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Multi-physics, multi-scale simulations of star formation: from large scale (1 kpc) turbulent magnetized Galactic disk to stellar clusters

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Abstract. I present new zoom-in AMR simulations that for the first time investigate star formation with fully coupled multi-physics including feedback from protostellar outflows and radiative transfer traversing the large scales of the ISM (∼1 kpc) down to the micro-scales of protostars and clusters (25 au). Our simulations follow the gravitational collapse of magnetized, supersonically turbulent, massive molecular clouds through to the formation of dense IRDC filaments, multiple turbulent clumps inside these IRDCs and magnetized cores which evolve to form protostars and stellar clusters. We examine in detail the comparison of several properties of the protostellar clusters that form with observations.

Key words. Stars: clusters –Turbulent Clouds: IRDCs – Filaments: fragmentation – Feedback: radiation – Feedback: outflows – AMR: zoom-in

1. Introduction

In this brief paper I will discuss some of the highlights my talk and recent simulations in our paper investigating the formation of stellar clusters in magnetized, supersonically turbulent filamentary Infrared Dark Clouds (IRDCs) that are simulated over a dynamic range from 4.6 pc to 28 au over 3.5×10^5 yrs. We start with an initially supersonically turbulent cloud and follow the collapse and evolution of this cloud to the formation of a large IRDC filament. Subsequent collapse and fragmentation of the filamentary structure results in the formation of a cluster of stars. We investigate the properties of this cluster and make detailed comparisons with observations. The simulations are performed with a multi-staged AMR zoom-in approach wth relevant physics entering at each stage in the evolution. A key advantage of using our large scale simulation (Li, McKee, & Klein 2015) as a starting point for the zoom-in simulation is that we can begin with a filamentary cloud that has already formed through the MHD turbulent cascade from the large scale turbulent driving through to gravitational collapse instead of beginning with ad-hoc initial conditions. This provides us with realistic initial conditions. Using zoom-in simulations on the larger scales on selected regions with fully coupled feedback physics (radiation-MHD with outflows) we compare in detail the resulting protostellar mass function (PMF), the protostellar luminosity function (PLF), the outflow properties and the multiplicity with observations (Li, Klein, & McKee 2017). Following

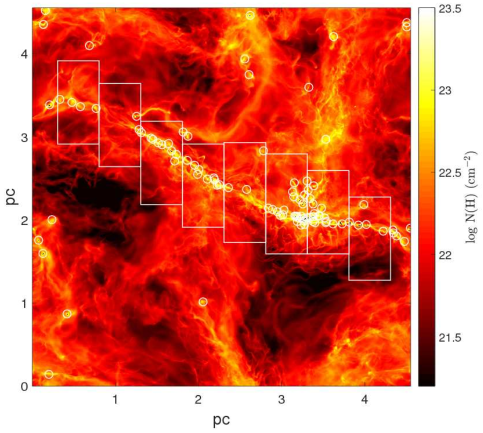

Fig. 1. Logarithmic scale column density of entire simulation region at $0.5t_{ff}$. The rectangular boxes mark the zoom-in region with AMR defined to 6 levels above the base grid. Protostars can form only inside the zoom-in region. The circles mark the 100 most massive clumps (Li, Klein, & McKee 2017)

a brief discussion of these comparisons I then discuss preliminary results on our recent work to follow the evolution of large scale turbulent clouds on the scale of the Galactic disk 1 kpc down to the scale of cluster formation ~25 AU.

2. Methodology and initial conditions

Our simulations are performed with ORION, a 3D parallel AMR magneto-radiation-hydrodynamic code we have developed at UC Berkeley. ORION has self-gravity, sink particles, radiation transfer and protostellar outflow physics. For molecular gas, the physical parameters of the the turbulent system: size of the cloud; crossing time; mass of the cloud and column density can be expressed with scaling relations by specification of basic dimensionless parameters of the system (McKee, et al. 2010). Using dimensionless parameters of the system for initial conditions for the strong field case (thermal Mach number = 10; Alven Mach number = 1, viral parameter = 1; mass-to flux ratio = 1.63 and plasma β = 0.02) we find that initially the total cloud mass $M = 3110\ M_{\odot}$; size = 4.55 pc; H_2 density = 480 cm^{-3}; temperature = 10K and magnetic field stength = 31.6 μG.

3. Results

3.1. Zoom-in from 5 pc to 25 au scale

Here I summarize key results of our simulations for the strong field case. For details see (Li, Klein, & McKee 2017). Within 800,000 years the initially supersonically turbulent cloud forms a massive IRDC filament with total mass 660 $M_{\odot}$, length ~ 5 pc, diameter along its length 0.1 - 0.2 pc, mean density $n(H_2) = 9.8 \times 10^3$ cm^{-3}, mean surface density $N(H_2) = 2.1 \times 10^{22}$ cm^{-2}, velocity dispersion 0.99 ~ 1.48 km s^{-1} and mean magnetic field $B = 39\ \mu$G; properties similar to observations of IRDC's. Examination of the magnetic field lines surrounding the filament reveals that the magnetic field lines are aligned perpendicular to the filament axis. Our resulting IRDC has a remarkable resemblance to observations (Andre et al. 2014) that have similar magnetic field lines perpendicular to the filament axis. The filamentary structure that develops (Li, Klein & McKee 2018 in preparation) has an intertwining fiber like substructure that fragments into chains of massive clumps and cores similar to the observations. In Fig. 1 we see the zoomed-in highly refined region along the massive IRDC filament showing the formation of ~100 massive clumps whose properties we have analyzed in (Li, McKee, & Klein 2015). We find that a cluster with a total of 82 protostars is formed along the filament in the clumps and cores with a total mass of ~ 29 $M_{\odot}$ with 32 of the protostars forming at the juncture of the collision of the main IRDC with another filament. This suggests that cloud collisions of turbulent filaments in clouds may play an important role in triggered star formation. The median mass fluctuates around 0.02 $M_{\odot}$ consistent with the Chabrier IMF. Several of the protostars in the cluster have approached their final mass. Most of the protostars have mass accretion rates in the range of 10^{-5}–10^{-7} $M_{\odot}$/yr in good agreement with observations. The change of the total number of stars in the cluster N_* with time shows that $N_* \propto t^{1.47}$ indicating star formation is accelerating in the cluster. The Star formation is shown to be superlinear in time with a efficiency SFE $\propto t^2$ implying that the star formation rate SFR $dM_*/dt \propto t$ is accelerating in agreement with recent observations. We find that SFE is accelerating for both driven and undriven turbulence (Myers, Klein et al. 2014), but for undriven decaying turbulence the SFE evolves as $\propto t^3$ so that SFR $\propto$ t^2 hence turbulence injected at large scales significantly reduces the SFE. A quantity of importance to look at to study star formation efficiency across different regions is the dimensionless star formation rate per free-fall time $\varepsilon_{ff} = M_*/t_{sf}/(M_{gas}/t_{ff})$. We find that $\varepsilon_{ff} \sim 0.036 - 0.046$ and SFE = 4.3%. Observations of Galactic clouds to high redshift galaxies show $\varepsilon \sim 0.015$ with some clouds in the Milky Way have higher rates than best fit 0.015 by factors of 2 - 6; thus our simulations are the range observed. We have made detailed comparisons with the cluster protostellar mass function (PMF) compared to the Chabrier IMF and 5 theoretical models. For details see (Li, Klein, & McKee 2017). We find at the end of our simulation (82 protostars) the median mass of the PMF is 0.02 M_* is in excellent agreement with the Chabrier IMF. Our overall fit to the Chabrier IMF is excellent. We have studied the time evolution of the mean and median cluster luminosity from the zoom-in simulations. We find that the mean and median luminosities from the cluster of stars are 5.4 and 2.1 $L_\odot$ which are in excellent agreement with recent observations (Dunham et al. 2013) (230 sources) where $\langle L \rangle \sim 5.5\ L_\odot$ and $L_{med} \sim 1.8\ L_\odot$. Similarly we have compared our protostellar luminosity function (PLF) with the observed PLF and it agrees well with a dispersion in the simulation of 0.75 dex and the observed dispersion is 0.65 dex. A key diagnostic used in observations of protostellar outflows is the relation between the amount of mass that is swept up in the outflow M_{swept} and the line of sight velocity in the rest from of each protostar. Observations show that $dM/dV \sim V^{-1.8}$ in a shallow part of a broken power law for low velocities and for high velocities a steeper power law index $n \sim 10$. We get excellent agreement with observations for the shallow part of the broke power law for several of out outflows and a similar break in the power law at higher velocities. A key property to compare simulations of cluster formation with observations is the time evolution of stellar multiplicity fractions (MF) and companion fractions (CF) in a cluster of stars. We have compared our resulting MF and CF with a variety of the most recent observations and we find that the multiplicity and companion fractions of our cluster are a good match to corresponding values of class I objects over a broad range of spatial scales.

3.2. Zoom-in from Galactic disk ∼ 1 kpc to stellar cluster scale 12 au

Recently we have begun the first sets of zoom-in simulations of cluster formation starting from the realistic large scale magnetized turbulent clouds on the scales of the Galactic disk (∼ 1 kpc) where we begin with models that include SNe feedback, shearing box boundary conditions, gas cooling and SFR regulated heating and evolve for hundreds of millions of years . Through a process of a series of zoom-in simulations an selected extractions and including all feedback physics, radiation heating, pressure is to be able allow the fully developed velocity fluctuations of turbulence to cascade down to the sonic scale ∼ 0.1 pc to set the stage for star formation.

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References

André, P., et al. 2014, in Protostars and Planets VI, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, T. Henning (Univ. Arizona Press, Tucson), 27
Dunham, M. M., et al. 2013, ApJ, 145, 94
Li, P. S., McKee, C. F., & Klein, R. I. 2015, MNRAS, 452, 2500
Li, P. S., Klein, R. I., & McKee, C. F. 2017, MNRAS, in press (arXiv:1708.06770)
McKee, C. F., et al. 2010, ApJ, 720, 1612
Myers, A., Klein, R. I., et al. 2014, MNRAS, 439, 3420