Radiation-hydrodynamical models of triggered star-formation: Synthetic observations

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ABSTRACT: We have simulated the radiatively driven implosion of a molecular cloud using a radiation-hydrodynamics code (TORUS) that employs a full treatment of the photoionization and radiative equilibrium. We use the code to compute radio and sub-mm continuum images along with recombinations, forbidden and molecular line diagnostics in order to make comparisons with observations of bright-rimmed clouds.

INTRODUCTION
Radiation-hydrodynamical models incorporating ionizing radiation fields have thus far relied on ray-based integral approaches that equate the flux of photons with the column-density and recombinations to calculate effective Strömgren surfaces. Typically a simple prescription for the local temperature is applied, often a temperature switch between neutral and ionized gas (e.g. Dale et al. 2007; Gritschneder 2009).

The TORUS radiative transfer code (Harries et al. 2004, Kurosawa et al. 2006; Pinte et al. 2009, Aczeman et al. 2010) employs a Monte-Carlo estimator of the mean intensity to compute ionization rates and heating terms, and an iterative approach similar to that of Lucy (1999) is used to solve radiation and photoionization equilibria. The code uses a full treatment of dust and gas and accounts for both the direct and diffusion radiation fields self-consistently in three dimensions. The radiative-transfer has been extensively benchmarked (see, e.g. Pinte et al. 2009). The hydrodynamics module uses a basic TVD scheme based on a superbee flux-limiter; whilst self-gravity is solved using a multi-grid technique. Parallelization is achieved using domain decomposition over MPI.

Although the radiative transfer part of TORUS can use an adaptive mesh, the calculations reported here were performed on a 256^3 fixed grid.

INITIAL CONDITIONS
The initial density distribution consisted of a Bonner-Ebert sphere (BES) of radius 195 pc containing 89 solar masses of material. The incoming flux of ionizing photons was 7 × 10^8 photons cm^{-2} s^{-1}. The following elements were included in the photoionization balance: H, He, C, N, O, Ne, and S. Outflow/inflow conditions were imposed on the boundaries perpendicular to the incoming ionizing flux, while periodic boundary conditions were applied elsewhere. The recombinations timescale is much shorter than the characteristic hydrodynamical timescales and we thus assume photoionization equilibrium at all times. For the purposes of this test calculation we neglect self-gravity (the total time of the simulation is significantly shorter than the cloud's free-fall time).

RESULTS
We plot the density distribution at five time-steps in Figure 1. An R-type front propagates quickly into the computational domain. A bow-shock like structure is evident after 50kyr, with dense neutral gas in the high density regions of the BES shielding a large volume of gas form direct ionizing radiation (although the diffuse field does penetrate this region). The shock front curves sharply about the core of the BES, and the shock is compressed by the hot gas from above and below (a result of the periodic boundary conditions). Some evidence of grid and Monte-Carlo noise induced numerical instabilities are evident in the shock front, particularly at 57k and 89k years. Qualitatively the simulation resembles that of Gritschneder et al., although our shock front appears rather more smoothly curved and relatively less structured.

SYNTHETIC OBSERVABLES
We computed an example sequence of continuum and line images from one step of the hydrodynamical simulation. Here we summarize the example images.

- Free-free emission. We computed the emissivities of the grid at a wavelength of 20cm. The emission traces out a bow-shock like structure that wraps around the front side of the BES, in a manner reminiscent of the observations in Morgan et al. (2009). (Figure 2).
- Dust continuum. Monochromatic images were calculated at 450 and 850 microns, tracing the cold (10-30K) gas in the regions shielded from direct illumination by ionizing radiation. We make the simplifying assumption that no dust exists in the ionized medium. (Figure 2).

Figure 2: Colour scale shows 850 µm dust continuum emission (linearly scaled). Contours show 20 cm radio emission.

Forbidden line emission. We computed lines of O I, O III and S II (Figure 3). The images include a small contribution from light scattered by dust embedded in the neutral gas.

Figure 3: Forbidden line image. Lines displayed are [O I] 6300Å (red), [O III] 5007Å (green) and [S II] 6731Å (blue).

-Molecular line emission. We assumed a CO abundance relative to H2 of 10^4. Although the code is capable of computing LTE level populations we assumed LTE here. A data cube was calculated in the co-moving frame over 40 equal-velocity bins, with a microturbulence of 1 km/s. (Figures 4 & 5). The non-gaussian profiles caused by bulk motion of the gas are seen near the illuminated surface of the BES. Similar profiles (although spatially unresolved) are seen in the Morgan et al. survey of C+CO J=2-1.

Figure 4: The greyscale shows total emission in CO+J=1-0. The red lines indicate spatially resolved spectra, plotted over ±6 km/s.

Figure 5: A projected false-colour image of the CO J=1-0 line emission. The data cube is binned into -6 to -3 km/s (blue), -3 to -1 km/s (green) and 1 to 6 km/s (red).

REFERENCES