Computational Star Formation
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Radiation-MHD Simulations of HII Region Expansion in Turbulent Molecular Clouds

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Abstract. We use numerical simulations to investigate how the expansion of an HII region is affected by an ambient magnetic field. First we consider the test problem of expansion in a uniform medium with a unidirectional magnetic field. We then describe the expansion of an HII region in a turbulent medium, taking as our initial conditions the results of and MHD turbulence simulation. We find that although in the uniform medium case the magnetic field does produce interesting effects over long length and timescales, in the turbulent medium case the main effect of the magnetic field is to reduce the efficiency of fragmentation of the molecular gas.

Keywords. HII regions, hydrodynamics, ISM: kinematics and dynamics

1. Introduction

Star formation triggered by the expansion of HII regions is strongly suggested by IR observations of the vicinity of HII regions such as RCW 120 (Deharveng *et al.* 2009). The expanding photoionized gas collects a layer of dense, neutral gas ahead of it, which could then become Jeans unstable, fragment and form new stars. Indeed, a number of Class I low-mass young stellar objects have been found in filaments parallel to the ionization front in RCW 120. Radiation-driven implosion of neutral material within or at the periphery of photoionized regions is another possible route to triggered star formation.

Magnetic fields have been detected in and around molecular clouds with strengths of, for example $10.2\,\mu$G (Ophiucus dark cloud large-scale field; Goodman & Heiles (1994)) to $\sim 500\,\mu$G (in globules of M17, and even higher fields are measured at higher spatial resolution; Brogan & Troland (2001)), indicating that the magnetic field has small-scale structure itself. In this work, we are interested in studying the extent to which the magnetic field on both local and larger scales, influences the evolution of an expanding HII region and what consequences can be expected for triggered star formation.

2. Radiation MHD Code and Test Case

We have developed a radiation-MHD code, which includes a full treatment of the heating and cooling processes in the neutral gas, taking into account the FUV and X-ray radiation field not only from the main ionizing source but also from the associated low-mass stellar cluster, as well as cosmic rays and dust (Henney *et al.* 2009). We have used this code to study the evolution of an HII region in a uniform magnetic field. This problem was first studied by Krumholz *et al.* (2007) and we adopt their parameters in order to aid comparison, that is, an ionizing source of $10^{46.5}$ photons s^{-1}, ambient density $n_0 = 100$ cm^{-2} and temperature $T = 11$ K, and uniform magnetic field of strength

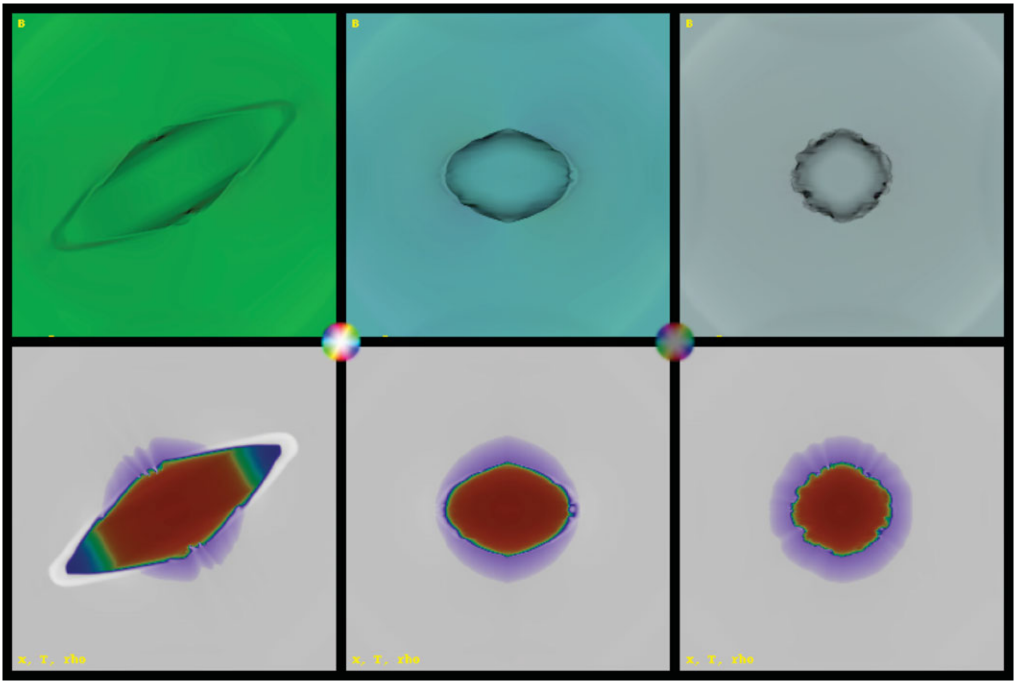

Figure 1. Cuts through the computational cube in the central xy-, xz- and yz-planes for an HII region expanding in a uniform medium with a unidirectional magnetic field after 6.8 Myr. *Top row:* Magnetic field strength and direction (black indicates perpendicular to plane). *Bottom row:* Ionization fraction, temperature and density. Low density, hot, ionized gas fills the center while high density, warm neutral gas piles up at the poles.

$|B| = 14.2\,\mu$G. In order to distinguish between physical instabilities and grid-induced effects we put our magnetic field at 30° to the x-axis in the xy-plane.

As reported by Krumholz *et al.* (2007), the photoionized gas expands, initially pushing the magnetic field aside because the thermal pressure dominates. However, once the thermal pressure in the ionized gas drops to the level of the magnetic pressure in the neutral gas, the magnetic field returns almost to its initial value and direction. The expansion of the HII region is fastest along the direction of the magnetic field, since the slow shock which precedes the ionization front travels fastest along the field lines and cannot travel perpendicular to them. At late times, we see the formation of instabilities in the ionization front where the ionization front is parallel to the magnetic field lines but cannot advance because of this restriction on the slow shock. Clumps form which, if slightly displaced from the equator of the HII region, are subject to the rocket effect and move off along the field lines like beads on a wire. As the magnetic field refills the HII region, it pulls in gas with it. This gas flows in at the equator then is directed along the field lines out of the poles, where it recombines forming dense neutral caps.

3. HII Region evolution in a magnetized turbulent molecular cloud

We use the results of MHD turbulence simulations (Vázquez-Semadeni *et al.* 2005) as the initial conditions for our simulations of HII region evolution in a magnetic, turbulent medium (cf. our previous paper Mellema *et al.* 2006a). The densest clump is taken to harbor the ionizing source and is moved to the center of the grid (the boundary conditions are periodic). The grid is a 256^3 box, 4 pc on a side with a mean number

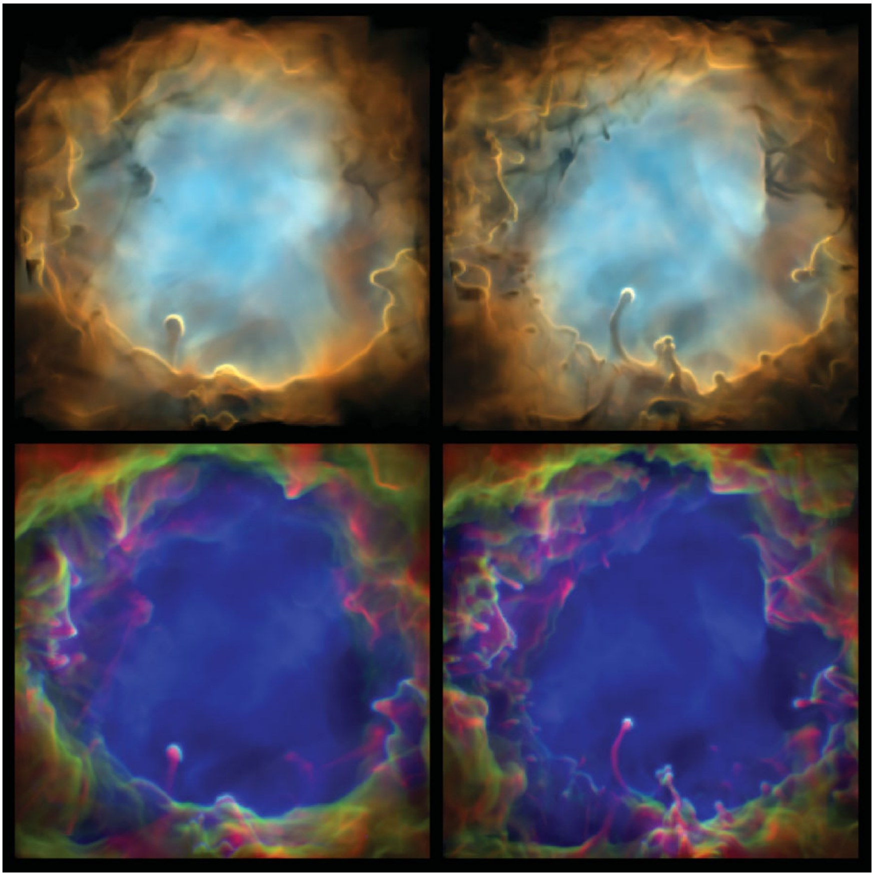

Figure 2. Simulated optical (top) and long-wavelength (bottom) emission maps for the expansion of an HII region due to an O star for MHD (left) and pure hydrodynamic (right) cases after 310,000 yrs of evolution. *Electronic verion only: Colors for the optical emission are: blue—[OIII], green—Hα, red—[NII]. Colors for the long-wavelength emission are: blue—6 cm radio free-free, green—generic PAH emission, red—cold neutral gas column density.*

density of $\langle n \rangle = 1000$ cm^{-3}, a neutral gas temperature of 5 K, and a mean magnetic field strength of $\langle B \rangle = 14.5\,\mu$G and r.m.s. magnetic field $B_{\rm rms} = 24.6\,\mu$G.

For these simulations we use ionizing sources corresponding both to a B-star ($Q_{\rm H} = 10^{46.5}$ s^{-1}) and to an O-star ($Q_{\rm H} = 10^{48.5}$ s^{-1}). For the O-star, we do not expect the magnetic field to become important compared to the thermal pressure of the expanding HII region in a global sense within the time it takes for the HII region to expand beyond the confines of the box. Indeed, this is the case, as seen in Figure 2, which shows the optical and long-wavelength emission maps of both MHD and pure hydro simulations after 310,000 yrs. However, locally there are differences between the amount of fragmentation into globules seen in the pure hydro case and the MHD case. Neutral globules are overrun by the ionization front, protruding into the photoionized region until they are swept away by radiation-driven implosion and the rocket effect. In general, the pure hydro case has more fragmentation, since there is no support for the globules from magnetic pressure.

For the B-star simulations, the mean initial conditions suggest that it is possible that the magnetic field could have an effect on the global properties of the HII region, within the time and spatial scales of the simulation. After 10^6 years of evolution, there are a few indications that the magnetic field is having a large-scale effect on the HII region

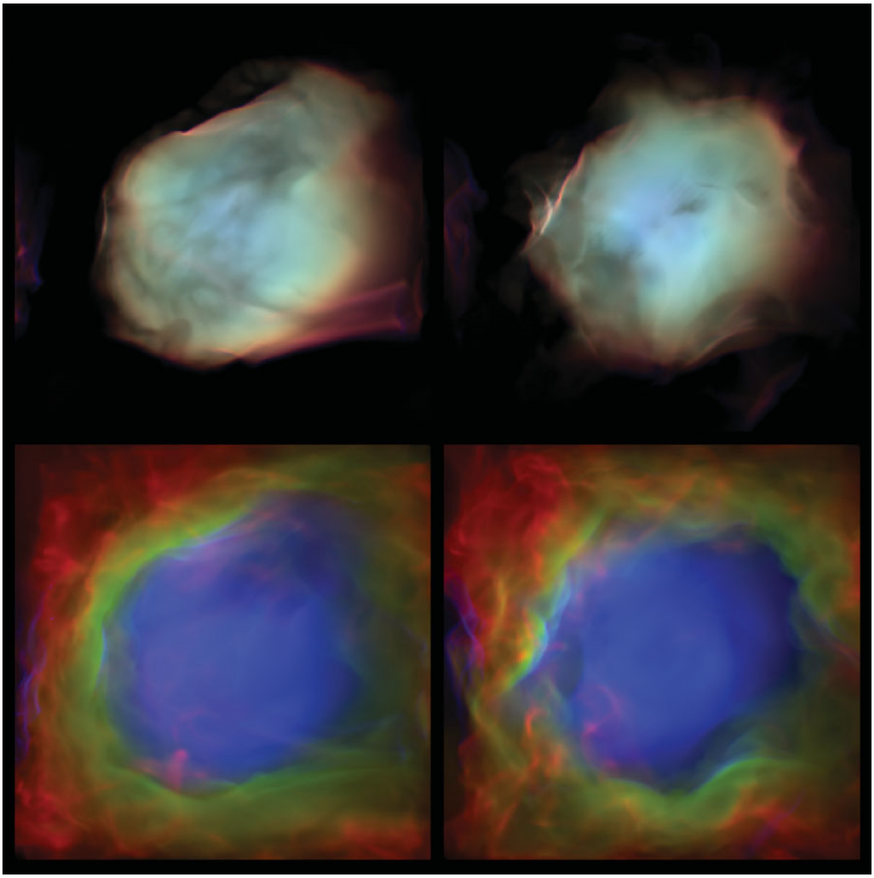

Figure 3. Same as Figure 2 but for a B star after 1 Myr of evolution. *Electronic version only: Colors for optical emission are: blue—[NII], green—Hα, red—[SII]. Colors for the long-wavelength emission are the same as in Figure 2.*

expansion, most notably in the lower part of the HII region as seen in Figure 3, where the magnetic field has become aligned with the ionization front and provides support for the neutral gas against expansion of the ionized gas in this direction. There is much less fragmentation in the B star case than in the O star case. This is because the clumps in the B star simulation are eroded by photoevaporation due to FUV radiation before the ionization front reaches them. The pressure of the warm neutral gas is insufficient to collapse underlying density inhomogeneities into dense globules and filaments.

References

Brogan, C. L. & Troland, T. H. 2001, *ApJ*, 560, 821
Deharveng, L., *et al.* 2009, *A&A*, 496, 177
Goodman, A. A. & Heiles, C. 1994, *ApJ*, 424, 208
Henney, W. J., Arthur, S. J., de Colle, F., & Mellema, G. 2009, *MNRAS*, 398, 157
Krumholz, M. R., Stone, J. M., & Gardiner, T. A. 2007, *ApJ*, 671, 518
Mellema, G., Arthur, S. J., Henney, W. J., Iliev, I. T., & Shapiro, P. R. 2006, *ApJ*, 647, 397
Vázquez-Semadeni, E., Kim, J., Shadmehri, M., & Ballesteros-Paredes, J. 2005, *ApJ*, 618, 344