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The Exponential and Gaussian Density Profiles of HI and Fe II in the Gaseous Halo of the Milky Way

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Abstract
This paper aims to investigate the exponential and Gaussian density profiles of the gaseous halo of the Milky Way galaxy for scale heights of $|z| \leq 1000$ pc. The density profile of the neutral hydrogen HI and that of the ionized iron Fe II is considered. The data of different values of scale heights and central number density from the literature have been used in order to determine the density profiles. More specifically, six density profiles of HI and two density profiles of Fe II have been determined. In addition, the average of both cases has been calculated and the results showed that the density of neutral hydrogen is significantly higher than that of the ionized iron.

Keywords: Galaxies, Gaseous haloes, Density profiles, Neutral hydrogen (HI).

التوزيع الاسي والكاوسي لكثافة الهيدروجين المتعادل والحديد المتأين في الهالة الغازية لمجرة درب التبانة

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الخلاصة
هذا البحث يهدف الى دراسة التوزيع الاسي والكاوسي لكثافة الهالة الغازية لمجرة درب التبانة فلكي عند ارتفاع المستوي المجري (z) اقل او يساوي من 1000 فرسخ فلكي. ركزنا على حساب توزيع الكثافة للهيدروجين المتعادل والحديد المتأين. تم استخدام بيانات سابقة من الادبيات لقيم مختلفة من المسافات عن المستوى المجري والكتلة العددية المركزية وذلك لحساب توزيع الكثافة. وبصورة اكثر تحديدا، فقد تم حساب ست توزيعات مختلفة للهيدروجين المتعادل وتوزيعين للحديد المتأين. بالاضافة الى ذلك فقد تم حساب المعدل لكلا الحالتين، حيث اظهرت النتائج بأن كثافة الهيدروجين المتعادل هي اكبر بكثير من كثافة الحديد المتأين.

Introduction

The existence of a gaseous halo or corona around massive spiral galaxies was first investigated in the 1950s [1]. A few decades later, it was shown that the gaseous matter extends for distances of about $|z| \sim 0.5$ kpc from the Galactic plane [2]. In 1984, the z distribution of neutral hydrogen (HI) in the inner Galaxy was studied and the results showed that there is HI in the inner Galaxy to $|z| \geq 1$ kpc from the Galactic plane [3]. It was found that the intergalactic medium (IGM) and the star-forming disks are connected by the gas in the coronae. This indicates that gas in the halos of galaxies is actually a mixture of new material from the IGM and recycled material from the disk [4-8]. The gas in

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the halos plays a significantly crucial role to improve our understanding of the evolution of galaxies because it traces inflowing star formation fuel and feedback from a galaxy's disk [8]. In 2007, the origin and nature of the HI halos around galaxies was discussed. Using HI observations of the galaxy NGC 891, the authors found that the gaseous halo around the galaxy NGC 891 contains approximately 30% of the HI, they also concluded that there are two possibilities for the origin of the HI halo: a galactic fountain and accretion from outside, also they note that HI halo shows structures at different scales from the plane-galactic about 20 kpc up to 22 kpc from disk galactic [9]. The scale height of HI disk is approximately constant in the inner Milky Way (< 8.5 kpc) [10].

The distribution of neutral gas in the halo of the Milky Way was studied in 2011 [11]. The study showed that our galaxy has a halo of neutral gas with a mass of HI in the halo of the Milky Way is $3.2^{+1.0}_{-0.9} \times 10^{8}$ $M_{\odot}$ which is ~ (5% – 10 %) of the total HI mass. In addition, the vertical scale height of the halo is found to be equal to $1.6^{+0.6}_{-0.9}$ kpc [11].

Investigations on the abundances and depletions of neutral hydrogen (HI) and five metals (Si, Mn, Fe, S and Zn) in the gaseous halo of the Galaxy were carried out in the 1980s (see [12]).Those studies were based on data from the International Ultraviolet Explorer (IUE). One of the key findings was that the mean vertical column density of Fe II (~ 1×10^{15} cm^{-2}) is significantly smaller than that of HI (~ 2×10^{20} cm^{-2}) [12].

Studying the gaseous halos of galaxies plays an important role in understanding the interstellar space. For example, they provide important information about different galactic phenomena like correlated supernova explosions in OB associations. Moreover, gaseous halos provide wealth of information about the nature of the intergalactic medium and the ionizing extragalactic radiation field [2].

In this work, six density profiles of HI and two density profiles of Fe II of the Milky Way gaseous halo have been determined using data of scale heights and central densities from the literature [2]. In the following section, we described the calculations of the neutral hydrogen HI and ionized iron Fe II density profiles as a function of the distances away from the plane galactic values [z =0-1000 pc]. The results are summarized in Table-1. We then the results have been discussed in this work. Finally, we make a conclusion in the last section.

Data collection and calculation of density profiles

The density profile of the gaseous halo at a scale height z_0 of the Milky Way can be expressed using exponential or Gaussian profiles.

The exponential mass density of the gaseous disk profile type (E) is given by [13, 14]:

$$\rho_E(z) = \rho_0 e^{-\left(\frac{z}{z_0}\right)} \quad (1)$$

whereas the Gaussian density profile type (G) is given by:

$$\rho_G(z) = \rho_0 e^{-\left(\frac{z}{z_0}\right)^2} \quad (2)$$

where ρ_0 is the central mass density in the galactic mid-plane in unit (g/cm^3), z_0 is the central scale height and (z) is the scale height from the galactic plane.

The number density of particles in the gas (n) is given by [13]:

$$n = \frac{\rho}{\mu m_H} \quad (3)$$

Where m_H is the hydrogen mass (m_H= 1.673532499 x 10^{-24} g), and μ is the mean molecular weight which is simply the average mass of a free particle in the gas, in units of the mass of hydrogen. The mean molecular weight depends on the composition of the gas as well as on the state of ionization of each species.

The mean molecular weight of the neutral hydrogen is one (μ_{HI} =1) [15]. Therefore, from equation (3), the central mass density of HI in the Galactic disk is calculated using:

$$\rho_{0(HI)} = n_0 m_H \quad (4)$$

whereas, the mean molecular weight of ionized metal can be calculated using [16]:

$$\frac{1}{\mu} = \frac{Z+1}{2Z} \quad (5)$$

Where (Z) is atomic number and its value for ionized iron ($Z_{Fe\ II}$ = 56). Thus, according to the equation above ,the mean molecular weight of ionized iron Fe II is calculated and was found to be approximately 2 ($\mu_{Fe\ II} \sim 2$). Therefore, also from equation (3), the central mass density of Fe II in the Galactic disk is calculated using:

$$\rho_{0(Fe\ II)} = 2n_0 m_H \quad (6)$$

Different values of scale heights z_0 and densities n_0 have been collected from the literature [2]. Here it is very important to point out that some observers preferred exponential scale heights (E) whereas others preferred Gaussian scale heights (G). Table-1 outlines the data that have been collected and used in this paper, and our results of central mass densities (ρ_0) calculated from equations (4 and 6) listed in the Table-1.

Table 1- Data analysis for different parameters of the HI and Fe II for Milky Way gaseous halo.

HI	z_0 (pc)	n_0 (cm^{-3})	ρ_0 (g.cm^{-3})	Type scale height
1	110	0.16	2.672×10^{-25}	G
2	250	0.09	1.503×10^{-25}	G
3	480	0.053	0.885×10^{-25}	E
4	330	0.46	7.682×10^{-25}	G
5	240	0.37	6.179×10^{-25}	E
6	800	0.1	1.670×10^{-25}	E
Fe II				
1	1110	8×10^{-8}	2.672×10^{-31}	G
2	500	8×10^{-8}	2.672×10^{-31}	E

Based on equations (1 and 2) and values (ρ_0), (z_0) from Table 1, we calculated exponential, Gaussian and mean mass density profiles $\rho(z)$ of the gaseous halo at a distances away from the galactic plane (z) of our Galaxy. Thus, the density profiles $\rho(z)$ for the six cases of neutral hydrogen HI have been determined using the following formulas:

$$\rho_1(z) = \rho_{01} e^{-\left(\frac{z}{z_{01}}\right)^2} \quad (7)$$

$$\rho_2(z) = \rho_{02} e^{-\left(\frac{z}{z_{02}}\right)^2} \quad (8)$$

$$\rho_3(z) = \rho_{03} e^{-\left(\frac{z}{z_{03}}\right)} \quad (9)$$

$$\rho_4(z) = \rho_{04} e^{-\left(\frac{z}{z_{04}}\right)^2} \quad (10)$$

$$\rho_5(z) = \rho_{05} e^{-\left(\frac{z}{z_{05}}\right)} \quad (11)$$

$$\rho_6(z) = \rho_{06} e^{-\left(\frac{z}{z_{06}}\right)} \quad (12)$$

$$\rho_{mean}HI(z) = \sum_{m}^{6} \rho_m(z)/6 \qquad (13)$$

where m = 1,2, ………6

On the other hand, the two density profiles of Fe II have been calculated using the following formulas:

$$\rho_1(z) = \rho_{01} e^{-\left(\frac{z}{z_{01}}\right)^2} \qquad (14)$$

$$\rho_2(z) = \rho_{02} e^{-\left(\frac{z}{z_{01}}\right)} \qquad (15)$$

$$\rho_{mean}FeII(z) = \sum_{m}^{2} \rho_m(z)/2 \qquad (16)$$

Results and Discussion

In this work, different values of z_o and n_o for HI and Fe II have been collected in order to calculate the density profile of the gaseous halo of our own galaxy. Six density profiles of HI and two density profiles of Fe II have been calculated using either exponential or Gaussian density profile. Then the averages of both cases have been calculated and the ratio of the average of HI to the average of Fe II demonstrated that there significantly higher amount of HI than Fe II in the Milky Way.

Figure-1 shows the six density profiles and the mean density profile of HI. Figure-2 shows the two density profiles and the mean density profile of Fe II. Figure-3 illustrates the ratio between the mean density profile of HI and that of Fe II. The results obviously show that the amount of neutral hydrogen is significantly higher than that of the ionized iron Fe II.

At this point, it should be pointed out that, the acceleration of free fall near the galactic plane cannot be constant, according to the hydrostatic equilibrium equation between vertical scale height (z) and the local acceleration of gravity (g) above the mid-plane galactic. This relation shows that the vertical scale height is dependent on the local acceleration of gravity (g) and the temperature (T) $\left(z_0 = \frac{kT}{\mu m g}\right)$, where k- Boltzmann's Constant 1.38x10 $^{-23}$ J/K. For our Galaxy, observations with (T=10 K^0) gives g=0.67x10^{-29} cm s^{-2} at distances z < 400 pc from the plane of the Galaxy, that is reasonably close to the observed value corresponding to the cold component (HI).

The presence of the exponential component (E) in equations (9, 11,12 and 15) and as shown in the Figures-(1, 2), can be understood after what we have done as a hot component that extends a great distance from the plane galactic z > 400 pc, where the change in the gravitational acceleration is significantly more slower than that near the plane and has a value of g ~ 6x10^{-9} cm s^{-2}. The second Gaussian component (G) in equations (7, 8,10 and 14) and also Figures-(1 , 2) can be explained by the presence of a hot gas, but with a temperature (or dispersion of velocities) less than that of the exponential component, and therefore it lies within the limits on which the gravitational acceleration is significant.

The key conclusion that can be drawn from the observed distribution equation (13) is that the interstellar gas, specifically the part of it that is represented by neutral hydrogen HI, is not substantially homogeneous in its phase composition, and includes at least three components (Exponential component E, Gaussian component G and mean component of HI) with different temperatures.

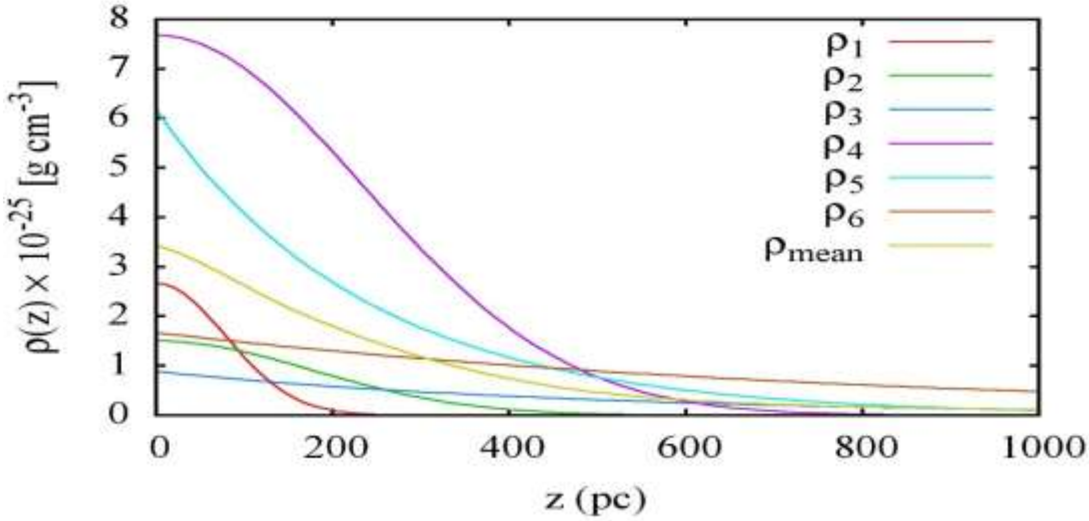

Figure 1- Six density profiles of HI in the gaseous halo of the Milky Way with the mean density profile.

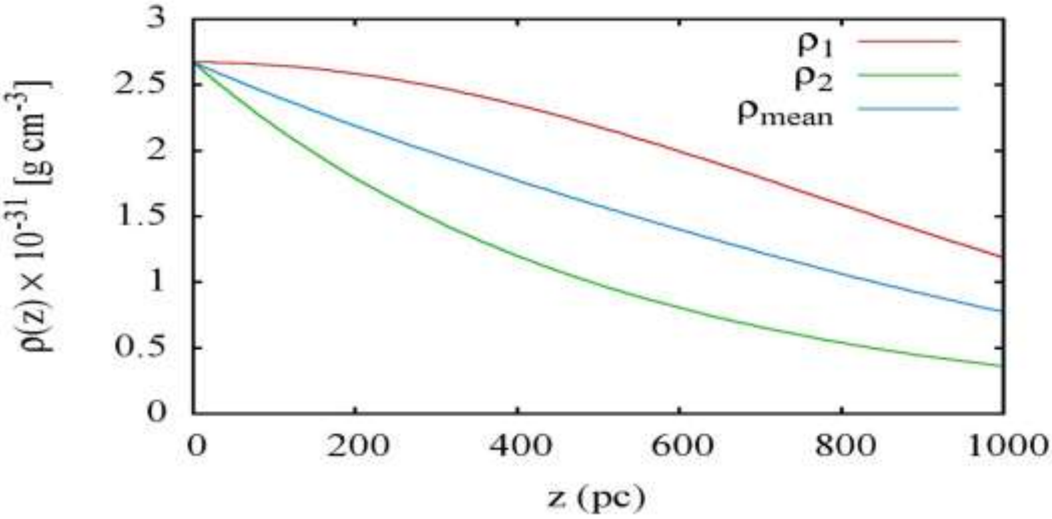

Figure 2- Two density profiles of Fe II in the gaseous halo of the Milky Way with the mean density profile.

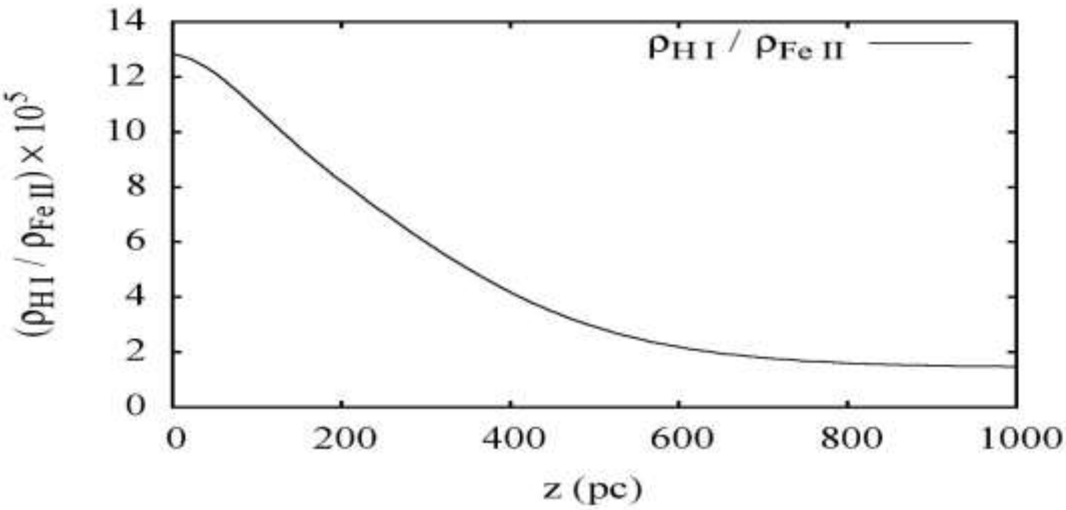

Figure 3- The ratio of mean density profile of HI to that of Fe II in the gaseous halo of the Milky Way.

Conclusions

According to the results of this paper, we found that the distribution of HI density in the halo gaseous of the Milky Way is 7.682×10^{-25} gm/cm^3 at scale height of the Gaussian profile (G), while this density value is 0.885×10^{-25} gm/cm^3 at scale height type the exponential profile (E). In addition, the density values of FeII are exactly the same for the two types scale height (G and E). Finally, the calculations showed that the density profile of neutral hydrogen HI is significantly higher than that of ionized iron FeII.

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