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The formation of Supersonically Induced Gas Objects (SIGOs) with H_2 cooling

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Abstract. During the recombination of the universe, supersonic relative motion between baryons and dark matter (DM) generally existed. In the presence of such streaming motions, gas clumps can collapse outside of virial radii of their closest dark matter halos. Such baryon dominant objects are thought to be self-gravitating and are called supersonically induced gas objects; SIGOs. We perform three-dimensional hydrodynamical simulations by including H_2 chemical reactions and stream velocity and follow SIGO's formation from $z = 200$ to $z = 25$. SIGOs can be formed under the influence of stream velocity, and H_2 cooling is effective in contracting gas clouds. We follow its further evolution with higher resolution. We find that there are SIGOs which become Jeans unstable outside of the virial radius of the closest DM halos. Those SIGOs are gravitationally unstable and trigger star formation.

Keywords. cosmology: theory, methods: numerical, galaxies: high-redshift, stars: Population III

1. Introduction

Recent observations have revealed the history of the universe. At the recombination epoch, the universe became neutral and transparent. At that time, Hydrogen and Helium atoms formed. After that, the first star formation started at around $z \sim 30$. The first stars consisted of only Hydrogen and Helium atoms. The first stars emitted UV radiation, which led to reionization and ended the dark age. An important effect to be considered in star formation in the early universe is the so-called stream velocity (SV). It is a relative velocity between baryons and DM, which originates from baryon acoustic oscillations. The typical value of the relative velocity is 30 km/s at the recombination period, which is about five times greater than the sound speed, so it causes supersonic gas flow. Furthermore, Tseliakhovich & Hirata (2010) argue that the velocity field is coherent over a few mega-parsec scales, thus stream velocity causes non-trivial effects on the first bound objects. Naoz & Narayan (2014) show analytically that SV can form baryon

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density peaks outside of the virial radius of its closest DM halo. Such objects are called Supersonically Induced Gas Objects (SIGOs) and are thought to be progenitors of star clusters in the early universe. The existence of SIGOs has been identified in several simulations. Popa et al. (2016) perform simulations with adiabatic gas and show that SIGOs are able to form in the early universe. Recently, Chiou et al. (2019) and Chiou et al. (2021) incorporate atomic hydrogen cooling in their hydrodynamical simulations. They show that atomic hydrogen cooling alone does not help SIGOs to condense to runaway collapse.

We argue that the reason why those SIGOs in previous research could not collapse is that gas clumps did not cool efficiently. In this study, we incorporate H_2 cooling in our simulations. Radiative cooling of H_2 plays a vital role in the early universe since the primordial gas consists of only H and He. H_2 cooling can lower the temperature of primordial gas clouds to $\sim$ 200K (Yoshida et al. (2006)). We expect H_2 cooling enables SIGOs to collapse.

2. Method

We use the moving mesh code AREPO (Springel (2010)) and perform cosmological hydrodynamical simulations. In the parent simulations, we adopt the simulation boxsize of 1.4cMpc/h with 512^3 DM particles and 512^3 gas cells, and follow the gas evolution from $z = 200$ to $z = 25$. Regarding to the chemistry, we use cooling library GRACKLE (Smith et al. (2017); Chiaki & Wise (2019)) and calculate 49 reactions of 15 chemical species; $e, \mathrm{H}, \mathrm{H}^+, \mathrm{He}, \mathrm{He}^+, \mathrm{He}^{++}, \mathrm{H}^-$, H_2, $\mathrm{H}_2^+, \mathrm{D}, \mathrm{D}^+, \mathrm{HD}, \mathrm{HeH}^+, \mathrm{D}^-$ and HD^+. We run four simulations with/without SV (2v/0v) and with/without H_2 cooling (H2/H). Those runs are labeled as "2vH2", "2vH", "0vH2" and "0vH" respectively.

SIGOs are identified by the following two conditions. The first one is that gas clouds are outside of the virial radii of their closest DM halos. The second one is that the local baryon fraction around the gas halos is over 60%. We select one of the SIGOs detected in Run-2vH2 case and call it "S1". To follow the evolution of S1, we cut out 10 kpc of the region around it and restart the simulation from $z = 25$. The second simulation can refine the gas cell automatically and follow the SIGO's evolution much more precisely than the parent one. The detailed settings are described in Nakazato et al. (2021).

3. Result

3.1. *SIGO's morphology in parent simulation*

Figure 1 shows the gas clouds formation from $z = 31$ to $z = 25$. The colormap shows the gas number density around S1.

We consider S1 which is identified as a SIGO in Run-2vH2. S1 is located at the center of Figure 1 at $z = 25$ with a physical size of $\sim$ 1 kpc. The distance between S1 and its closest DM halo is four times greater than the virial radius of the DM halo. The large gas filament that contains S1 is displaced by $\sim$ 5 comoving kpc to the right from the underlying filamentary structure of DM. This is owing to the stream velocity which flows from left to right (which corresponds to the direction of $+x$).

By definition, S1 is not hosted by DM halos and thus its baryon density is lower than ordinary primordial gas clouds hosted by DM halos (non-SIGOs). For instance, the halo located at the bottom of Figure 1 is identified as a non-SIGO hosted by a DM halo. We refer to it as S2. In comparison with number density, S1 has a much smaller maximum density of $\sim$ 7.9 /cc at $z = 25$ than S2 of 6.89×10^3 /cc.

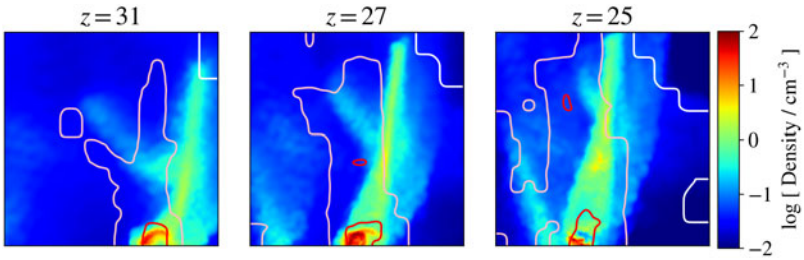

Figure 1. The projected number density of baryons in Run-2vH2. Contours show the DM density. White, pink and red contour lines show 2, 20, and 200 times of the critical density respectively. The side of the length is 40 ckpc.

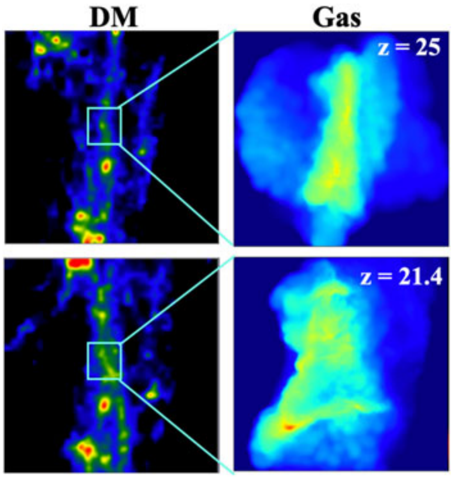

Figure 2. The upper and bottom panels show the S1 at $z = 25$ and $z = 21.4$, when S1 reached Jeans instability. Left: projected DM density distribution around S1 normalized by the critical density of DM. The side of the length is 5 kpc. Right: projected gas number density of S1. The side of the length is 1 kpc.

3.2. *High resolution simulation of S1*

We conduct a high-resolution simulation around S1. S1 become Jeans unstable at $z = 21.4$ (see Figure 3). Figure 2 shows the evolution of S1 from $z = 25$ to $z = 21.4$. We see that S1 reaches high density without being hosted by DM halos.

Figure 3 shows the thermal evolution of S1 at $z = 21.4$. H_2 cools S1 to ~ 200 K and contracts S1 to $\sim$ 100 /cc. We calculate the ratio of the enclosed mass to the Jeans mass $M_J = (\pi/6)\ c_s^3/(G^{3/2}\rho^{1/2})$. We use the mass-weighted average temperature and gas density at all radii. We define the center of the radial profile as the highest density position and calculate the enclosed mass. From the right panel of Figure 3, it is clearly seen that $M_{\rm enc}/M_J$ is over 1 at $z = 21.4$, which suggests that S1 is Jeans unstable. The Jeans mass at $z = 21.4$ is $M_J = 5 \times 10^4\ M_\odot$, which is over 50 times larger than normal (without SV) Jeans mass $M_J \sim 10^3\ M_\odot$ (Abel et al. (2002)).

3.3. *Comparison of the same region in each run*

In order to confirm whether a SIGO is also formed in the other runs, we have checked the same region as Figure 1 in Run-0vH2 and 2vH. Figure 4 shows three projected gas density colormaps. From left to right, the colormaps are for Run-0vH2, 2vH2 and 2vH. In the case of 2vH (the most right), there are no gas clumps formed. This is due to

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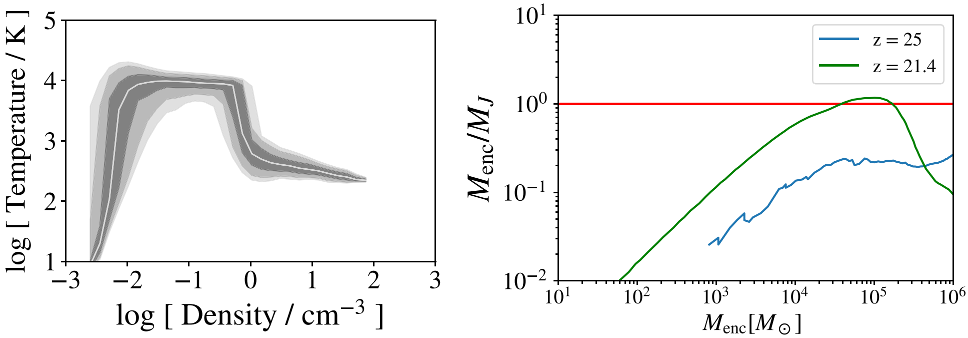

Figure 3. The left figure is a density-temperature phase diagram of S1 at $z = 21.4$. The right figure is radial profiles of the ratio of the enclosed gas mass to the Jeans mass. The red line indicates that S1 reaches Jeans instability.

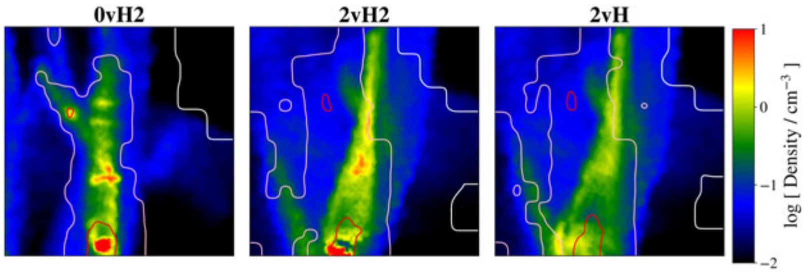

Figure 4. Colormaps of the gas density in the region with the same coordinates as the region of SIGO S1 identified by Run-2vH2 ($z = 25$). Note that 2vH2 corresponds to Figure 1, and the contour lines represent the DM density. Gas clumps S1 and S3 are located in the center of the Run-2vH2 and 0vH2 figures, respectively. The length of one side of each color map is 40 ckpc.

the combined effects of SV and cooling inefficiencies. The stream velocity smoothes the baryon density peak (Park et al. (2020)), and causes an offset between the density peak of baryon and that of DM. The offset effectively delays the gas contraction. Atomic hydrogen cooling is efficient for gas with 8000 K (Barkana & Loeb (2001)). On the other hand, molecular hydrogen cooling can lower gas to 200 K, where the gas contracts to the density of $n_{\rm gas} \sim 10^3$ /cc, reaches Jeans instability, and finally starts runaway collapse (Yoshida et al. (2006)). In Run-2vH, which does not include the H_2 chemical reactions, the gas cooling is inefficient and the clouds contraction to higher density is delayed. Due to these two effects, there was no gas clouds corresponding to S1 in Run-2vH case.

Run-0vH2 is performed without SV but with H_2 cooling. Since there is no SV, the position of the DM density peak traces the position of the gas density peak. H_2 cools the gas efficiently, and we find a gas clump corresponding to S1 at the center of figure 4. We name it S3. Figure 5 shows the radial profiles of the baryon fractions of S1 and S3 at $z = 25$, respectively. The green line is the average baryon fraction in the universe, $\Omega_b/\Omega_m = 0.044/0.27 = 0.16$. For S1, the baryon fraction $F_{\rm bar}$ is always larger than the cosmic mean fraction in the region $r \lesssim 10^3$ pc. In S3, $F_{\rm bar}$ is always smaller than the cosmic mean baryon fraction. This means that S3 is hosted by a DM halo. We conclude that SIGOs are formed via the combined effects of SV and H_2 cooling; SV causes the offset of the density peak between gas and DM, whereas H_2 cooling enables the gas to condense to reach high densities.

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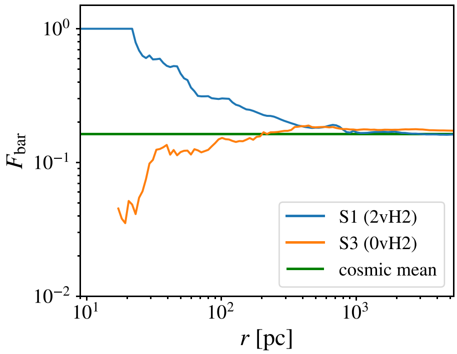

Figure 5. Radial profiles of baryon fraction at $z = 25$. Blue and orange lines shows the fraction for S1 and S3 respectively. The green line is a cosmological baryon density. We calculate the baryon fraction as (encolosed gas mass)/(enclosed (DM+ gas) mass).

4. Conclusion

We have performed cosmological hydrodynamical simulations and followed the formation of a SIGO. We find, for the first time, that a SIGO forms in the environment with stream velocity and condenses via H_2 cooling enough to become Jeans unstable. The SIGO is expected to experience runaway collapse and become a star-forming cloud.

Previous studies have conducted cosmological simulations and showed the characteristics of SIGOs (Popa et al. (2016); Chiou et al. (2018, 2019, 2021); Lake et al. (2021)). A recent study by Schauer et al. (2021) also incorporates non-equilibrium chemical reactions into their simulations and follows the formation of SIGOs. They conclude that H_2 cools such DM-deficient gas clumps to the density of $n_{gas} \sim 10$ /cc, which is not enough to gravitational collapse. They calculate the metallicity required to make the gas clump gravitationally unstable and find that if the gas contains the metal of $Z \sim 10^{-3} Z_{\odot}$, it can be cooled and condensed enough to runaway collapse.

In our study, we conduct high-resolution simulation after S1 reaches $n_{gas} \sim 10$/cc, and follow the SIGO's contraction with H_2 cooling. It is important to follow the long-term chemo-thermal evolution of individual gas clouds to identify SIGOs that finally collapse gravitationally. We show that a SIGO contracts slowly with its free-fall time, which is also the same as H_2 cooling time scale. The SIGO eventually cools down to 200 K and reaches high-density without being hosted by DM halos.

In our future study, we will investigate physical properties of the other 50 SIGOs which are located in Run-2vH2 to study statistics (Nakazato in prep.). We run additional 50 high-resolution simulations and examine the rate of SIGOs which collapse without being hosted or swallowed by the nearby halos. Moreover, we will follow further evolution of the SIGO to see if it fragments and forms a star cluster by introducing sink particles in our simulations. The protostellar evolution in star-forming regions of the SIGO will unveil the properties of the first star cluster. Since the SIGO we have studied here is a DM poor object, it can be a candidate progenitor of a globular cluster. Combing these future studies will reveal the fate of star-forming SIGOs and their typical properties such as mass, baryon fraction and so on, and clarify the relationship between SIGOs and globular clusters.

5. Q & A

In this section, we attach questions and answers that followed our talk at the IAU Symposium 362.

1. *Does the high-resolution simulation also include DM background?*

We also include DM particles in our high-resolution simulation. As mentioned in Section 2, we cut off a region of 10 kpc on a side, center on S1. Notice that we refine only gas cells but DM particles. The zoom-in simulations, in which the cut region is reverted to the initial redshift $z = 200$ and follow SIGOs' evolution, will be performed in the next study.

2. *What is exactly the stream velocity physically doing that it's allowing for SIGOs' formation?*

Stream velocity produces the spatial offset between the density peak of baryons and one of DM (Naoz & Narayan (2014)). This offset allows for clouds to exist outside of the corresponding DM halo. The following gas contraction is triggered by H_2 cooling. (The detail is in the next question and Section 3.3.)

3. *What do you mean by hydrogen cooling? Is H_2 cooling the recombination of* H^+ *and* e^- *or the molecular bond between two hydrogen atoms?*

For primordial gas, H_2 is generated via the following "H^- process"

$$H + e^- \rightarrow H^- + \gamma, \quad H + H^- \rightarrow H_2 + e^-, \tag{5.1}$$

where the electrons act as a catalyst (Yoshida et al. (2006)). The main cooling process for metal-free gas is the emission from the vibration and rotation transition of H_2. This radiation cooling enables primordial clouds to contract effectively.

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