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CHEMICAL ELEMENTS DIFFUSION IN THE SOLAR INTERIOR

H.S.Ali
Department of Astronomy, College of Science, University of Baghdad.

Abstract

The standard solar model and equation of state have been used to study relative diffusion of Hydrogen and Helium in the present time for solar interior, as a function of distance and depth from the center of the star. The effects of temperature and density on diffusion velocity for these chemical elements have been explaned.

It is found that heat flow which is arising from these reactions leads to an increase in helium diffusion velocity, while the temperature and density leading to a decrease in Hydrogen diffusion velocity. This means that Hydrogen behaves inversely with that for helium does through these reactions. Accordingly, diffusion percentages for Hydrogen, Helium and other Heavy Elements could be determined for the main sequence stars and white dwarf stars.

Introduction

The Sun contains about 99.8 % of the mass of the solar system; it is now widely believed to be composed mostly of hydrogen (H) [1]. The line classification of the different elements in the solar spectrum shows that hydrogen (H) is the most abundant element in the Sun's atmosphere [2]. The discovery of energy released in H-fusion and the desire to explain solar luminosity have played a role in change our views about elemental abundances [3]. The H-model of the Sun may be attractive because it is consistent with the nebular model for the formation of the solar system and with the Standard Solar Model (SSM). This assumes that the Sun formed in an instant of time as a fully convective, spherically symmetric, homogeneous body, with no gain or loss of mass [4]. Accordingly, the composition of the bulk Sun is much like that of its atmosphere. Therefore, the reason for solar luminosity remains widespread and its energy comes from the fusion of protons (^{1}H) into the most abundant helium isotope (^{4}He) [5]. Standard Solar Model (SSM) suggesting that the Sun and its planetary system formed over a very different time scale, from chemically and isotopically heterogeneous supernova (SN) debris with abundant Fe but little H or He in the central region where the Sun and the inner planets formed [6]. Wherein, nuclear systematic is used to examine the elemental and isotopic abundances of the SSM [7].

In this paper, we study the relative diffusion of hydrogen (H) and helium (^{4}He) inside the sun, depending on the changes in temperature and charge density properties. This is arising from thermonuclear fusion inside the sun, using the equation of state. We choose this equation because it contains relatively detailed physics, which is usually used in standard solar modeling.

Hydrogen and Helium Diffusion:

Chemical elements diffusion in stars is driven by pressure gradients (or gravity), temperature gradients and density gradients. Gravity tends to concentrate the heavier elements towards the center of the star. In pure hydrogen-helium plasma, helium diffuses towards the center of the star, while hydrogen diffuses outwards. The local rate of change of the hydrogen mass fraction is equal and opposite to the rate of change of the helium mass fraction. This follows from the condition of momentum conservation. The light electrons also tend to rise, but are held back by an electric field which counteracts gravity. Temperature and density gradients lead to thermal diffusion, which tends to concentrate more highly charged and more massive species towards the hottest region of the star, its center [8]. Our work in this paper divided into two parts:

Firstly, calculate the physical structure of the solar interior; our reference standard solar model is constructed using the default physics and parameters of the stellar evolution code, details in [9], which solves the conservation and transport equations of stellar structure using the *Henyey relaxation method*, details in [10], that will generate values for mass (M_r), luminosity (L_r), pressure (P_r), density (ρ_r), and temperature (T_r), for each value of stellar radius.

Secondly, using outputs for this model and equation of state, which written in equation (1), to calculate the diffusion of hydrogen and helium ratio inside the sun at present [11]:

$$P_r = \frac{kT_r}{um_p}\rho_r \quad \text{...} (1)$$

Where m_p is the mass of the proton ($1.6726231*10^{-24}$ g), k is Boltzmann's constant ($1.380658*10^{-16}$ erg K^{-1}), and u is the mean molecular weight [11].

$$u = \frac{1}{2X + \left(\frac{3}{4}\right)Y + \left(\frac{1}{2}\right)Z} \quad \text{..............................} (2)$$

Where X, Y, and Z are the mass fractions of hydrogen, helium, and heavy elements, respectively, then it holds by definition [11]:

$$X + Y + Z = 1 \quad \text{..} (3)$$

The solar matter is at present approximately 70% hydrogen, 28% helium and 2% metals by mass fraction [12]. Throughout the solar interior, u is approximately 0.62, especially in the core, where the chemical composition is altering due to nuclear burning. Finally, implement of equations (1), (2) and (3), to find the chemical composition ratio at each point in solar interior, and plotted against fraction of the radius and mass, because it is the most intuitive way to look at a spherical body (like solar stars), these are shown in Figs. (1) and (2), which illustrate the distribution of the hydrogen and helium ratio, as a function of radius and mass fractions in the center to the surface of the present time for solar interior.

The below Figures are showing that the decline in percentages for hydrogen and helium with increasing radius and mass fractions. There declinations are the product of the thermonuclear reactions that are powering the Sun. During solar evolution, hydrogen is converted into helium in the hot, dense core. The ^4He content in the core of the Sun is enhanced as the star uses up its fuel.

We have noticed that there is a strongly peaked distribution of helium, in the solar interior.

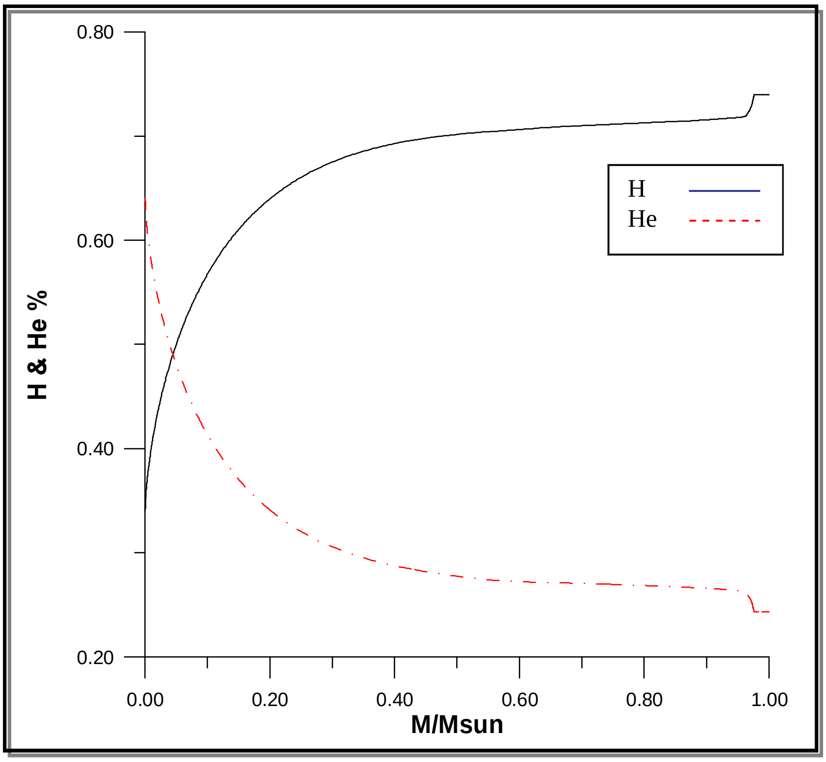

Fig.(1): Diffusion of Hydrogen & Helium in the Sun, as a function of mass.

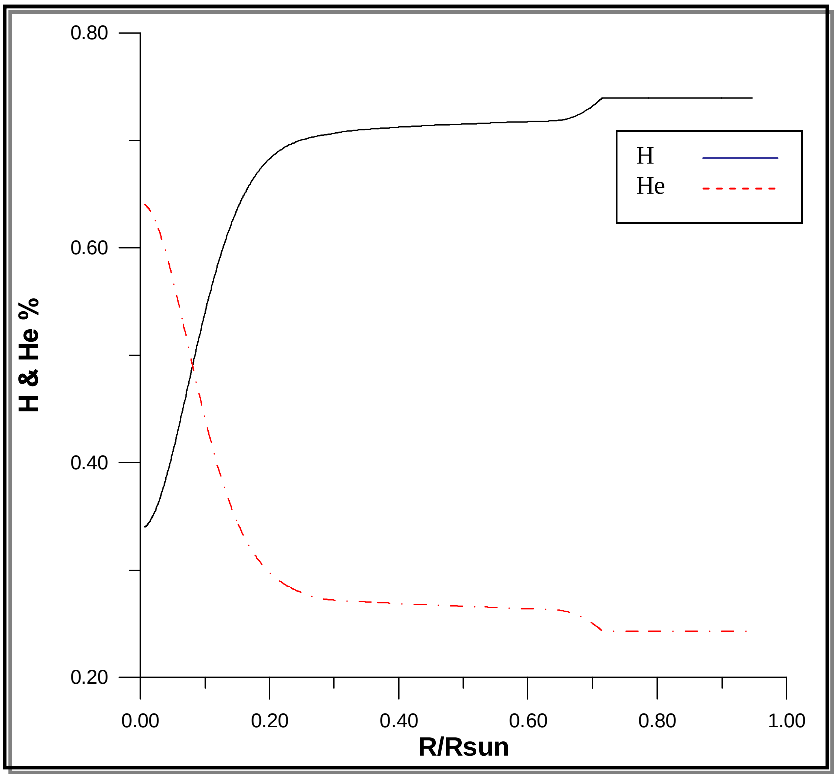

Fig. (2) : Diffusion of Hydrogen & Helium in the Sun, as a function of radius.

We have noticed that there is a strongly peaked distribution of helium, in the solar interior. This is due to the fact that hydrogen is quickly consumed by the *proton –proton (pp)* chain reaction in the inner regions of the Sun, but has no mechanism for formation in the outer regions. In the peak region, helium is produced via the first two reactions by *pp*-chain, but the temperature is not high enough for the subsequent reaction to take place. In *Carbon-Nitrogen-Oxygen (CNO)* process, we show composition changes at intermediate temperatures are described by individual cross sections to follow the reaction flows. High temperatures lead to chemical equilibrium, as illustrated in Fig.(3), this because abundance distributions on isotopic lines which show maxima at specific proton or neutron separation energies. Therefore, in such cases individual reactions might not be that important, but such equilibrium depend on correct reaction energies (Q-values) or separation energies. The behavior of shell effects and shell closures deserves special attention. While strong interaction timescales can support equilibrium at high temperatures and densities as shown in Fig.(4), weak interactions lead very rare to chemical Equilibrium.

Finally, from the above results we can note the intercept points (when H=He), for hydrogen and helium ratio with all variables that are used in our work (as shown as in Table (1)) represent the equilibrium state for the star.

Table (1)
Represent the Intercept Points with Equilibrium Points in the Solar interior.

Intercept Points	*Equilibrium Points*	*Variables*
0.47	0.08	M/M_{sun}
0.478	0.1	R/R_{sun}
0.48	1.1	ρ_r*10^2
0.48	1.4	T_r*10^7

The transformation process to convert the hydrogen to helium at the center of the star can be classified from the type *pp*-chain, while the hydrogen burning process will be taking longer time than that the *CNO* process, therefore, the star will produce the radiation energy from this process. If we draw the intercept points as function of equilibrium points, we can see that the consuming ratio of hydrogen and helium at the center of the star is almost equal, as show in Fig.(5).

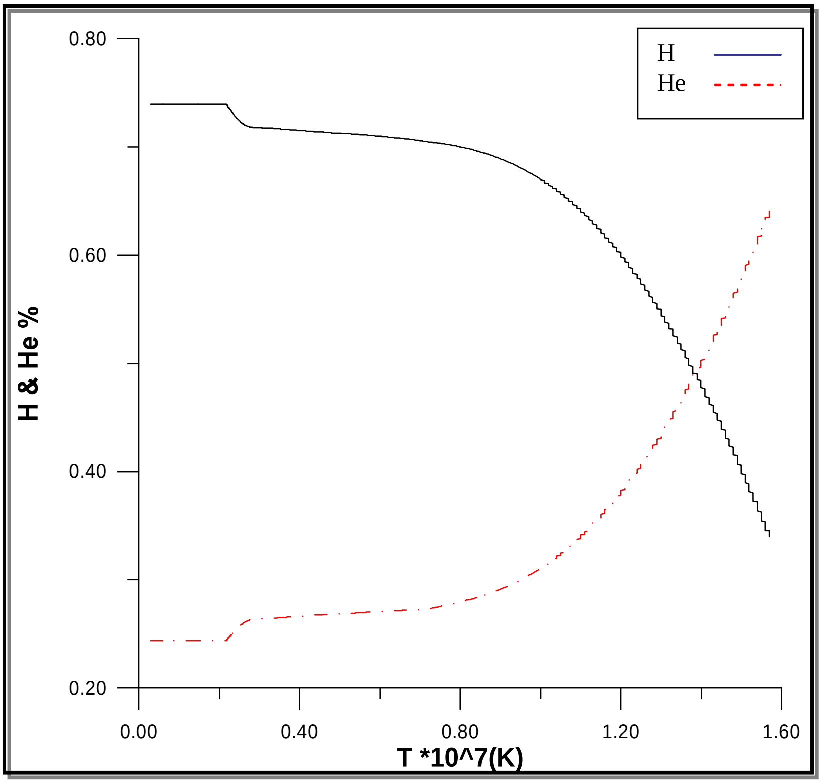

Fig. (3): Diffusion of Hydrogen & Helium in the Sun, as a function of temperature.

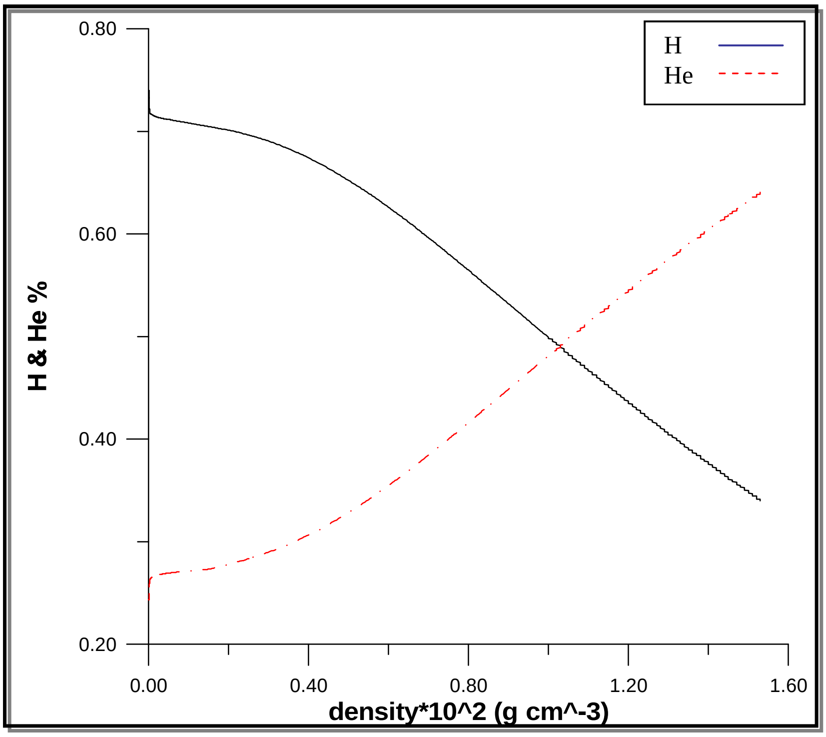

Fig. (4). Diffusion of Hydrogen & Helium in the Sun, as a function of density.

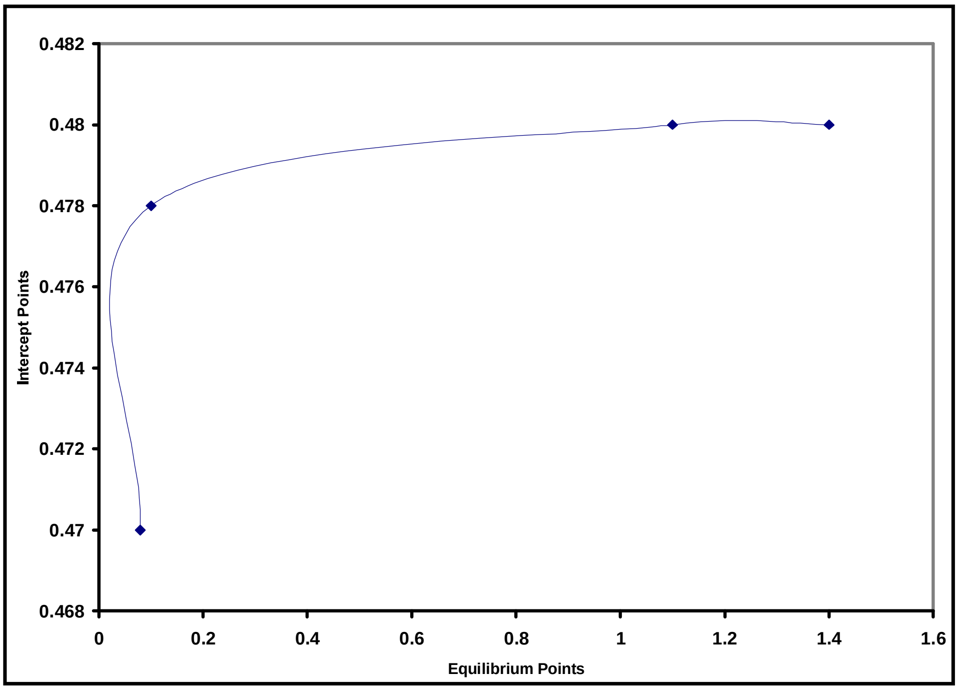

Fig.(5) : The relation between Intercept Points and Equilibrium Points in the Solar interior.

Discussion and Conclusion

The aim of this work is to study the theory of hydrogen and helium diffusion (as percentages ratio) for the Sun at the present time, using a faster and simple mathematical method, in comparison with previous researches. The work is divided into two parts:

1) Hydrogen and Helium diffusion as a function of the radius and mass of the Sun. Figs.(1 and 2) shows a very low percentage of Hydrogen at the center, radius (r=0) and mass (m=0) in comparisons with that for Helium. This is because Hydrogen is being burnt since 4.5 billion years ago [12]. This means that temperature, gravitational and radiation pressure at this region is very high, which leads to the consumption of Hydrogen via *proton-proton* nuclear reaction at the center. As a result, a huge production of Helium existed compared with other parts of the star.

Helium and Hydrogen, as in Figs. (1and2) have an intercept point at $r=0.1R_{sun}$ and $m=0.08M_{sun}$. This is because nuclear reactions near the center of star, reached a balance between the consumption of Hydrogen and the production of Helium in *pp*-chain reaction only with a rate less then that at the center. While we have noticed that the diffusion of Hydrogen is increased gradually as we go outward to reach the surface of star. In comparison, Helium ratio decreases as Hydrogen ratio increases, in the same direction. This is because of the weak nuclear reactions at the outer regions, as we ignore their effect in this work.

2) The diffusion of Hydrogen and Helium as a function of temperature and density, as shown in Figs. (3) and (4), show the same behaviors as mentioned in above. The temperature and density at the center is very high. These decrease as we go outward to the surface of the star, with an increase in Hydrogen percentage.

Finally, Fig.(5) shows the ratio of Hydrogen and Helium are almost equal in the present time for solar interior, which mean the star in equilibrium state and the Sun luminosity would stay approximately constant during this time.

When we compare these results with that done by [9], we've found an excellent agreement, which means that the mathematical method used in this work is reasonable and applicable for finding the percentage ratios for heavy elements that present inside the Sun.

This method could be used for the main sequence stars and white dwarf stars.

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الخلاصة

تم أستخدام النموذج الشمسي القياسي ومعادلة الحالة لدراسة الإنتشار النسبي للهيدروجين والهليوم داخل الشمس في الوقت الحاضر كدالة للمسافة والعمق مقاسة من مركزالنجم إلى السطح. تم تفسير تأثير درجة الحرارة والكثافة على سرعة أنتشار هذه العناصر،حيث لوحظ بأن التدفق الحراري الناتج من هذه التفاعلات، يؤدي الى زيادة سرعة أنتشارعنصر الهليوم .بينما يؤدي ذلك الى نقصان سرعة أنتشار عنصرالهيدروجين ،والتي تعني بأن سلوك عنصر الهيدروجين معاكس لسلوك عنصر الهليوم خلال هذه التفاعلات.

وتأسيساً على هذه الطريقة يمكن حساب نسب أنتشار عناصر الهيدروجين، الهليوم والعناصر الثقيلة الاخرى لنجوم التتابع الرئيسي ونجوم الأقزام البيضاء.