Star formation and feedback in the multi-phase interstellar medium

Stefanie Walch

I. Physics Institute, University of Cologne

D. Seifried, F. Dinnbier, S. Haid (University of Cologne)
T. Naab, T.-E. Rathjen (MPA Garching)
P. Girichidis (AIP Potsdam)
R. Wünsch (Czech Academy of Sciences, Prague)
R. Klessen, S. Glover (ITA Heidelberg)
P. Clark (Cardiff University)

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The life-cycle of gas in the multi-phase interstellar medium:
A schematic view

Multi-phase ISM in a galactic disk

Compression & Cooling

1. Self-gravity
2. Magnetic fields
3. Chemistry

Molecular cloud hosting dense filaments

Collapse & Fragmentation

“Make things as simple as possible, but not any simpler”
- Albert Einstein

Bubbles on different spatial scales

Star and star cluster formation

Radiation
Radiation pressure
Stellar winds
Supernovae
Cosmic Rays
Multi-wavelength Milky Way

superimposed contours: CO survey (Dame et al. 2001):

Molecular gas accumulates in the galactic plane

Volume filling fractions:
Mihalas & Binney (1981); Kulkarni & Heiles (1988)
SILCC Project

SIMulating the Lifecycle of Molecular Clouds

University of Cologne: S. Walch, D. Seifried, F. Dinnbier, S. Haid
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AMR code FLASH 4 with...
- Self-gravity
- External galactic potential
- Ideal MHD
- Heating & Cooling and
- Molecule Formation
- TreeRay (diffuse radiation for shielding + radiative transfer from point sources)
- Sink Particles with subgrid cluster model/massive star model
- Supernova Feedback
- Wind
- Cosmic Rays

Walch +15, Girichidis +16
Peters+17, Gatto+17, Seifried+17, +18

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New SILCC simulations: stellar winds + ionizing radiation (TreeRay) + supernovae

See also:

Cluster mass:
- $10^2 \, M_\odot$
- $10^3 \, M_\odot$
- $10^4 \, M_\odot$

Gatto et al. (2017)
Peters et al. (2017)
Wünsch, SW+ in prep.
Dinnbier, SW+ in prep.
New SILCC simulations:
winds + ionizing radiation + supernovae + Cosmic Rays

Cluster mass:
- $10^2 \, M_\odot$
- $10^3 \, M_\odot$
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CR description:
Girichidis +2016,
Girichidis +2018

Rathjen+in prep.
A quick word on Cosmic Rays...

Outflows become cooler and smoother

(Girichidis +2018)

Lyman-alpha line profiles become in agreement with observations only with Cosmic Rays:
Low intensity at line center and asymmetric wings

(Gronke+2018)
Stellar feedback driven bubbles in the Lobster Nebula (NGC 6357)

The impact of star formation:
The signatures of stellar feedback are ubiquitous in the ISM

Stellar feedback:
- UV radiation
- Radiation pressure
- Stellar winds
- Type II Supernovae

Blue: ionized gas
Red: dust
Image taken from: APOD 26.12.2018

~ 60 pc
Dean Carr: 2017
Comparing the energy input: Stellar winds, ionizing radiation & Supernovae: How is this energy coupled to the ISM?

see Haid +2018a
The SILCC project (www.astro.uni-koeln.de/silcc):
Typical mass distribution in the multi-phase ISM in a star forming galactic disk

Walch et al. (2015)

Mass-weighted temperature – density PDF

Walch et al. (2015)
Stellar winds vs. ionizing radiation: Simulations with FLASH + TreeRay + Chemical Network

CNM: T=20 K, n=100 cm$^{-3}$; WIM: T=$10^4$ K, n=0.1 cm$^{-3}$

Haid et al. (2018a)
Momentum input: Stellar winds vs. ionizing radiation:

Relative impact of wind and radiation

Here: for 23 $M_\odot$ star

Radiation does not couple in low density/warm ambient medium $\Rightarrow$ stellar winds become dominant there!

Haid et al. (2018a)

CNM: $T=20$ K, $n=100$ cm$^{-3}$; WIM: $T=10^4$ K, $n=0.1$ cm$^{-3}$
Momentum input:
Stellar winds, ionizing radiation and Supernovae:
Coupling of radiation is inefficient!

The effective momentum input from supernovae is larger than from winds and ionizing radiation
Exception: Very massive stars

Supernova 1 event at end of stellar lifetime in the same gas

Stellar winds are more important than radiation in a warm environment (WIM)

CNM: $T=20 \text{ K}, n=100 \text{ cm}^{-3}$; WIM: $T=10^4 \text{ K}, n=0.1 \text{ cm}^{-3}$

Haid et al. (2018a)
The role of photo-ionization and stellar winds on few 100 parsec scales

Wind+Supernova already regulate star formation: $\Sigma_{\text{SFR}}$ on KS relation

$\Rightarrow$ Role of radiation?
$\Rightarrow$ Shift to lower $\Sigma_{\text{H}_2}$ at similar $\Sigma_{\text{SFR}}$

Kennicutt-Schmidt relation

SILCC scales: few 100 pc

SFR vs. molecular gas

Outflows are only launched if there is a hot, volume-filling phase: Supernova driving

- No Feedback
- Wind only
- Supernova only
- $n_{\text{sink}} > 10^2/\text{cc}$ Wind + Supernova
- $n_{\text{sink}} > 10^3/\text{cc}$ Wind + Supernova
- $n_{\text{sink}} > 10^4/\text{cc}$ Wind + Supernova

Gatto +17
Time = 70 Myr
Mass loading vs. hot gas volume filling fraction

Mass loading at $z=\pm 1$ kpc is strongly correlated with the hot gas volume filling factor in the galactic midplane => fountain/outflow regulated by thermal feedback

See also:
Not yet final... Conclusions:
Impact of stellar feedback in different ISM phases

![Graph showing impact of different ISM phases: Supernovae, Radiation dominated, Wind dominated.](image)
Radiation Pressure on dust: Active in dense clouds / early during the stellar feedback process

Walch et al., in prep.  

**Boost factor:** $f_{RP} = \frac{dp}{dt} (L/c)^{-1}$ calculated using RADMC-3D

Prediction: Diffusion limit assuming a constant grey opacity and a uniform cloud: $f_{RP} \sim \Sigma_{gas}$  
However, in the uniform cloud case we find: $f_{RP} \sim (\Sigma_{gas})^{0.5}$  
⇒ wavelength of photon progressively becomes longer due to absorption / re-emission events  
⇒ Fewer interactions than expected  
In broad fractal case: Gas is locally heated up => Planck-mean opacity is increased => $f_{RP} \sim \Sigma_{gas}$
Conclusions:
Impact of stellar feedback in different ISM phases

![Diagram showing the impact of stellar feedback on different ISM phases with labels for Supernovae, Wind dominated, Radiation dominated, and Radiation pressure.]