for the high and low limit of the reaction rate as given by Kunz et al [8]. The measured rate has an uncertainty of 35% at temperature relevant to Sun. The lower and upper limits of the reaction rate are 4.11×10^{-19} and 7.96×10^{-19} in units of $cm^3\ mol^{-1}\ s^{-1}$, respectively. The adopted value is 5.92×10^{-19} at temperature 1.2×10^8K. We therefore show in fig.3 the predicted $^{12}C/^{16}O$ abundance ratio for the lower and upper limits of the reaction rate. The $^{12}C/^{16}O$ abundance ratio for the Sun for the adopted value, lower and upper limits of the reaction rate are 0.549, 0.757 and 0.404 respectively. The uncertainty in this ratio at the end of helium burning is about 38%.

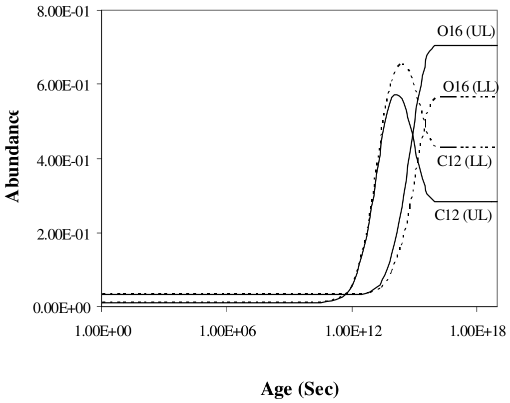

Fig. 2 Time evolution of ^{12}C and ^{16}O abundance from the beginning of helium burning from reaction network code.

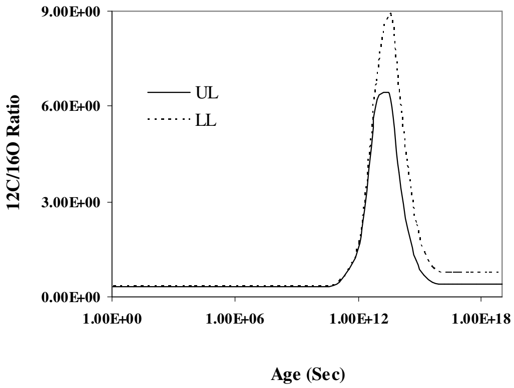

Fig.3 Time evolution of ratio of ^{12}C to ^{16}O abundance (as shown in fig.2).

Summary

In this report we have predicted the value of ^{12}C to ^{16}O abundance ratio in Sun at the end of helium burning. We have also calculated the amount of uncertainty in this ratio due to an uncertainty in the $^{12}C(\alpha,\gamma)$ reaction rate using a stellar evolution code and helium burning reaction network. The calculations indicate that the $^{12}C(\alpha,\gamma)$ reaction needs to be better understood in terms of theoretical models in order to predict the $^{12}C/^{16}O$ abundance ratio more accurately.

References

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