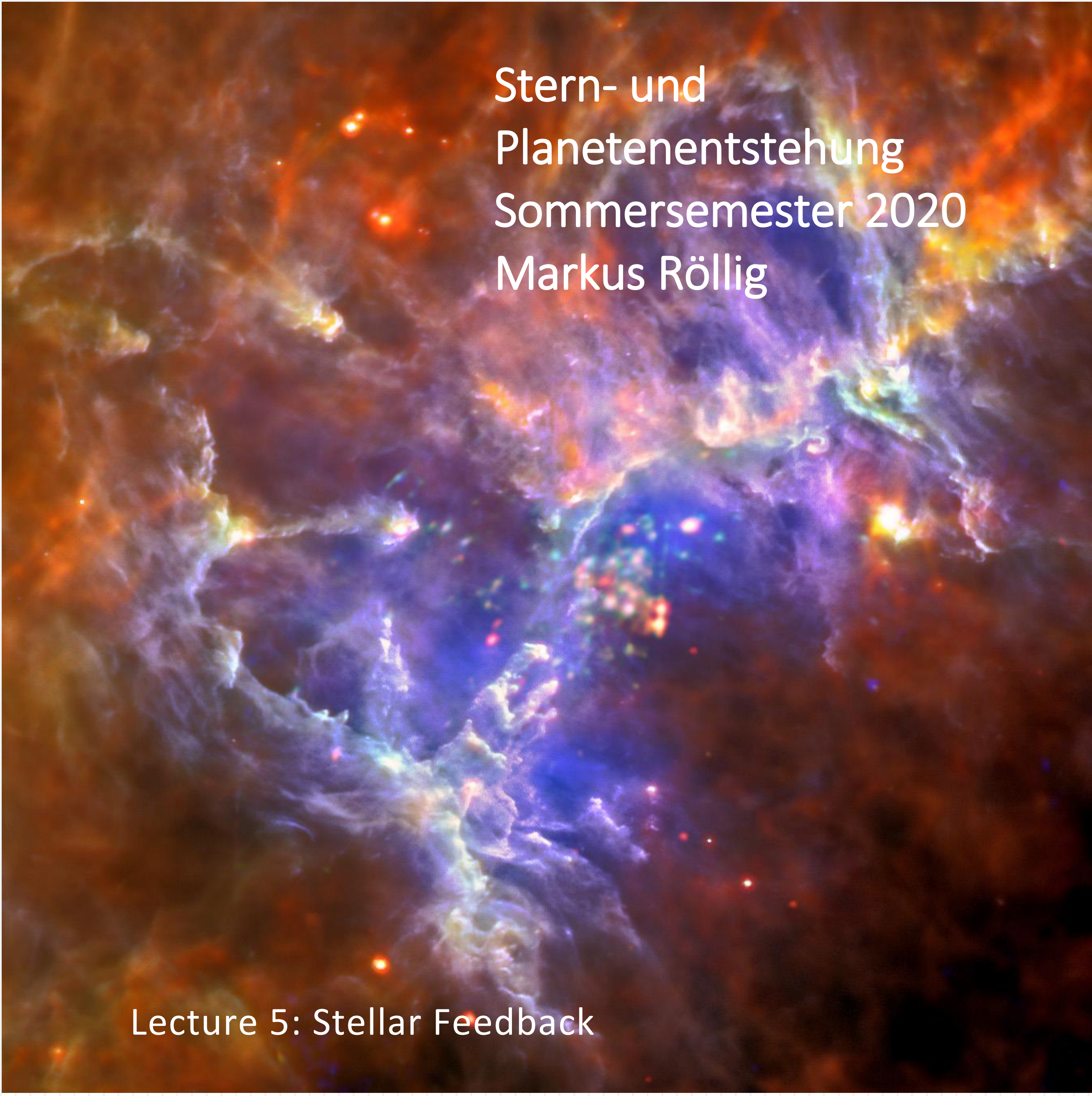


# Stern- und Planetenentstehung

Sommersemester 2020

Markus Röllig

## Lecture 5: Stellar Feedback

http://exp-astro.physik.uni-frankfurt.de/star_formation/index.php

**Vorlesung/Lecture**

Raum: Physik - 02.201a

dienstags, 12:00 - 14:00 Uhr

**Sprechstunde:**

Raum: GSC, 1/34, Tel.: 47433, (roellig@ph1.uni-koeln.de)

dienstags: 14:00-16:00 Uhr

| Nr. | Thema | Termin |
|---|---|---|
| 1 | Observing the cold ISM | 21.04.2020 |
| 2 | Observing Young Stars | 28.04.2020 |
| 3 | Gas Flows and Turbulence<br>Magnetic Fields and Magnetized Turbulence | 05.05.2020 |
| 4 | Gravitational Instability and Collapse | 12.05.2020 |
| 5 | Stellar Feedback | 19.05.2020 |
| 6 | Giant Molecular Clouds | 26.05.2020 |
| 7 | Star Formation Rate at Galactic Scales | 02.06.2020 |
| 8 | Stellar Clustering | 09.06.2020 |
| 9 | Initial Mass Function – Observations and Theory | 16.06.2020 |
| 10 | Massive Star Formation | 23.06.2020 |
| 11 | Protostellar disks and outflows – observations and theory | 30.06.2020 |
| 12 | Protostar Formation and Evolution | 07.07.2020 |
| 13 | Late Stage stars and disks – planet formation | 14.07.2020 |

# 5 Stellar Feedback

## 5.1 General Formalism

### 5.1.1 IMF –Averaged Yields

Instead of single stars we will describe populations of stars, i.e. collective properties of those populations.

IMF: $$\xi(m) = \frac{dn}{d\ln m} \qquad \left(\int \xi(m)dm = 1\right)$$

mean stellar mass: $$\bar{m} = \frac{\int_{-\infty}^{\infty} m\xi(m)d\ln m}{\int_{-\infty}^{\infty} \xi(m)d\ln m} = \frac{1}{\int_{-\infty}^{\infty} \xi(m)d\ln m} = \frac{total\ mass}{total\ number}$$

$Q$: quantity produced by stars with rate $q$ (e.g: Q: total radiant energy E, $q$: bolometric luminosity $L(m,t)$ of a star of mass $m$ and age $t$)

Instantaneous production rate:

$$q(t) = M\int_{-\infty}^{\infty} d\ln m\ \xi(m)q(m,t)$$

IMF-averaged production rate:

$$\langle\frac{q}{M}\rangle = \int_{-\infty}^{\infty} d\ln m\ \xi(m)q(m,t)$$

$\langle q/M\rangle$: instantaneous rate at which stars are producing Q per unit stellar mass

Over lifetime of stellar population:

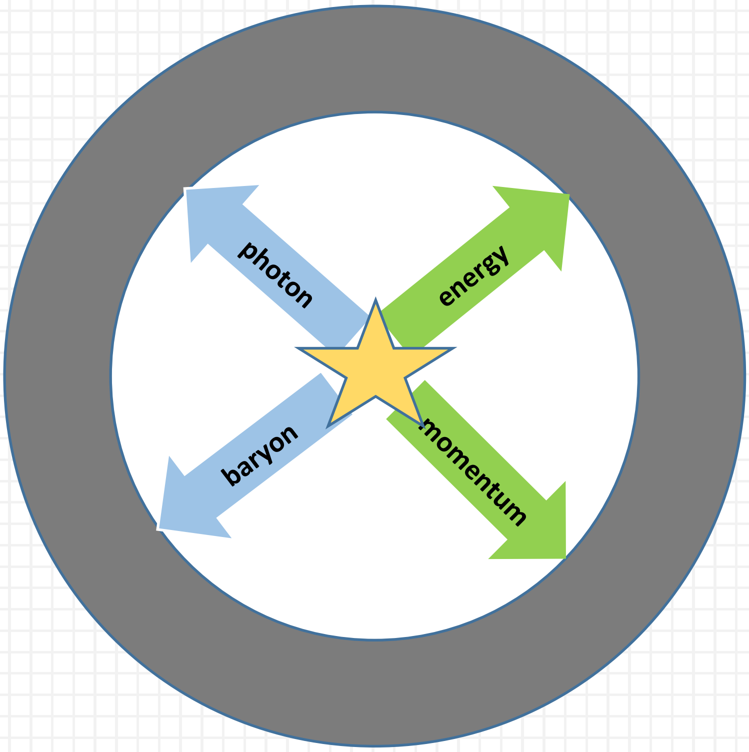
$$Q = M\int_{-\infty}^{\infty} d\ln m\ \xi(m)\int_{0}^{\infty} dt\ q(M,t)$$

IMF-averaged yield:

$$\langle\frac{Q}{M}\rangle = \int_{-\infty}^{\infty} d\ln m\ \xi(m)\int_{0}^{\infty} dt\ q(M,t)$$

$\langle Q/M \rangle$: total amount of Q produced per unit stellar mass of stars formed over the stars' entire lifetimes.

### 5.1.2 Energy- versus Momentum-Driven Feedback




stars inject energy and momentum into the surrounding ISM (by photons and baryons)

gas heating difficult because energy can be radiated away

energy input (e.g. by FUV radiation) only important if mechanism can keep the ISM hot for a significant time (e.g. crossing time)

| | |
|---|---|
| momentum-driven feedback: | feedback mechanism where energy is lost rapidly |
| energy-driven feedback: | feedback mechanism where energy is kept for some significant time |

Consider a star surrounded by a uniform region of gas, that turns on at $t = 0$ with energy injection rate $\dot{E}_w$ and momentum injection rate $\dot{p}_w$ (by photons and baryons, i.e. stellar wind)

Properties of the gas shell:

all energy radiated away

momentum of shell at $t$ is all the radial momentum injected up to $t$.

$$p_{sh} = M_{sh} \mathrm{v}_{sh} = \dot{p}_w t$$

kinetic energy of the shell ($v_{sh}$~few 10 km s[-1])

$$E = \frac{\dot{p}_{sh}^2}{2M_{sh}} = \frac{1}{2} v_{sh} \dot{p}_w t$$

no energy radiated away

kinetic energy

$$E = \dot{E}_w t$$

$$\frac{\text{E in energy} - \text{conserving case}}{\text{E in all energy} - \text{lost case}} = \frac{1}{v_{sh}} \frac{2\dot{E}_w}{\dot{p}_w}$$

If $\dot{E}_w$ is carried by baryons $\frac{2\dot{E}_w}{\dot{p}_w} = v_{wind}$ ($v_{wind}$ ~ few 1000 km s$^{-1}$)

If $\dot{E}_w$ is carried by photons $\frac{2\dot{E}_w}{\dot{p}_w} = 2c$

It matters a great deal whether the energy is kept in the ISM or not!

## 5.2 Momentum-Driven Feedback Mechanisms

### 5.2.1 Radiation Pressure & Radiatively-Driven Winds

radiation pressure is probably momentum-driven (because radiation energy will be re-radiated quickly in most cases)

Murray & Rahman (2010) find

$$\langle \frac{L}{M} \rangle = 1140\, L_\odot M_\odot^{-1} = 2200 \text{ erg g}^{-1}$$

Then the momentum injection rate is

$$\langle \frac{p_{rad}}{M} \rangle = \frac{1}{c} \langle \frac{L}{M} \rangle = 7.3 \times 10^{-8} cm\, s^{-2} = 23 \text{ km s}^{-1}\text{Myr}^{-1}$$

Every gram of matter that goes into stars, those stars produce enough light over 1 Myr to accelerate another gram of ISM matter to a speed of 23 km $s^{-1}$.

If massive stars produce strong winds, they might carry ~ 50% of the momentum of the photons => $\langle \frac{p_{rad}}{M} \rangle$ becomes larger.

Total energy production (integrated over 100 Myr)

$$\langle \frac{E_{rad}}{M} \rangle = 1.1 \times 10^{51} \text{ erg M}_\odot^{-1}$$

Majority produced in first 5 Myr (by massive stars).

Energy budget in units of $c^2$ gives dimensionless efficiency by which stars convert mass into energy:

$$\epsilon = \frac{1}{c^2} \langle \frac{E_{rad}}{M} \rangle = 6.2 \times 10^{-4}$$

Radiation momentum budget:

$$\langle \frac{p_{rad,tot}}{M} \rangle = \frac{\epsilon}{c} = 190 \text{ km s}^{-1}$$

Total radiation momentum output by stars is significant (compare with circular velocity of a typical galaxy ~200 km $s^{-1}$).

## 5.2.2 Protostellar Winds

*Abbildung 1 Credit: NASA/JPL-Caltech/Univ. of Michigan, Spitzer image: Infrared light with a wavelength of 3.6 microns has been color-coded blue; 4.5-micron light is green; and 8.0-micron light is red.*

Accretion disks produce a wind (jet) that carries away some of the accreted mass and angular momentum (few 10% of the total accreted mass) at a velocity ~ Keplerian speed at the stellar surface.

Consider a star of mass $M_*$ and radius $R_*$. Its wind will move at a speed of order

$$v_w \sim \sqrt{G\frac{M_*}{R_*}} = 250\ km\ s^{-1} \left(\frac{M_*}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{R_*}{3R_\odot}\right)^{-1/2}$$

The kinetic energy per unit mass carried by the wind is $v_w^2/2$, and when the wind hits the surrounding ISM it will shock and this kinetic energy will be converted to thermal energy. We can therefore find the post-shock temperature from energy conservation. The thermal energy per unit mass is $\left(\frac{3}{2}\right) k_B T/\mu m_H$ thus the post-shock temperature will be

$$T = \frac{\mu m_H v_w^2}{3k_B} \sim 5 \times 10^6 K$$

This is low enough that gas at this temperature will be able to cool fairly rapidly, therefore proto-stellar winds are most-likely momentum-driven because (shocked gas (T~few million K) cools quickly via radiation)

Consider stars forming over a time $t_{form}$ with constant accretion rate. Thus, a star of mass $m$ accretes with a rate $\dot{m} = \frac{m}{t_{form}}$, over the forming time and during that time it produces a wind with a mass flux $f\dot{m}$ that is launched at speed $\mathrm{v}_K$.

IMF-averaged yield of wind momentum:

$$\langle\frac{p_w}{M}\rangle = \int_{-\infty}^{\infty} d\ln m\ \xi(m) \int_0^{t_{form}} dt \frac{fm\mathrm{v}_K}{t_{form}} = f\mathrm{v}_K \int_{-\infty}^{\infty} d\ln m\ \xi(m) = f\mathrm{v}_K$$

.

$$f\mathrm{v}_K \sim \text{few } 10 \text{ km s}^{-1}$$

assuming $f$ and $\mathrm{v}_K$ are constant

- ⇨ protostellar winds supply over their full lifetime as much momentum as radiation does in 1 Myr.
- ⇨ Compared to total stellar lifetime radiation injects much more momentum!
- ⇨ But radiation pressure is strongest from most massive stars, but most stars are low mass stars.
- ⇨ Protostellar winds produce the ~ same amount of momentum independent of stellar mass, every star contributes the same
- ⇨ During the accretion time, winds are much more powerful than radiation

## 5.3 (Partly) Energy-Driven Feedback Mechanisms

### 5.3.1 Ionizing Radiation

$h\nu > 13.6\,eV$

Massive stars produce ionizing radiation. Murray & Rahman (2010) find a yield of ionizing photons from a zero-age population:

$$\langle\frac{S}{M}\rangle = 6.3 \times 10^{46} \text{ photons s}^{-1} M_\odot^{-1}$$

Averaged over total lifetime

$$\langle\frac{S_{tot}}{M}\rangle = 4.2 \times 10^{60} \text{ photons } M_\odot^{-1}$$

#### 5.3.1.1 HII Region Expansion

HII ← singly ionized H
HI ← neutral H

(Hydrogen) Ionizing photons will be absorbed with a very short mean free path, producing a bubble of $H^+$ gas within which all photons are absorbed.

The size of the bubble (Strömgren radius) results from equating the recombination rate with the production rate of ionizing photons

$$S = \frac{4}{3}\pi r_S^3 n_e n_p \alpha_B$$

$$\alpha_B \approx 3 \times 10^{-13} \text{cm}^3\text{s}^{-1}$$

$\alpha_B$: recombination rate coeffici

$r_S$: Strömgren radius

$n_e, n_p$: electron and proton number densities

$\mu_H$: mean mass per hydrogen nucleus in the gas

$\rho_0$: initial density before photoionization starts

$n_p = \rho_0/\mu_H$ and $n_e = 1.1\rho_0/\mu_H$ (1.1 because we add singly ionized He 1/10 He per H nucleus)

$$r_S = \left(\frac{3S\mu_H^2}{4(1.1)\pi\alpha_B\rho_0^2}\right)^{1/3} = 2.8\, S_{49}^{1/3} n_2^{-2/3} \text{pc}$$

$$S_{49} = S/10^{49} \text{ s}^{-1},\ n_2 = \frac{\left(\frac{\rho_0}{\mu_H}\right)}{100 \text{ cm}^{-3}},\ \ \alpha_B = 3.46 \times 10^{-13} \text{ cm}^3\text{s}^{-1}$$

The ionized gas will be heated to ~$10^4$ K. The corresponding sound speed is

$$c_i = \sqrt{\frac{k_B T_i}{\mu_H/2.2}} = 11\, T_{i,4}^{1/2} \text{km s}^{-1}$$

where $T_{i,4} = T_i/10^4$K, $\mu_H = 2.3 \times 10^{-24}$ g (2.2 because that is the number of particles per H nucleus, i.e. electrons)

Pressure inside $r_S$ $\quad P_i = \rho_0 c_i^2 \gg \rho_0 c_0^2 = P_{ISM}$ $\quad$ ambient pressure

⇨ HII region will start to expand

⇨ time scale for ionization balance is short compared to dynamical time scale=> ionization balance will remain during expansion

For a given radius $r_i$ after expansion started, the density inside the HII region will be

$$\rho_i = \left(\frac{3S\mu_H^2}{4(1.1)\pi\alpha_B r_i^3}\right)^{1/2}$$

⇨ The expanding HII region sweeps up the surrounding gas

⇨ mass accumulates in a neutral shell surrounding the HII region

⇨ at late times, when $r_i \gg r_S$, and $\rho_i \ll \rho_0$ we can neglect the mass in the shell interior

⇨ then the shell mass is $\quad M_{sh} = \frac{4}{3}\pi\rho_0 r_i^3$

Equation of motion for shell (neglecting ambient pressure):

$$\frac{d}{dt}(M_{sh}\dot{r}_i) = 4\pi r_i^2 \rho_i c_i^2$$
$$\frac{d}{dt}\left(\frac{1}{3}r_i^3\dot{r}_i\right) = c_i^2 r_i^2 \left(\frac{r_i}{r_S}\right)^{-3/2}$$

$$\rho_i = \rho_0\left(\frac{r_i}{r_S}\right)^{-3/2}$$

General solution: numerically, for late times, when $r_i \gg r_S$ analytic solution possible

If $r_i \gg r_S$ we can take $r_i(t \to 0) \approx 0$ as BC

➔ similarity solution of the ODE

trial solution $\quad r_i = f r_s \left(\frac{t}{t_S}\right)^{\eta}$, with $t_S = \frac{r_S}{c_i} = 240 S_{49}^{\frac{1}{3}} n_2^{-\frac{2}{3}} T_{i,4}^{-\frac{1}{2}}\ \mathrm{kyr}$

insert $r_i$

$$\frac{1}{4}\eta(4\eta - 1) f^4 \left(\frac{t}{t_S}\right)^{4\eta - 2} = f^{1/2}\left(\frac{t}{t_S}\right)^{\eta/2}$$

solution only if $4\eta - 2 = \eta/2$ , therefore $\eta = 4/7$, and $f = \left(\frac{49}{12}\right)^{2/7}$

$$r_i = r_S \left(\frac{7t}{2\sqrt{3} t_S}\right)^{\frac{4}{7}} = 9.4\ S_{49}^{\frac{1}{7}} n_2^{-\frac{2}{7}} T_{i,4}^{\frac{2}{7}} t_6^{\frac{4}{7}}\ \mathrm{pc}$$

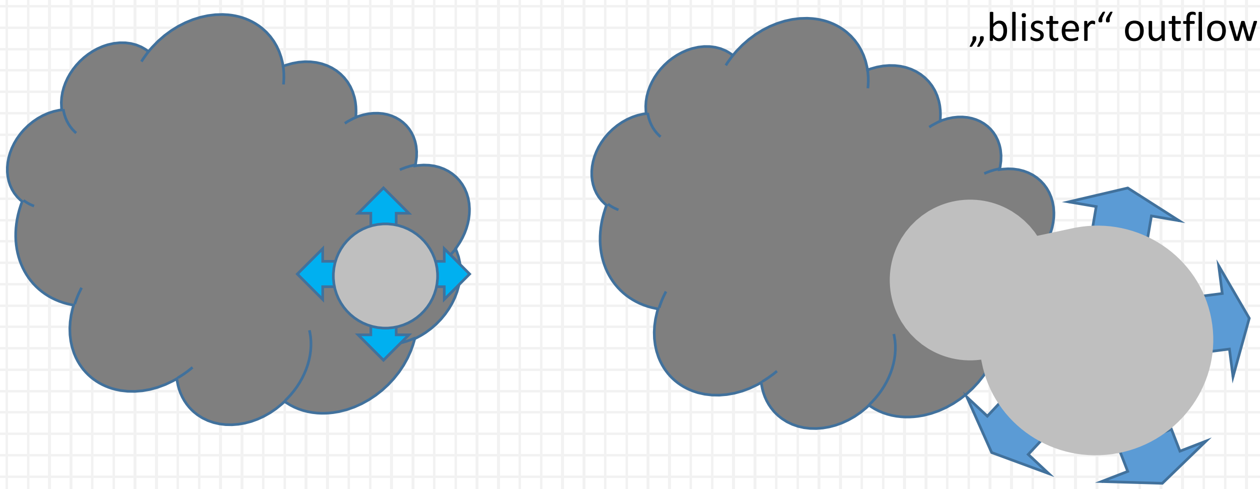
at late times, where $t_6 = t/1\mathrm{Myr}$

### *5.3.1.2 Feedback Effects of HII Regions*

Ionization can

- ⇨ eject mass
- ⇨ drive turbulent motion
- ⇨ possibly disrupt clouds

Mass ejection:



Maximum mass flux carried by the ionized wind:

$$\dot{M} = 4\pi r_i^2 \rho_i c_i$$

$$\dot{M} = 4\pi r_S^2 \rho_0 c_i \left(\frac{7t}{2\sqrt{3}t_S}\right)^{\frac{2}{7}} = 7.2 \times 10^{-3} t_6^{2/7} S_{49}^{4/7} n_2^{-1/7} T_{i,4}^{1/7} M_\odot^{-1} \text{yr}^{-1}$$

Over the lifetime of an O star: 3-4 Myr, it can eject $\sim 10^3 - 10^4 M_\odot$ of mass from its parent cloud (if $n_2$ is not too high)

**Massive stars can eject many times their own mass from a GMC.**

Energy contained in the expanding shell

$$E_{sh} = \frac{1}{2} M_{sh} \dot{r}_i^2 = \frac{32}{147} \pi \rho_0 \frac{r_S^5}{t_S^2} \left(\frac{7t}{2\sqrt{3}t_S}\right)^{6/7}$$
$$= 8.1 \times 10^{47} t_6^{6/7} s_{49}^{5/7} n_2^{-10/7} \text{erg}$$

Compare: binding energy of $10^5 M_\odot$ GMC with surface density of 0.03 g cm$^{-2}$ is ~$10^{50}$ erg.

⇨ single O star has a comparable little effect on the GMC

⇨ cluster of ~ 100 O stars can produce HII regions whose energies are comparable to the total binding energy of the GMC

⇨ sometimes HII regions can disrupt entire GMCs

Momentum of the expanding shell:

$$p_{sh} = M_{sh} \dot{r}_i = 1.1 \times 10^5 n_2^{-1/7} T_{i,4}^{-8/7} S_{49}^{4/7} t_6^{9/7} M_\odot \text{km s}^{-1}$$

Non-linearity in $S_{49}$ and time => effects depend on how the stars are clustered and how long they live

Typical numbers: $L_{ionization} = 10^{49}$ photons/s, age 4 Myr, $n_2 = 1$, and $T_{i,4} = 1$

momentum injected per $10^{49}$ photons $s^{-1}$

$$\Rightarrow p = 3 - 5 \times 10^5 M_\odot \mathrm{km\ s^{-1}}$$

A zero-age population gives $6.3 \times 10^{46}$ photons $\mathrm{s^{-1}} M_\odot^{-1}$

The momentum injection rate for HII regions is (very roughly)

$$\langle \frac{\dot{p}_{HII}}{M} \rangle \sim 3 \times 10^3 \mathrm{\ km\ s^{-1}}$$

**HII regions are most likely the dominant feedback.**

Limitation: $v_i(t = 0) \sim 10 \mathrm{\ km\ s^{-1}}$ , very massive cluster might have comparable escape velocities, it will prevent disruption of the GMC

## 5.3.2 Stellar Winds

O stars have winds of $\mathrm{v}_w \sim 1000 - 2500 \mathrm{\ km\ s^{-1}}$ and mass fluxes of $\dot{M}_w \sim 10^7 M_\odot^{-1} \mathrm{yr}^{-1}$.

- ⇨ Momentum small compared to other effects.
- ⇨ high $\mathrm{v}_w$ produces very high post-shock temperatures of $T \sim 10^8 \mathrm{K}$
- ⇨ gas with $T \sim 10^8 \mathrm{K}$ has a very long cooling time
- ⇨ **energy-driven feedback**

Wind momentum comparable to stellar radiation momentum (Repolust et al. 2004):

$$\dot{M}_w \mathrm{v}_w \approx 0.5 \frac{L_*}{c}$$

$L_*$: stellar luminosity

Mechanical luminosity of the wind

$$L_w = \frac{1}{2}\dot{M}_w \text{v}_w^2 = \frac{L_*^2}{8\dot{M}_w c^2} = 850\, L_{*,5}^2 \dot{M}_{w,-7}^{-1} L_\odot$$

The integrated power output over the ~4Myr lifetime of a massive star

$$E_w = L_w t = 1.0 \times 10^{50} L_{*,5}^2 \dot{M}_{w,-7}^{-1} t_6 \text{ erg}$$

**The total mechanical power in the wind is comparable to the amount of energy released when the star goes supernova.**

Equation of motion: assume energy is conserved (1/2 goes into heating)

$$\frac{d}{dt}\left(\frac{2}{3}\pi\rho_0 r_b^3 \dot{r}_b^2\right) \approx \frac{1}{2} L_w$$

Similar to HII region we try a similarity solution with: $r_b = At^\eta$

$$\frac{4}{3}\pi\eta^2(5\eta - 2)\rho_0 A^5 t^{5\eta-3} \approx L_w$$

Because of energy conservation this must be independent of $t$ and then implies $\eta = 3/5$ and $A = [25L_W/(12\pi\rho_0)]^{1/5}$.

$$r_b = 16 L_{*,5}^{2/5} \dot{M}_{w,-7}^{-1/5} n_2^{-1/5} t_6^{3/5} \text{pc}$$

(greater than radius of HII region!)

- ⇨ Wind will move faster and drive the ionized gas into a thin layer between hot wind gas and outer cool shell – *if the energy-driven limit is correct*!
- ⇨ Major assumption that energy remains confined in a closed shell may not be true. Possibly break out of gas.
- ⇨ Theoretically difficult to predict.
- ⇨ Observations can help: if shocked gas is trapped it should produce x-ray emission!

Pressure of x-ray emitting gas:

Shell expanding for time $t$. Then the total energy within that shell is $E_w \approx L_w t$.

Pressure is 2/3 of energy density (monoatomic gas)

$$P_X = \frac{2E_W}{3[(4/3)\pi r^3]} = \frac{L_*^2 t}{16\pi \dot{M}_w c^2 r^3}$$

The pressure exerted by the radiation (twice that exerted by the wind in the momentum-driven limit)

$$P_{rad} = \frac{L_*}{4\pi r^2 c}$$

ratio is called trapping factor:

$$f_{trap} = \frac{P_X}{P_{rad}} = \frac{L_* t}{4\dot{M}_w c r} \approx \frac{L_*}{4\dot{M}_w c \mathrm{v}}$$

$\mathrm{v} = r/t$

expansion vel. of shell

Using $\dot{M}_w \mathrm{v}_w \approx \left(\frac{1}{2}\right) L_*/c$

$$f_{trap} = \frac{\mathrm{v}_w}{2\mathrm{v}}$$

If the shell expands in energy-driven limit due to winds: the pressure of the hot gas within should exceed the direct radiation pressure by about a factor $\mathrm{v}_w/\mathrm{v}$.

In the momentum-driven limit $P_X/P_{rad} \sim 1/2$

Example: Lopez et al. 2010 observed 30 Doradus

Theory: $v_{expansion} \approx 20\ km\ s^{-1}, v_w \approx 1000\ km\ s^{-1} \Rightarrow f_{trap} = 20$

Obs: $f_{trap} \approx 0.5$ therefore momentum-driven limit more likely.

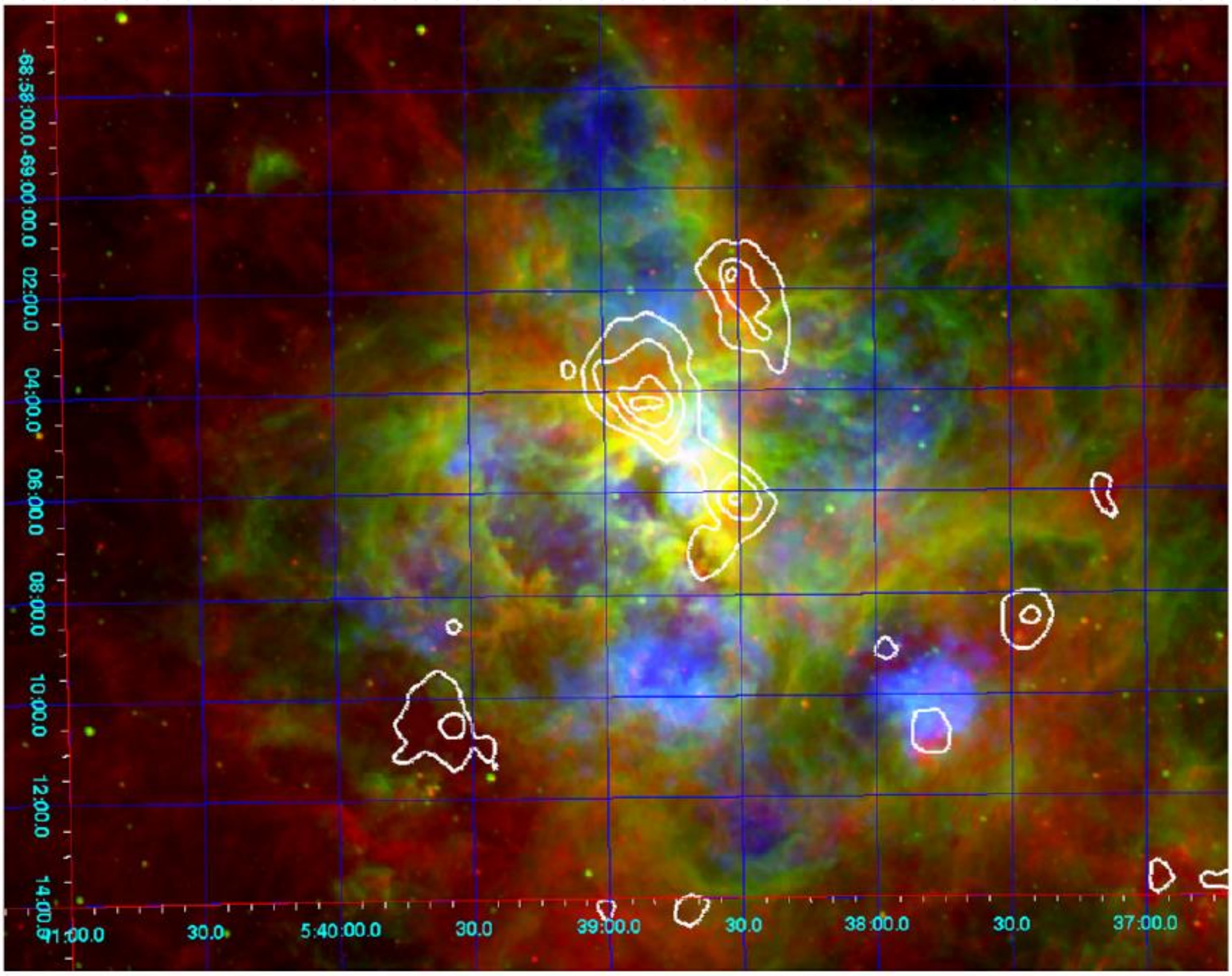



*Abbildung 2 Lopez et al. 2012 : Three-color image of 30 Doradus: MIPS 8 μm (red), Hα (green), and 0.5–8 keV X-rays (blue). White contours show the 12CO(1–0) emission (Johansson et al. 1998) in the region. Both large- and small-scale structures are evident. north is up, east is left.*

### 5.3.3 Supernovae

Model $q(m,t)$ as $\delta$ function: all the energy and momentum of the SN released in a single burst at a time $t = t_l(m)$, where $t_l(m)$ is the lifetime of the progenitor star.

We assume an energy yield per star of $10^{51}$ erg. Its minimum mass is $\sim 8M_\odot$

SN energy per unit mass:

$$\langle\frac{E_{SN}}{M}\rangle = E_{SN}\int_{m_{min}}^{\infty} d\ln m\, \xi(m) = E_{SN}\,\langle\frac{N_{SN}}{M}\rangle$$

$\langle N_{SN}/M\rangle$: number of stars above $8M_\odot$ , which is the number of expected SN

For the Chabrier IMF from $0.01 - 120M_\odot$ we find:

$$\langle\frac{N_{SN}}{M}\rangle = 0.011 M_\odot^{-1}, \quad \langle\frac{E_{SN}}{M}\rangle = 1.1\times10^{49}\mathrm{erg}\, M_\odot^{-1} = 6.1\times10^{-6}c^2$$

MW SFR $\sim 1 M_\odot^{-1}\mathrm{yr}^{-1}$ $\Rightarrow$ 1 SN per century in the MW

Momentum yield from SN:

ejection velocity: $\mathrm{v}_e \approx 10^9 cm\ s^{-1}$

momentum: $p_{SN} = 2E_{SN}/\mathrm{v}_{ej}$

$$\langle\frac{p_{SN}}{M}\rangle = \frac{2}{\mathrm{v}_{ej}}\langle\frac{E_{SN}}{M}\rangle = 55\mathrm{v}_{ej,9}^{-1}\ \mathrm{km\ s^{-1}}$$

(small compared to other effects)