The Journal of Open Source Software

ORION2: A magnetohydrodynamics code for star formation

Pak Shing Li[1], **Andrew J. Cunningham**[2], **Brandt L. Gaches**[3], **Richard I. Klein**[1, 2], **Mark R. Krumholz**[4], **Aaron T. Lee**[5], **Christopher F. McKee**[1], **Stella S. R. Offner**[6], **Anna L. Rosen**[7], and **Aaron Skinner**[2]

1 UC Berkeley **2** Lawrence Livermore National Laboratory **3** University of Cologne **4** Australian National University **5** Saint Mary's College of California **6** The University of Texas at Austin **7** Center for Astrophysics | Harvard & Smithsonian

DOI: 10.21105/joss.03771

Software

- Review
- Repository
- Archive

Editor: Dan Foreman-Mackey

Reviewers:

- @zingale
- @changgoo

Submitted: 30 July 2021
Published: 28 December 2021

Summary

The formation of stars and stellar clusters remains a grand challenge problem in astrophysics that has important implications for the evolution of the interstellar medium as well as shaping the evolution of galaxies. The computational challenges are formidable and involve a coupling of highly non-linear physical processes such as hydrodynamics, self-gravity, magnetic fields, radiation transfer, supersonic turbulence, ionization, protostellar outflows, stellar winds and chemistry that have both disparate timescales as well as operate over many decades of physical length scale. These processes can regulate the feedback from nascent protostars onto the surrounding turbulent gas clouds that are the embryos of new star formation, and as a result, the feedback itself can influence the gaseous reservoir feeding newly formed protostars which in turn influence the star formation process.

Statement of need

To address the myriad of problems associated with star and cluster formation we have advanced the development of ORION2 over the past several years. ORION2 is a radiation-magneto-hydrodynamic (MHD) 3-D code that operates in the block structured Adaptive Mesh Refinement (AMR) framework of CHOMBO for parallel computation. The code is written in C++, C and Fortran. We developed a new magneto-hydrodynamic (MHD) module using a Constrainted Transport scheme for adaptive mesh refinement (Li et al., 2012) based on the framework of the publicly released PLUTO code version 3.0 (Mignone et al., 2012, 2007). We also implemented a variety of additional functionality needed for modeling our target problems, which focus on the dynamics of the interstellar medium and star formation. Our first code release includes MHD, self-gravity, sink and star particles, protostellar outflows and main sequence stellar winds. ORION2 is state of the art and compares well with other commonly used packages. It has an extremely robust MHD for adaptive grids with multiple options for Godunov solvers and a robust and efficient gravity solver (Li et al., 2012). The code includes several packages that enable feedback effects from star particles, which are not included in some of the other commonly used packages in the community. Future releases of ORION2 will include a hybrid ray trace moment radiative transfer method enabling the computation of radiative forces associated with massive star formation. Data from ORION2 simulations can be analyzed straightforwardly using yt and VISIT. Example Python analysis scripts are included in the release.

The ORION2 methodology in this release has been described in a variety of prior publications:

- MHD: (Li et al., 2012)
- Gravity: (Martin et al., 2008; Miniati & Colella, 2007)
- Sink particles: (Krumholz et al., 2004)
- Star particles: (Offner, Klein, et al., 2009)
- Protostellar Outflows: (Cunningham et al., 2011)
- Stellar Winds: (Offner & Arce, 2015; Rosen et al., 2021)

Research with ORION2

ORION2 has been used to explore a variety of problems in the field of star formation. Notable papers that utilize the release functionality have been written on:

- The Jeans condition and resolving gravitational fragmentation: (Truelove et al., 1997)
- Bondi accretion under turbulent conditions with and without magnetic fields: (Krumholz et al., 2005; Lee et al., 2014)
- Properties of stars and dense cores under driven and decaying turbulence conditions: (Offner, Krumholz, et al., 2008; Offner, Klein, et al., 2008; Offner & Krumholz, 2009)
- Stellar kinematics and clustering of young star clusters: (Kirk et al., 2014; Offner, Hansen, et al., 2009)
- Impact of protostellar outflows on low-mass star formation: (Hansen et al., 2012)
- Chemical mixing in star-forming clouds and metallicity homogeneity in open clusters: (Feng & Krumholz, 2014)
- Momentum- and energy-driven feedback from stellar winds in star-forming environments: (Offner & Liu, 2018; Rosen et al., 2021)
- Magnetized turbulence excited by stellar winds: (Offner & Liu, 2018)
- Binary and multiple star formation in magnetized clouds: (Lee et al., 2019)
- Magnetic properties of cloud clumps: (Li et al., 2015)
- Cluster formation in filamentary dark clouds: (Li et al., 2018)
- Infrared dark clouds formation simulation: (Li & Klein, 2019)

Acknowledgements

We acknowledge ORION2 code contributions from Daniel Martin, Drummond Fielding and Andrew Myers as well as from the PLUTO codebase and development team. We also acknowledge contributors to ORION, the forerunner of ORION2, by Kelly Truelove, Charles Hansen and Robert Fisher. Support for ORION2 development and code release has been funded by the following sources: NSF though grant AST-1211729; NASA through the Astrophysical Theory Program (ATP) through grants NNX09AK31G; NNX13AB84G; NNX17AK39G; 80NSSC20K0530; NASA through the TCAN PROGRAM grant NNX14AB45G; Australian Research Council, award number FT180100375; NASA through Hubble Fellowship grant HF-51311.01 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555; NSF Career grant AST-1748571; NASA through Einstein Postdoctoral Fellowship grant No. PF7-180166 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060.

References

Cunningham, A. J., Klein, R. I., Krumholz, M. R., & McKee, C. F. (2011). Radiation-hydrodynamic Simulations of Massive Star Formation with Protostellar Outflows. *The*

Astrophysical Journal, 740(2), 107. https://doi.org/10.1088/0004-637X/740/2/107

Feng, Y., & Krumholz, M. R. (2014). Early turbulent mixing as the origin of chemical homogeneity in open star clusters. *Nature*, *513*(7519), 523–525. https://doi.org/10.1038/nature13662

Hansen, C. E., Klein, R. I., McKee, C. F., & Fisher, R. T. (2012). Feedback Effects on Low-mass Star Formation. *The Astrophysical Journal*, *747*(1), 22. https://doi.org/10.1088/0004-637X/747/1/22

Kirk, H., Offner, S. S. R., & Redmond, K. J. (2014). The formation and evolution of small star clusters. *Monthly Notices of the Royal Astronomical Society*, *439*(2), 1765–1780. https://doi.org/10.1093/mnras/stu052

Krumholz, M. R., McKee, C. F., & Klein, R. I. (2005). Bondi Accretion in the Presence of Vorticity. *The Astrophysical Journal*, *618*(2), 757–768. https://doi.org/10.1086/426051

Krumholz, M. R., McKee, C. F., & Klein, R. I. (2004). Embedding Lagrangian Sink Particles in Eulerian Grids. *The Astrophysical Journal*, *611*(1), 399–412. https://doi.org/10.1086/421935

Lee, A. T., Cunningham, A. J., McKee, C. F., & Klein, R. I. (2014). Bondi-Hoyle Accretion in an Isothermal Magnetized Plasma. *The Astrophysical Journal*, *783*(1), 50. https://doi.org/10.1088/0004-637X/783/1/50

Lee, A. T., Offner, S. S. R., Kratter, K. M., Smullen, R. A., & Li, P. S. (2019). The Formation and Evolution of Wide-orbit Stellar Multiples In Magnetized Clouds. *The Astrophysical Journal*, *887*(2), 232. https://doi.org/10.3847/1538-4357/ab584b

Li, P. S., & Klein, R. I. (2019). Magnetized interstellar molecular clouds - II. The large-scale structure and dynamics of filamentary molecular clouds. *Monthly Notices of the Royal Astronomical Society*, *485*(4), 4509–4528. https://doi.org/10.1093/mnras/stz653

Li, P. S., Klein, R. I., & McKee, C. F. (2018). Formation of stellar clusters in magnetized, filamentary infrared dark clouds. *Monthly Notices of the Royal Astronomical Society*, *473*(3), 4220–4241. https://doi.org/10.1093/mnras/stx2611

Li, P. S., Martin, D. F., Klein, R. I., & McKee, C. F. (2012). A Stable, Accurate Methodology for High Mach Number, Strong Magnetic Field MHD Turbulence with Adaptive Mesh Refinement: Resolution and Refinement Studies. *The Astrophysical Journal*, *745*(2), 139. https://doi.org/10.1088/0004-637X/745/2/139

Li, P. S., McKee, C. F., & Klein, R. I. (2015). Magnetized interstellar molecular clouds - I. Comparison between simulations and Zeeman observations. *Monthly Notices of the Royal Astronomical Society*, *452*(3), 2500–2527. https://doi.org/10.1093/mnras/stv1437

Martin, D. F., Colella, P., & Graves, D. (2008). A cell-centered adaptive projection method for the incompressible Navier-Stokes equations in three dimensions. *Journal of Computational Physics*, *227*(3), 1863–1886. https://doi.org/10.1016/j.jcp.2007.09.032

Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., & Ferrari, A. (2007). PLUTO: A Numerical Code for Computational Astrophysics. *The Astrophysical Journal Supplement*, *170*(1), 228–242. https://doi.org/10.1086/513316

Mignone, A., Zanni, C., Tzeferacos, P., van Straalen, B., Colella, P., & Bodo, G. (2012). The PLUTO Code for Adaptive Mesh Computations in Astrophysical Fluid Dynamics. *The Astrophysical Journal Supplement*, *198*(1), 7. https://doi.org/10.1088/0067-0049/198/1/7

Miniati, F., & Colella, P. (2007). Block structured adaptive mesh and time refinement for hybrid, hyperbolic + N-body systems. *Journal of Computational Physics*, *227*(1), 400–430. https://doi.org/10.1016/j.jcp.2007.07.035

Offner, S. S. R., & Arce, H. G. (2015). Impact of Winds from Intermediate-mass Stars on Molecular Cloud Structure and Turbulence. *The Astrophysical Journal*, *811*(2), 146. https://doi.org/10.1088/0004-637X/811/2/146

Offner, S. S. R., Hansen, C. E., & Krumholz, M. R. (2009). Stellar Kinematics of Young Clusters in Turbulent Hydrodynamic Simulations. *The Astrophysical Journal Letters*, *704*(2), L124–L128. https://doi.org/10.1088/0004-637X/704/2/L124

Offner, S. S. R., Klein, R. I., & McKee, C. F. (2008). Driven and Decaying Turbulence Simulations of Low-Mass Star Formation: From Clumps to Cores to Protostars. *The Astrophysical Journal*, *686*(2), 1174–1194. https://doi.org/10.1086/590238

Offner, S. S. R., Klein, R. I., McKee, C. F., & Krumholz, M. R. (2009). The Effects of Radiative Transfer on Low-Mass Star Formation. *The Astrophysical Journal*, *703*(1), 131–149. https://doi.org/10.1088/0004-637X/703/1/131

Offner, S. S. R., & Krumholz, M. R. (2009). The Shapes of Molecular Cloud Cores in Simulations and Observations. *The Astrophysical Journal*, *693*(1), 914–921. https://doi.org/10.1088/0004-637X/693/1/914

Offner, S. S. R., Krumholz, M. R., Klein, R. I., & McKee, C. F. (2008). The Kinematics of Molecular Cloud Cores in the Presence of Driven and Decaying Turbulence: Comparisons with Observations. *The Astronomical Journal*, *136*(1), 404–420. https://doi.org/10.1088/0004-6256/136/1/404

Offner, S. S. R., & Liu, Y. (2018). Turbulent action at a distance due to stellar feedback in magnetized clouds. *Nature Astronomy*, *2*, 896–900. https://doi.org/10.1038/s41550-018-0566-1

Rosen, A. L., Offner, S. S. R., Foley, M. J., & Lopez, L. A. (2021). Blowing Bubbles around Intermediate-Mass Stars: Feedback from Main-Sequence Winds is not Enough. *arXiv e-Prints*, arXiv:2107.12397. http://arxiv.org/abs/2107.12397

Truelove, J. K., Klein, R. I., McKee, C. F., Holliman, I., John H., Howell, L. H., & Greenough, J. A. (1997). The Jeans Condition: A New Constraint on Spatial Resolution in Simulations of Isothermal Self-gravitational Hydrodynamics. *The Astrophysical Journal Letters*, *489*(2), L179–L183. https://doi.org/10.1086/310975