Simulating radiative feedback in the interstellar medium

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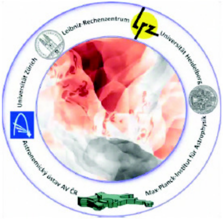


The SILCC Project

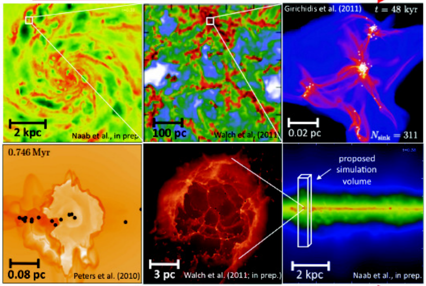
SImulating the LifeCycle of Molecular Clouds

S. Walch, T. Naab, P. Girichidis, R. Klessen, S. Glover, P. Clark, T. Peters, R. Wünsch

AMR code FLASH 4 with...

Lifecycle of molecular clouds

Cooling & Collapse



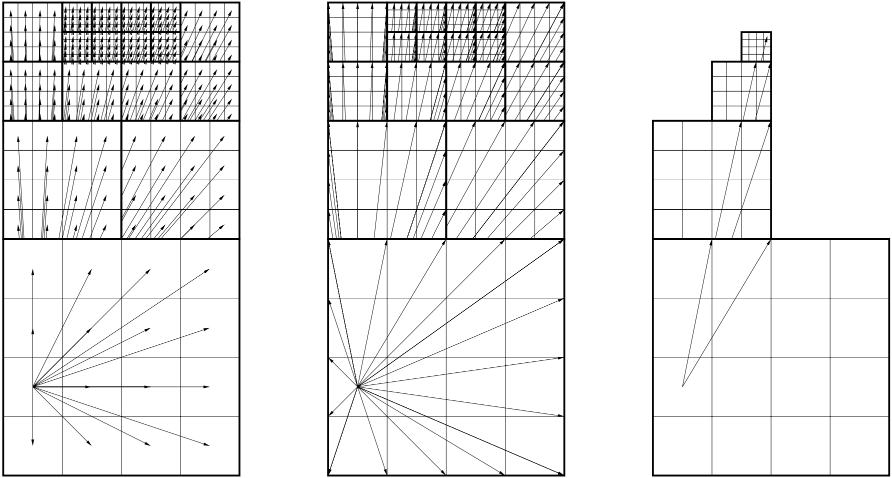
Stellar Feedback & Outflows

- tree self-gravity (Wünsch et al. in prep.)
- external potential
- ideal MHD
- heating & cooling, molecule formation (Glover et al. 2011)
- TreeCol (Clark et al. 2012)
- Sink particles with subgrid cluster/star model
- ionization, wind, and supernova feedback

42 million CPU-hours on SuperMuc@Leibniz-Rechenzentrum, Garching

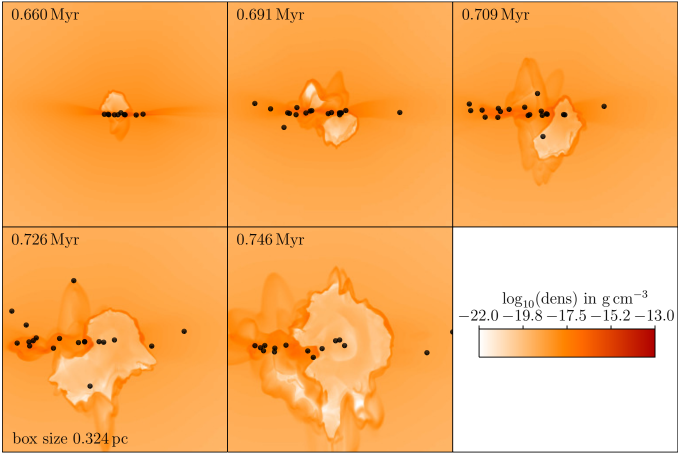
Gatto+'15,'16, Walch+'15, Girichidis+'16a,b, Peters+'15

Hybrid characteristics raytracing



Rijkhorst+'06, Peters+'10a,b,c,'11

Hybrid characteristics raytracing



- Raytracing gives column densities, which are used to compute photoionization and heating rates.
- Application to simulations of massive star formation with ionization feedback.

Hybrid radiation transport scheme

- Combine direct stellar light with diffuse radiation, $\boldsymbol{F} = \boldsymbol{F}_* + \boldsymbol{F}_{\mathrm{th}}$.
- The stellar radiation flux is

$$F_*(r) = F_*(R_*) \left(\frac{R_*}{r} \right)^2 \exp\left(-\tau(r)\right)$$

with $F_*(R_*) = \sigma T_*^4$ and

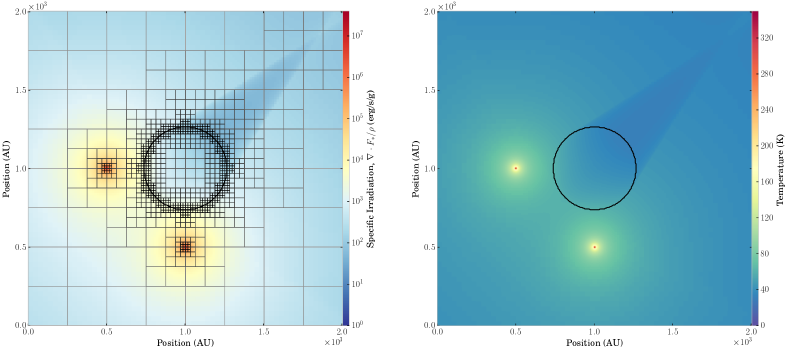
$$\tau(r) = \int_{R_*}^{r} \kappa_P(T_*) \rho(r') \, \mathrm{d}r'.$$

- The diffuse radiation is propagated with flux-limited diffusion,

$$\begin{aligned} \partial_t \rho\epsilon &= -\kappa_P \rho c \left(a_R T^4 - E_{\mathrm{th}} \right) - \boldsymbol{\nabla} \cdot \boldsymbol{F}_* \\ \partial_t E_{\mathrm{th}} + \boldsymbol{\nabla} \cdot \boldsymbol{F}_{\mathrm{th}} &= +\kappa_P \rho c \left(a_R T^4 - E_{\mathrm{th}} \right). \end{aligned}$$

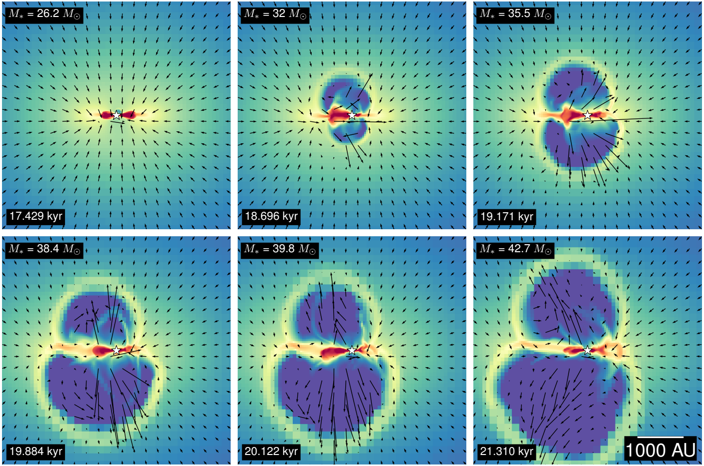
Klassen+'14,'16

Hybrid radiation transport scheme



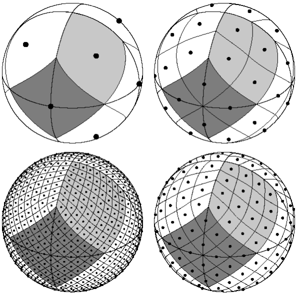
- two sources in low-density medium ($\rho = 10^{-20}$ g cm^{-3}) irradiating dense clump ($\rho = 10^{-17}$ g cm^{-3}) with radius $R_c = 267$ AU
- much better shadow than expected for pure FLD method

Hybrid radiation transport scheme



- Pure FLD methods can underestimate the radiative force by 2 orders of magnitude (Kuiper+'12, Owen+'12, Harries+'12) .
- We find stable radiation bubbles in all our collapse simulations.

Fervent



Gorski+'05

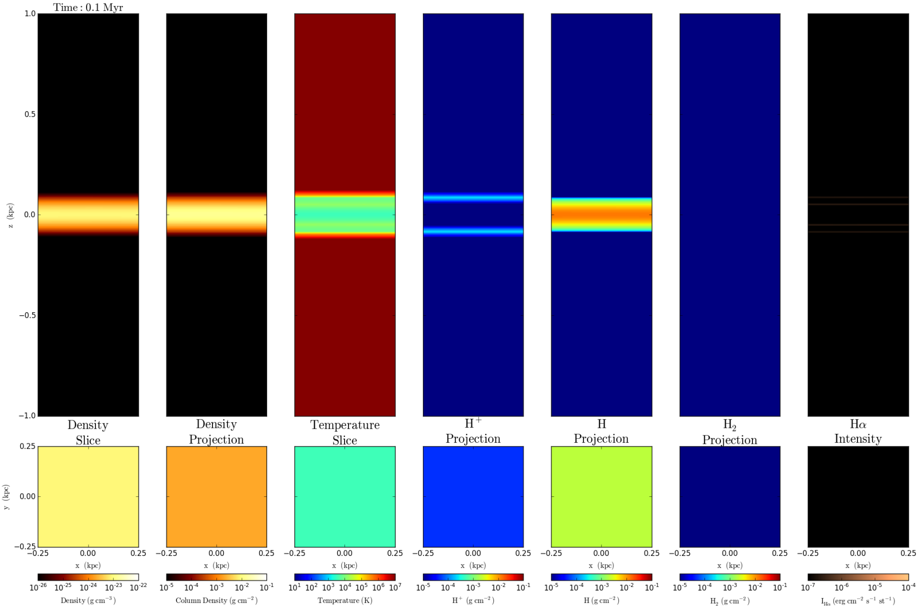
- HEALPix-based raytracing scheme
  similar to ENZO's MORAY (Wise+'11)
- ionization, dissociation and heating processes fully coupled to SILCC chemical network (Walch+'15)

Baczynski+'15

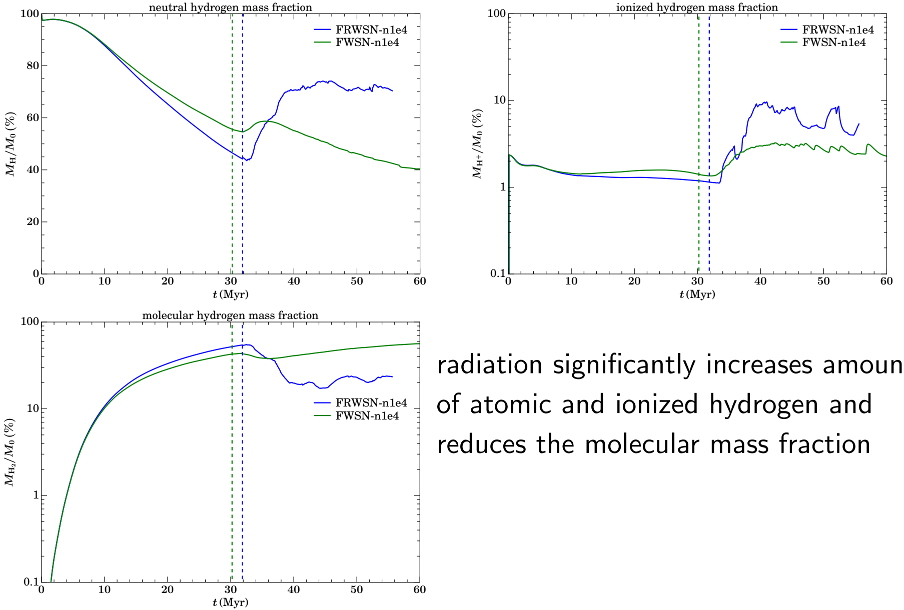
Fervent

- star cluster luminosities from Starburst99 tracks (Leitherer+'99)
- frequency-dependent opacities for four energy bins:
  (1) 5.6 eV $< E_{5.6} <$ 11.2 eV
  (2) 11.2 eV $< E_{11.2} <$ 13.6 eV
  (3) 13.6 eV $< E_{13.6} <$ 15.2 eV
  (4) 15.2 eV $< E_{15.2}$
- include photochemistry and radiative heating for:
  (i) $\mathrm{H_2} + \gamma_{11.2} \rightarrow \mathrm{H} + \mathrm{H}$ (molecular hydrogen photodissociation)
  (ii) $\mathrm{H} + \gamma_{13.6} \rightarrow \mathrm{H^+} + \mathrm{e^-}$ (atomic hydrogen photoionization)
  (iii) $\mathrm{H} + \gamma_{15.2^+} \rightarrow \mathrm{H^+} + \mathrm{e^-}$ (atomic hydrogen photoionization)
  (iv) $\mathrm{H_2} + \gamma_{15.2^+} \rightarrow \mathrm{H_2^+} + \mathrm{e^-}$ (molecular hydrogen photoionization)

SILCC simulation with radiation feedback



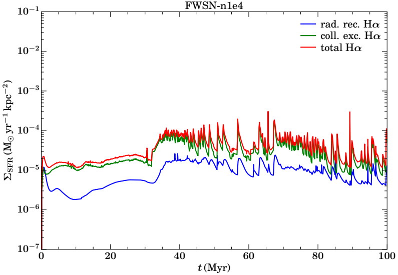
Mass fractions



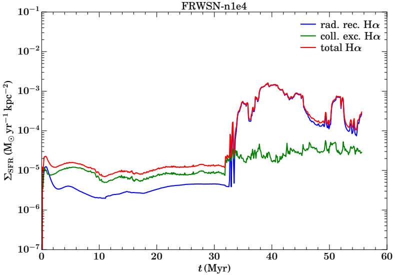
radiation significantly increases amount of atomic and ionized hydrogen and reduces the molecular mass fraction

Hα emission as an SFR tracer

winds + supernovae



radiation + winds + supernovae

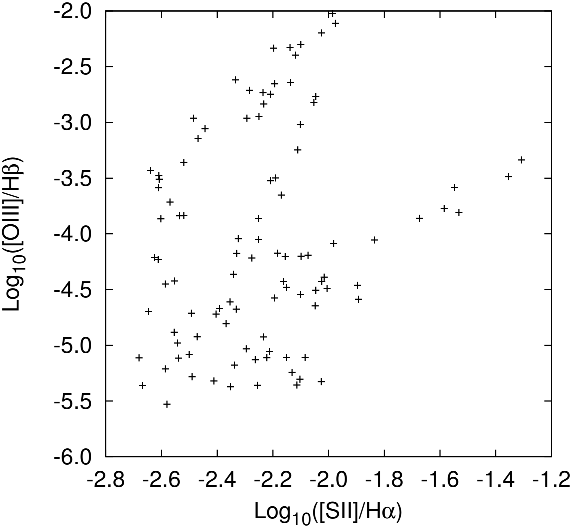


Emission line diagnostics with BPT diagrams

with Eric Pellegrini

- Important probes of ISM conditions are emission line diagnostics with BPT diagrams (Baldwin+'81).
- We model line emission in post-processing with Cloudy (Ferland+'98).
- Computational task for each simulation grid cell:
    - given: density, temperature, cell size and incident photon flux in the 4 energy bands
    - wanted: abundance of different ionization stages for e.g. N, S, O and level populations for line emission
- We do NOT compute photoionization equilibrium models, because this would not include the emission from shock-ionized gas.
- We do NOT run one-zone Cloudy models, because this will lead to wrong emissivities at our simulation grid resolution.
- These calculations are expensive, but since the problem is local we can recycle previously computed emissivities by storing our results in a database.

Emission line diagnostics with BPT diagrams



Conclusions

- ISM simulations with time-dependent networks for H_2 and CO chemistry and self-consistent stellar feedback from radiation, winds and supernovae are available now.
- Feedback by dissociating and ionizing radiation significantly increases the mass fraction of atomic and ionized hydrogen, respectively, and reduces the molecular hydrogen mass fraction with respect to feedback by winds and supernovae only.
- SFR derived from Hα emission of young H II regions qualitatively follows true SFR closely, but it can underestimate the real SFR by an order of magnitude (Calzetti+'07 calibration). How does this depend on surface density and metallicity? Are there better calibrations?
- Synthetic BPT diagrams enable us to investigate systematic errors in deriving ionizing continuum radiation fields, gas chemical abundance gradients, gas-to-dust ratios etc. as function of metallicity, surface density and stellar feedback processes.