Evolution of virial clouds-I: From the surface of last scattering up to the formation of population-III stars

Noraiz Tahir

Department of Mathematics and Physics "E. De Giorgi", University of Salento, Lecce, Italy
and
INFN, Sezione di Lecce, Lecce Italy

noraiz.tahir@le.infn.it

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1. Galactic Halos

- There is more matter in the galaxies outside the core and disks (see Rubin, *ApJ*, **451**, 419 (1995); Rubin et al. *ApJ*, **159**, 379 (1970)).
- This missing matter is known as “dark matter”.
- To fit in with the observations it is necessary that dark matter go out to $\sim$10 times the radius of the core and hence much more dark matter *should* lie in the outer parts of galaxies.

- These parts are called “dark halos” or “galactic halos”.

2. The Missing Baryon Problem

- According to the standard cosmological (ΛCDM) model of the Universe $\sim 5\%$ of the observable Universe is composed of baryonic dark matter (Ade et al. *A&A*, **594**, A13 (2016)).
- $\sim 60\%$ of these baryons are detected in luminous parts of galaxies, warm-hot intergalactic gas, the circum-galactic medium (CGM), the intra-cluster medium (ICM), and cold gas, leaving $\sim 40\%$ still undetected at present. This is the so-called missing baryon problem.
- Expectations are these baryons might be in the cosmic filaments which is in the form of warm/hot intergalactic medium (WHIM), but it is not possible that *all* baryons reside in them.
- There is evidence of a non negligible fraction of these baryons in the galactic halos (Zhang et al. *ApJ*, **911**, 58 (2021)).

3. Cold Molecular Clouds in the Halos

In 1995 it was proposed that galactic halos contain *pure* molecular hydrogen clouds, exactly at the cosmic microwave background (CMB) radiation temperature and they contribute a non negligible fraction in the galactic halo dark matter (De Paolis et al. *PRL*, **74**, 14 (1995)).

To look for these *chameleon* clouds one suggestion was to look for an asymmetric Doppler shift in the CMB, due to the rotation of these clouds in the M31 halo (De Paolis et al. *A&A* **299**, 647 (1995)).

4. Constraints from the Cosmic Microwave Background Radiation

- *Planck* cosmic microwave background (CMB) data open up a window to observe these clouds.
- The analyzed data showed temperature asymmetry not only for the M31 disk but also for the galactic halo (De Paolis et al. *A&A*, **565**, L3 (2014)).
- This observed asymmetry was almost frequency independent which was a strong indication of the Doppler shift effect due to the halo rotation.

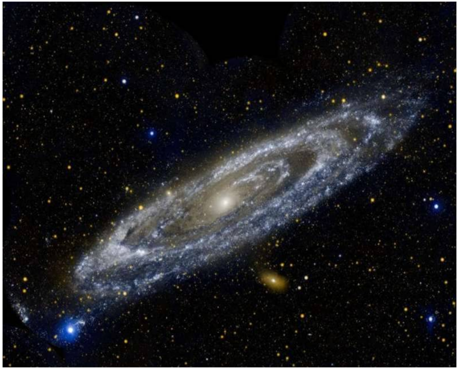

Figure: M31 Galaxy

Other Evidence

Centaurus A
De Paolis et al. A&A, **580**, L8 (2015).

M82
Gurzadyan et al. *A&A*, **582**, A77 (2015).

M33
De Paolis et al. *A&A*, **593**, A57 (2016).

M81
Gurzadyan et al. *A&A*, **609**, A131 (2018).

Sombrero
De Paolis et al. *A&A*, **629**, A87 (2019).

5. Virial Clouds

- The fact that the temperature asymmetry was almost frequency independent strongly supports the Doppler shift explanation to observe pure molecular hydrogen clouds in the halos.
- This did not prove that the clouds are made by pure molecular hydrogen, since helium, dust and other heavier molecules may also be present, and they might contaminate these clouds with a significant fraction.
- These clouds were to survive on account of the virial temperature being in equilibrium with the CMB, we called them "virial clouds".
- Virial clouds were then modeled to estimate the mass, radius and densities at the current CMB temperature (Qadir et al. *PRD*, **100**, 043028 (2019)).

6. Evolution of Virial Clouds

- Observing the Doppler shift due to galactic halo rotation and modeling the virial clouds at the current CMB temperature does not explain the true nature of these clouds.
- To take the matter further we need to trace the evolution of these clouds when they were formed to the present, so as to confront the model with the observational data.
- The task needs to be done in two steps
  Evolution-I: from last scattering surface (LSS) up to the formation of population-III stars.
  Evolution-II: form the formation of population-III stars to the present.

6.1. Evolution-I

- Virial clouds would have been formed at the time of the last scattering surface (LSS) at $z = 1100$ when the CMB temperature was about 3000 K.
- At LSS the Universe constituted mainly on primordial abundance of atomic hydrogen and helium i.e. $\sim 75\%$ H, and $\sim 25\%$ He by mass.
- There were other molecules and atoms that would have been present at that time like deuterium, helium-3, lithium and molecular hydrogen, but the ratio of these molecules and atoms was negligible that they will not give any significant contribution in the evolution-I of the virial clouds.

6.1. Evolution-I

- Since the clouds must be considered to be in thermal equilibrium because they are embedded in the heat bath of the CMB.
- We need to use the canonical distribution function for a fixed temperature and use the cooling of the heat bath to provide a quasi-equilibrium.
- Also the clouds should start to form in the potential well of cold dark matter (CDM).
- As virial clouds are thermalized the potential well will not cause them to collapse to form population-III stars.

6.1. Evolution-I

- For generality we consider a virial cloud composed of an arbitrary mixture of H and He, with mass fractions α and β.
- Then, we use the primordial cosmological fractions of H and He for the final computation.
- The total mass of the cloud can be written as $M_{cl}(r) = \alpha M_H(r) + \beta M_{He}(r)$, with the condition $\alpha + \beta = 1$.
- Here $M_H(r)$ is the total mass of atomic hydrogen and $M_{He}(r)$ is the total mass of helium within r.
- The density distribution for two fluids is given by (Qadir et al. *PRD*, **100**, 043028 (2019))

$$\rho_{cl}(r) = \zeta exp\left[-\frac{1}{2}\left(\frac{\alpha G M_H(r) m_H}{r k_B T} + \frac{\beta G M_{He}(r) m_{He}}{r k_B T}\right)\right], \quad (1)$$

6.1.1. Evolution-I

where, $\zeta = \sqrt{\frac{64}{27}\frac{(G\rho_{c_H}\rho_{c_{He}})^{3/2}}{(kT)^{9/2}}}(m_H m_{He})^{5/2}$, ρ_{c_H} and $\rho_{c_{He}}$ are the central densities of atomic hydrogen and helium in the cloud, m_H and m_{He} are the masses of single atom of hydrogen and helium, k_B is the Boltzmann constant, T is the cloud temperature, and G is the Newton's gravitational constant,.

The corresponding differential equation can be written as

$$r\frac{d\rho_{cl}(r)}{dr} - r^2\left(\frac{2\pi G}{k_B T}\right)[\rho_{cl}(r)(\alpha\rho_{c_H}m_H + \beta\rho_{c_{He}}m_{He})] - \rho_{cl}(r)\ln\left(\frac{\rho_{cl}(r)}{\tau}\right) = 0, \quad (2)$$

where, $\tau = (8/3\sqrt{3})[(G\rho_{c_H}\rho_{c_{He}})^{3/2}/(kT)^{9/2}][m_H m_{He}]^{5/2}$.

6.1.1. Evolution-I

- We now solve eq.(2) numerically with a guess value for the central density at a fixed temperature starting from T=3000 K, and see where the density becomes zero.
- We then check the value of the Jeans radius with that central density.
- We then adjust the value of the central density so that the density becomes zero exactly at the Jeans radius.
- In this way we get a self-consistent solution of the differential equation subject to the given boundary conditions i.e. $\rho(r)|_{r\to 0} = \rho_c$, and $(d\rho(r)/dr)|_{r\to 0} = 0$.

6.1.2. Evolution-I

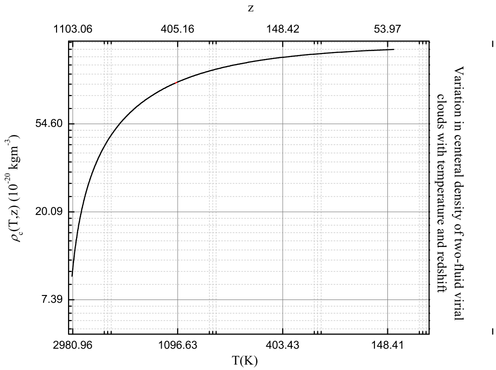

Figure: Variation in central density of primordial H-He clouds

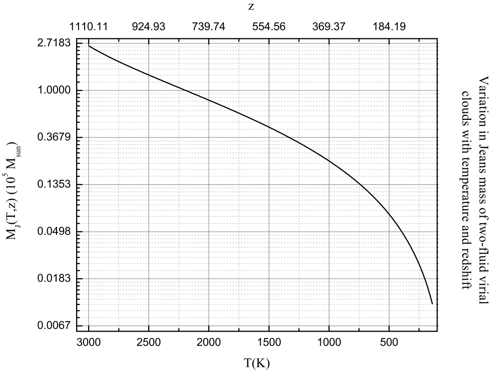

Figure: Variation in Jeans mass of primordial H-He clouds

6.1.1. Evolution-I

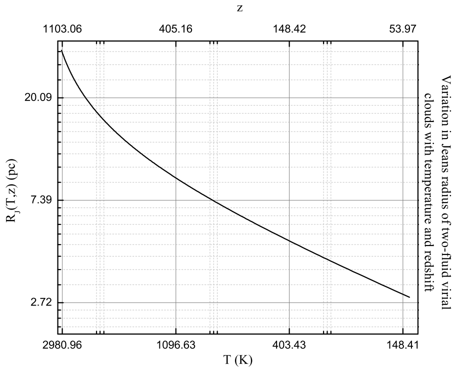

Figure: Variation in Jeans radius of primordial H-He clouds

7. Future Prospects

- It has been shown that the evolution of the virial clouds is *precisely* determinable from the LSS up to the formation of population-III stars.
- Since we are dealing with an era from z=1100 to z=50, one might expect that there would be gravitational clumping in the dark matter gravitational potential well, where there will be gravitational binding energy and hence cooling, so that molecular hydrogen would be more likely to form.
- The H_2 component would be negligible in any case, but more so as there would be no nucleating particles for it in the absence of dust grains to speed up the formation of the molecules.
- If any H_2 molecule formed during this era it was dissociated by the radiation until the density low enough for them to be stable.
- Hence we do not need to consider the effect of cooling from molecular hydrogen till population-III stars exploded.

7. Future Prospects

- Till the explosion of Population III stars no other fluids or substantial contaminants should be present in the virial clouds.
- However, for the subsequent steps of the cloud evolution we will need to include more fluids (heavier atoms) and dust grains produced by population III stars and ejected into the interstellar medium (ISM) through their explosions.
- These dust grains should have an important role in the cloud evolution since they would act as catalysts for the formation of molecular hydrogen, possibly leading to rapid changes in the cloud physical parameters, as higher modes would be excited.
- All these things need to be considered in Evolution-II of virial clouds.