From cloud scales, to core scales, and back up again: Completing the *feedback loop* of star formation

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INTRODUCTION: Stars are the powerhouses of the universe. They are responsible for the majority of the interstellar radiation field and can drive the means to support potential biospheres. Yet, we still do not fully understand how their masses are determined, which in turn governs the amount of radiation they emit. The reason this question has yet to be answered is the sheer complexity of the star forming environment, due to protostellar winds, outflows, and radiation that *feed back* on the environment. While NASA's Cosmic Origins Project has revealed the dramatic effects of feedback in young star forming regions through the *Hubble*, *Spitzer, and Herschel* Space Telescope Programs (Fig. 1), there is much to learn about the physics of feedback. A theoretical framework that explains the cumulative effects of feedback does not yet exist, much less a predictive model for the initial masses of stars in a forming cluster. Developing a successful theoretical model of feedback, however, rests upon appropriate, supporting numerical experiments.

Modern simulations of feedback are often limited in their *single-scale* nature: initial conditions are not generated self-consistently, but are rather prescribed by the simulator. This not only generates highly idealized environments, but can also lead to spurious numerical results, as simulation outcomes can change depending on the choice of initial conditions (Girichidis et al. 2011). Thus, it is important to model the initial conditions of star formation as accurately and self-consistently as possible. This can be done using *multi*-scale simulations that instead model protostellar feedback, *beginning from the molecular cloud phase*. Multiscale simulations can provide a deeper understanding of the physics of feedback, which can in turn advance understanding of how feedback regulates mass accretion in young clusters.

Multiscale simulations are still in their infancy. Offner et al. (2008) has modeled clump-to-core protostellar formation, beginning with a gravitationally unstable, turbulent sphere. These simulations included self-gravity and sink particles, but not magnetic fields, radiative transfer, and feedback. Offner et al. (2012) also started with a turbulent sphere, but now included radiative-transfer and feedback. These simulations zoomed-in on a set of protostars within a forming cluster at four different evolutionary time states. The focus here was to generate synthetic spectra of the objects and compare to observations. On larger scales, cosmological and galaxy formation simulations have recently employed zoom-in techniques. On these scales, simulations study the thermal evolution of gas following supernova injection from cluster particles (e.g. Colin et al. 2016), as well as synthetically observe simulated molecular clouds that form in the arm and inter-arm regions of Milky Way type galaxies (Duarte-Cabral et al. 2016). The power of multiscale simulations is clear, and should now be directed toward better understanding feedback physics in relation to star formation regulation.

PROPOSAL: As a Hubble Fellow, I will develop the first multiscale simulations that follow protostellar formation and feedback, *beginning from realistically generated molecular clouds.* These simulations will include radiative transfer, magnetic fields, self-gravity, cooling, and protostellar feedback. The focus of this project will be on the physics of feedback and its role in regulating the initial mass function. Developing a deeper understanding of feedback physics is a crucial next step in star formation research. Such a framework will greatly aid in the interpretation of the upcoming rich dataset that the James Webb Space Telescope and other missions will provide. My PhD research on the multiple scales of star formation, as well as my experience with high-performance numerical methods, has given me the preparation needed to carry out this research plan.

NUMERICAL PROCEDURE: The clouds for this project will be supplied by my recent colliding flows simulations (Fogerty et al. 2016). Instead of forcing turbulence, the colliding flows model naturally generates turbulent molecular clouds via numerous fluid instabilities that are excited in the post-shock region between the flows. The colliding flows in these simulations were 40 pc across, and were resolved to a minimum cell size of $\Delta x=0.05$ pc. These simulations were evolved for 27 Myr, and included self-gravity, magnetic fields and cooling, following a parametrized cooling curve appropriate for the interstellar medium (ISM). This cooling curve was modified from Inoue & Inutsuka (2008) to account for UV shielding, thus allowing the gas to cool to 10 K. The density, temperature, magnetic field strength and speed of the flows were chosen to match standard ISM values. Reminiscent of physically realized molecular clouds, these simulated clouds contain cores, embedded within rich filamentary substructure (Fig. 2).

The cloud-to-core simulation will proceed in two steps, beginning with these molecular cloud simulations. The first step entails selecting a gravitationally bound and unstable clump, using criteria similar to Offner et al. (2008). This clump will be on the order of 1-10 pc across, the typical size scale of a protocluster. In order to zoom-in on this clump and follow its subsequent evolution, I will selectively increase its resolution using adaptive mesh refinement (AMR). This represents the *cloud-to-clump* leg of the loop shown in Fig. 3. Meanwhile, regions that are not spatially correlated with the clump will be de-refined to conserve computational cost. As the clump evolves and forms protostellar cores, I will repeat this process again, now selectively increasing the resolution of a single protostellar *core* that is bound, gravitationally unstable, and .1 pc-10,000 AU across (Fig. 3, *clump-to-core* leg). In this way, I will *self-consistently track the evolution of a single protostellar core, beginning from the molecular cloud scale*.

COMPLETING THE FEEDBACK LOOP: To ‘complete the loop’ means following the collapse of this selected protostellar core as it forms a protostar that begins to feed back on its environment. This protostar will be modeled using a sink particle, a numerical sub-grid algorithm that gravitationally interacts with its surroundings. Sink particles will form only after satisfying strict criteria (Federrath et al. 2010) that ensures the gas is gravitationally bound and collapsing (i.e. would go on to form a protostar, given infinite resolution), and will produce both both radiative and outflow feedback (see Section: AstroBEAR). This stage of the simulation represents the core-protostar-core (c-p-c) *loop* in Fig. 3. In studying the c-p-c loop, I will develop a physical model for how feedback *couples* to the protostellar environment, and how this coupling regulates mass accretion onto the young stellar object. To this end, I will isolate each feedback mechanism and study its effect on the gas. These results will be compared to previous work on single-scale simulations (Machida & Hosokawa 2013; Bate, Tricco & Price 2014; Offner & Arce 2014). During the tenure of this fellowship, I will also model the larger c-c-p-c-c loop, in order to investigate feedback from many star systems. This project would expand the c-p-c model by increasing the resolution of *multiple* collapsing cores within the parent clump, simultaneously, as in Offner et al. (2012).

ASTROBEAR: Cloud-to-core simulations will be performed using the astrophysical fluid code, AstroBEAR (Carroll-Nellenback et al. 2013), which solves the conservative equations of magnetohydrodynamics (MHD), including self-gravity and flux-limited diffusion radiative transfer (Krumholz et al. 2007). AstroBEAR is well-tested, massively parallelized, and has adaptive mesh refinement (AMR). This makes it computationally feasible to model the many orders of magnitude change in size scale detailed in this proposal. To study feedback, I have already incorporated routines into AstroBEAR that track and inject accretion luminosity from sink particles, as well as two-component outflows, following Federrath et al. (2014). These routines are performing well with AMR, and I am in the final stages of testing them (Fig. 4).

ESTIMATE OF RESOURCES: The complete cloud-to-core simulation will require two restarts. For the first restart, the protocluster clump will be resolved to five additional levels of refinement, on top of the resolution of the cloud simulation. Based on my previous gravito-hydrodynamic work on protostellar collapse (Kaminski et al. 2014), I estimate this restart will require ~500,000 CPU hours, with the addition of MHD. Five additional levels of refinement will be added for the next restart, as well as radiative transfer and feedback. Based on preliminary results using these routines, I estimate an additional factor of eight in computing time, or ~4 million CPU hours. Thus, the complete cloud-to-core simulation will require approximately *4.5 million CPU hours,* or 2 months, running on 3,000 CPU cores at the Massachusetts' Green High Performance Cluster.

TIMELINE: ***1st Year (2017-2018):*** Develop numerical method and execute production run. Prepare publication on the physics of feedback in protostellar cores, as well as the numerics of cloud-to-core simulations. ***2nd year (2018-2019).*** Develop cluster-scale feedback simulations and execute production run. Prepare publication on the physics of feedback coupling at the cluster scale, and produce synthetic emission maps of the data. ***3rd year (2019-2020)***. Repeat simulations on different mass clumps and explore changes to identified feedback mechanisms. Prepare publication on the role of clump mass in regulating feedback coupling.

Fig. 1 — Feedback shapes the local star forming environment and regulates star formation. As shown here, feedback from protostars occurs through jets and outflows, as well as radiation forces. NASA/HUBBLE.

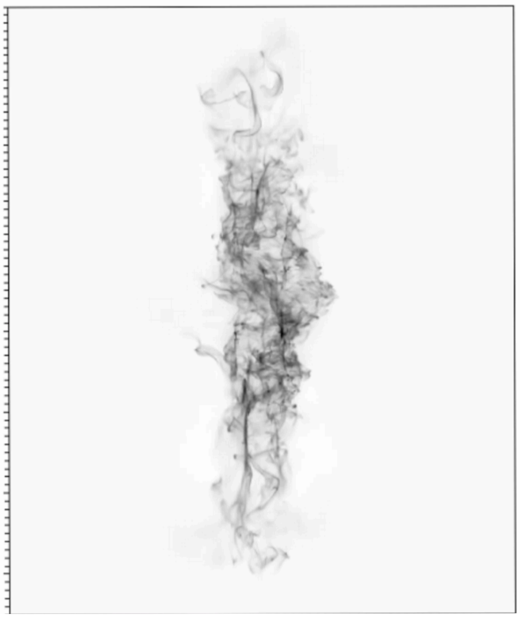

Fig. 2 — Column density map of molecular cloud simulation. A variety of fluid instabilities in the magnetized, self-gravitating gas produce a rich, filamentary molecular cloud complex.

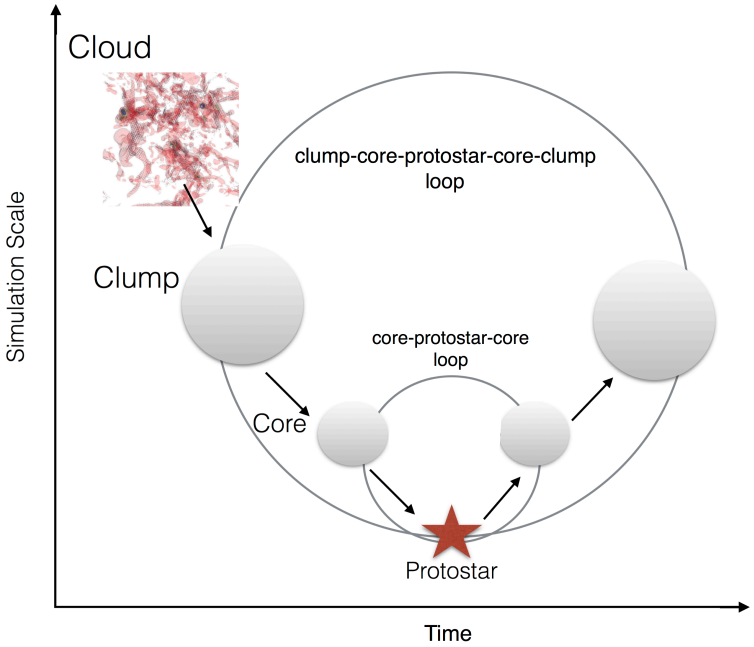

Fig. 3 — Multiscale star formation simulations will begin at the cloud scale, and zoom-in to the formation of a single protostar. Feedback loops show the interaction between various scales of the simulations.

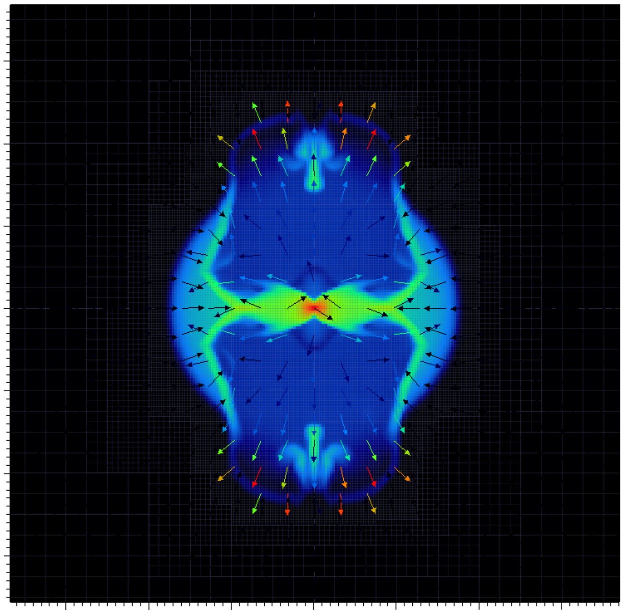

Fig. 4 — Feedback routines produce outflows and radiation from sink particles as shown in this density plot of a rotating, collapsing core with overlaid velocity vectors. Adjustments to the outflow temperature are still needed.

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