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Population III Sink Particle mergers and IMF convergence: Resolution Study

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ABSTRACT
The Population III initial mass function (IMF) is currently unknown, but recent studies agree that fragmentation of primordial gas gives a broader IMF than the initially accepted singular star per halo. Sink particles introduced at high densities can prevent artificial fragmentation of the gas once the mesh stops refining, but an incorrect choice of sink particle creation density will effect the resulting IMF. This study introduces sink mergers into AREPO, and presents the effects of varying the sink particle creation density from ρ_{sink}=10^{-10}-$10^{-7} gcm^{-3}$. While the total mass accreted onto sinks remains invariant to the ρ_{sink}, the total number of sinks forms increases with increasing ρ_{sink} and does not converge within the range tested. Numerical estimations of the primordial IMF using sink particles are reliant on the authors choice of sink creation density. The velocity power spectra taken just after the formation of the first sink show that the turbulent field is independent of the sink parameters.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

The first stars, known as Population III (Pop III) stars, are responsible for the first ionising radiation which began the epoch of reionisation, and when they died as supernovae, they injected the interstellar medium (ISM) with the first metals, which would go on to form the next generation (Pop II) of stars. During their formation, the primordial magnetic seed field was amplified via the small-scale magnetic dynamo (REF), which may have been the first step in converting the small scale chaotic fields into the coherent, large scale galactic magnetic fields observed today. Evidently the initial mass function (IMF) of Pop III stars has a huge effect on the evolution of the Universe. Initially it was thought that Pop III stars formed in isolation, and were massive (REF), yet further studies showed they were susceptible to fragmentation in the presence of subsonic turbulence (REF). Since then, numerical studies have attempted to improve the picture of Pop III star formation by including feedback mechanisms (REF), live dark matter (DM) potentials (REF) and magnetic fields (REF). Despite this, the Pop III IMF is still in dispute, and there are still many factors left to study.

The Jeans length λ_J of a structure of given density and temperature marks the maximum size it can achieve before thermal pressure cannot resist against gravitational collapse. Hence artificial fragmentation occurs in hydrodynamic codes if the local λ_J falls below the size of mesh cells Δx. To prevent this, the mesh refines itself based on the local λ_J, which depends on the temperature and density of the gas. The Truelove condition (REF) requires a Jeans number $\Delta x/\lambda_J$ of 0.25, corresponding to at least 4 cells spanning across any λ_J to prevent artificial fragmentation. Numerical simulations cannot refine indefinitely as the gas gets denser, and at higher densities (smaller λ_J), it becomes computationally expensive to refine further. Sink particles (REF: Bate 1995) provide an alternative to indefinite refinement, they are non-gaseous particles that contain all of the mass within the area they occupy and can accrete matter from their surrounding cells. As they cannot fragment, either naturally or artificially, their implementation at high densities overcomes the Jeans refinement criteria. In present day star formation simulations, the sink creation density is chosen to be $\sim 10^{10} gcm^{-3}$ (e.g. REF), corresponding to the first adiabatic core (REF). During an adiabatic collapse , the radial density profile is flat within the central λ_J (REF: Larson69), so the radius of the of sink particle is chosen to be the Jeans length at the creation density and temperature. In primordial star formation, there is no clear 'first core' (REF Omiki graph), and so the appropriate time to introduce a sink particle is unclear. Sink particles are not a perfect solution to the indefinite refinement problem, and authors choice of sink particle creation density will change the morphology of the resulting cluster. This paper explores the effect of varying the sink particle creation density within the frame of primordial Pop III gas collapse. The most important parameters to track are the total number of sinks formed and the total combined mass of the sinks.

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Table 1. Sink creation density, temperature, sink radius, minimum cell size and minimum gravitational softening lengths used in the study.

ρ_{sink} [gcm^{-3}]	T [K]	λ_J [cm]	V_{min} [cm^3]	L_{soft} [cm]
10^{-10}	2	1.37e14	5.10e39	1.72e13
10^{-9}	4	4.56e13	1.86e38	5.70e12
10^{-8}	5	1.53e13	6.95e36	1.91e12
10^{-7}	e	e	e	e
10^{-6}	e	e	e	e

2 SINK PARTICLES

The radius of a sink particle is chosen to be λ_J corresponding to the sink creation density, given by

$$\lambda_J = \sqrt{\frac{k_B T}{G\rho_{sink}(\mu m_p)}}. \tag{1}$$

where k_B is the Boltzmann constant, T is the temperature, $\rho_s ink$ is the sink creation density, μ is the mean molecular weight and m_p is the mass of a proton. To estimate λ_J before running the simulation, an estimate of T at ρ_{sink} is needed. To achieve this, a lower resolution simulation was performed without turbulence, resulting in 1 central star. The simulation was run up until the maximum creation density testing in this study was reached, figure REF shows the resulting relationship between density and temperature. This gives an effective relationship between ρ and λ_J using equation 1. The sink radius was chosen to be 8 times smaller than λ_J in compliance with the Truelove condition. This radius sets the minimum cell size and gravitational softening length of the simulation. The ρ_{sink}, T, λ_J, minimum cell volume and minimum gravitational softening lengths are given in table 1.

2.1 Sink mergers

The total number of sinks formed is not representative of the IMF if they were allowed to bunch up and lie on top of one another. Similarity to REF(federath2010), we allow sinks to merge if they fit four criteria: they lie within eachothers accretion radius, they are moving towards eachother $(\nabla \cdot v) < 0$, their accelerations give $(\nabla \cdot a) < 0$ and they are gravitationally bound. Since sink particles carry no thermal data, the last criteria simply requires that their gravitational potential well exceeds the kinetic energy of the system. When the criteria is met, the larger of the sinks gains the mass and linear momentum of smaller sink, and its position is shifted to the center of mass of the system. We allow multiple mergers per timestep based on mass hierarchy; if sink A is flagged to swallow sink B, and sink B is flagged to swallow sink C, then both B and C will be merged into sink A simultaneously.

3 SIMULATIONS

Four iterations were performed with identical initial conditions with the moving mesh code AREPO (REF), varying the sink parameters as given in table 1. The chemistry used was the same as (REF clark), with abundances of H_2, H^+, D^+ and HD as x_{H_2}=10^{-3}, x_{H^+}=10^{-7}, x_{D^+}=2.6×10^{-12} and x_{HD}=3×10^{-7}. The initial conditions consist of a Bonner Ebert sphere categorised by central density n_c=2×10^{-20} and radius R_{BE}=1.87pc, which was placed in a box of side length 4R_{BE}. The density was enhanced by a factor of 1.87 to promote collapse. A random velocity field was generated from the turbulent power spectrum $\propto k^{-2}$. The rms velocity was scaled to give a ratio of kinetic to gravitation energy α=0.05 and the initial box temperature was 200K.

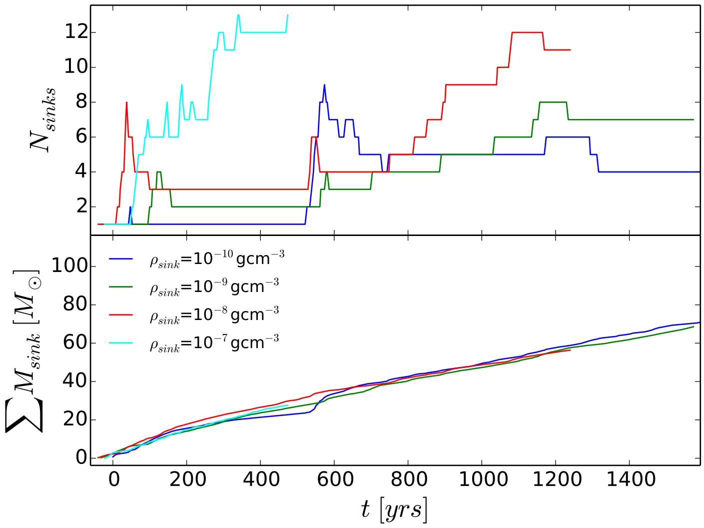

Figure 1. Evolution of the number of sinks and the total mass of all sinks with sink mergers allowed.

4 VELOCITY POWER SPECTRA

To investigate possible effects of sink creation density on the resulting velocity field, we calculate the velocity power spectrum at the same time for each of the runs, at a time just after the all of the runs have finished forming their first sink. The AREPO unstructured mesh of the inner ~ 1300AU region of simulation box was projected the onto a uniform 1000^3 grid cube. Taking the Fourier transform of the velocity fields A_v gives a 3-dimensional k space of velocity amplitudes, where k is the number of wavelengths per box length. The average energy in each k mode $\hat{A}_v$ was found by averaging the amplitudes within k shells spanning out from k=1 to k=500 i.e the Nyquist frequency of the data. The power spectrum P_v was obtained using

$$P_v \delta k = \int_1^{500} \hat{A}_v^2 4\pi k^2 \delta k \tag{2}$$

The radial velocity profile was removed by taking the cross product $v_\theta = (v \times r)/|r|$, to subtract the effects of material falling into the sink, giving the pure turbulent field. The resulting velocity power spectra are given in figure REF

5 DISCUSSION

Figure 1 shows that even with sink mergers enabled, the total number of sinks formed did not converge within the range of sink formation densities used. Higher values of ρ_{sink} gave higher number of sinks formed. Due to the sink accretion radius decreasing with increasing ρ_{sink}, mergers were less likely to occur for higher ρ_{sink} runs, aiding the number of surviving sinks. N_{sink} may converge for higher ρ_{sink} than tested in this study, but it is currently computationally impractical to run collapse problems to densities that high if the study attempts to cover a large parameter space such as turbulent energy or magnetic field strength. However, after a threshold period of time, the total mass in sinks was invariant with changing sink parameters. As higher ρ_{sink} produces higher N_{sink} while M_{tot} remains unaffected, using higher ρ_{sink} produces lower mass stars and a broadened IMF, while lower ρ_{sink} give higher mass stars. The resulting IMFs at time t=REF are given in figure REF. The results show that numerically obtained IMFs using sink particles are reliant on the authors choice of ρ_{sink}. Figure (REF) shows that the velocity power spectra after the formation of the first sink was also invariant with changing ρ_{sink}.

6 CONCLUSIONS

The last numbered section should briefly summarise what has been done, and describe the final conclusions which the authors draw from their work.

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DATA AVAILABILITY

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APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.

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