Galaxy formation and evolution
53863, 5 op, autumn 2020

on Zoom

Lecture 9: Star formation and supernova feedback in galaxies, 06/11/2020

On this lecture we will discuss

1. Star formation in molecular clouds.
2. The formation and stability of giant molecular clouds.
3. The self-regulation of star formation in galaxies.
4. Thermal and gravitational instabilities.
5. Empirical laws of star formation. Global and local relations.
6. Supernova feedback in galaxies. Ejection and heating of gas by supernovae.
7. The lecture notes correspond to: MBW: pages 393-397, 417-448 (§8.5, §9.1-9.7)

9.1 Star formation in molecular clouds

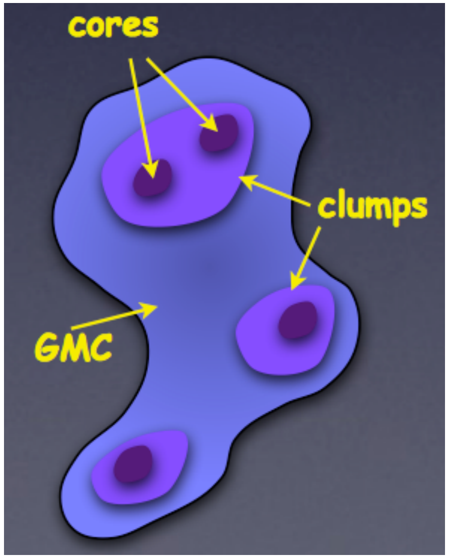
- Stars form in giant molecular clouds (GMCs), which have densities of n_{H2}~100-500 cm^{-3} (ρ~10^{-22} gcm^{-3}, M~10^5-10^6 $M_\odot$) and sizes of tens of parsecs. Stars have sizes of 10^{-7} pc and densities of ρ~1 gcm^{-3} -> star formation involves a density increase of 22 orders of magnitude and a large temperature increase from T~10 K in the GMCs.
- Molecular clouds rotate in general due to differential rotation in the disk. During the collapse a large fraction of the angular momentum must be transferred to explain the relatively slow rotation periods of stars. In addition, the potential energy of the collapse must be released. For the Sun ($E_{pot} \propto GM^2/r$ would last 3×10^7 yrs at $L_\odot$).
- The structure of GMCs is extremely clumpy and within the GMC we have high density clumps (n~10^2-10^4 cm^{-3}, M~10^2-10^4 $M_\odot$) and very dense cores (n>10^5 cm^{-3}, M~0.1-10 $M_\odot$), where star formation ultimately takes place.

Giant molecular clouds

- GMCs are strongly correlated with young massive stars ($t<10^7$ yrs), but little correlation with older stars.
- The free-fall time of a GMC can be estimated as:

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} \simeq 3.6 \times 10^6 \ \text{yrs} \left(\frac{n_{\rm H_2}}{100\ \text{cm}^{-3}}\right)^{-1/2}$$

- However, the observed lifetimes of GMC is much longer at $t \sim 10^7$ yrs, GMC must somehow be supported against collapse.
- We can also define a star formation efficiency of a GMC as $\varepsilon_{SF}=t_{ff}/t_{SF}$, where the star formation timescale $t_{SF}=M_{GMC}/SFR$. Observations indicate that $\varepsilon_{SF}\sim 0.002$. Why is the star formation efficiency in GMCs so low?



Models of Giant molecular clouds

- Using the virial theorem, ignoring external pressure and assuming spherical clouds: kinetic energy: $K=3/2Mc_s^2$ and potential energy $W=-3/5GM^2/r_{cl}$ we can derive the collapse condition for GMCs:

$$M > M_J = \left(\frac{5c_s^2}{G}\right)^{3/2}\left(\frac{3}{4\pi\bar{\rho}}\right)^{1/2} \simeq 40M_\odot \left(\frac{c_s}{0.2\ \mathrm{km/s}}\right)^3 \left(\frac{n_{H_2}}{100\ \mathrm{cm}^{-3}}\right)^{-1/2}$$

- A decrease in temperature (i.e. the sound-speed) or an increase in density, causes a decrease in the Jeans mass, resulting in fragmentation of the cloud into smaller clumps.
- Including pressure equilibrium with an external gas pressure and assuming an isothermal sphere, we can derive the Bonnor-Ebert mass which presumably describes GMCs better:

$$M_{\mathrm{BE}} \simeq 1.182\frac{c_s^3}{(G^3\rho)^{1/2}}$$

GMCs and magnetic fields

- A prime source for non-thermal pressure in GMCs is the magnetic field, which has assumed to be the critical stabilizing force in classical star formation models. Equating the potential energy of a cloud with its magnetic energy yields:

$$M_\Phi = \frac{5^{3/2}}{48\pi^2}\frac{B^3}{G^{3/2}\rho^2} \simeq 1.6\times10^5 M_\odot \left(\frac{n_{H_2}}{100\ \mathrm{cm}^{-3}}\right)^{-2}\left(\frac{B}{30\mu G}\right)^3$$

- Here the assumption is that the magnetic field is uniform across the cloud. If $M>M_\Phi$ the magnetic field cannot prevent the gravitational collapse, and the cloud is magnetically super-critical. If $M<M_\Phi$ the cloud is prevented from collapsing by magnetic forces and the cloud is magnetically sub-critical.
- To be stable (sub-critical) GMCs need typically B~10-100 μG.

GMCs and supersonic turbulence I

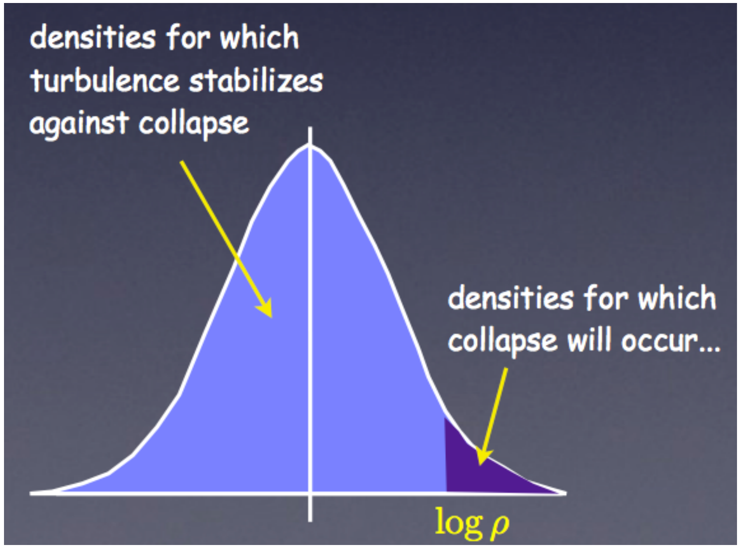
- Since the 1990s the standard magnetic pressure theory for star formation has been increasingly replaced by a new paradigm, in which GMCs are supported by supersonic turbulence instead of magnetic fields.
- In this theory the sound speed in the Jeans mass should be replaced by an effective sound speed that accounts for turbulence:

$$c_{\mathrm{s,eff}} = \sqrt{c_s^2 + \frac{1}{3}\langle v^2 \rangle} = \sqrt{c_s^2 + \sigma_v^2}$$

- For GMCs to be stabilized by turbulence σ_v>6 km/s is required, which is roughly consistent with the observed line-widths of GMCs.
- GMCs have low temperatures of T~10 K (corresponding to v~0.2 km/s) -> The turbulent motions in the GMCs must be supersonic.

GMCs and supersonic turbulence II

- Turbulence is driven at some large scale and then decays to smaller scales until the turbulent energy is dissipated at the dissipation scale.
- Turbulence affects both the effective sound speed of the gas and its density (at areas of compression the density is boosted by the Mach number squared):



$$M_J \propto \frac{(c_s^2 + \sigma_v^2)^{3/2}}{\mathcal{M}\rho^{1/2}}$$

- On large scales $\sigma_v >> c_s$ turbulent motions increase the effective pressure. On small scales $\sigma_v < c_s$ and turbulent compression boosts gas densities. This results in a log-normal density distribution.

Drivers of the turbulence

- The turbulent picture of star formation is fairly successful, but the critical question remains: What drives the turbulence?
- **External processes:** important for the formation of GMCs.

1. Galaxy formation itself (cold flows, mergers, tidal interactions).
2. Supernova explosions (outside of the GMC).
3. Spiral arms in disk galaxies.
4. Instabilities (gravitational, thermal, magnetodynamical).

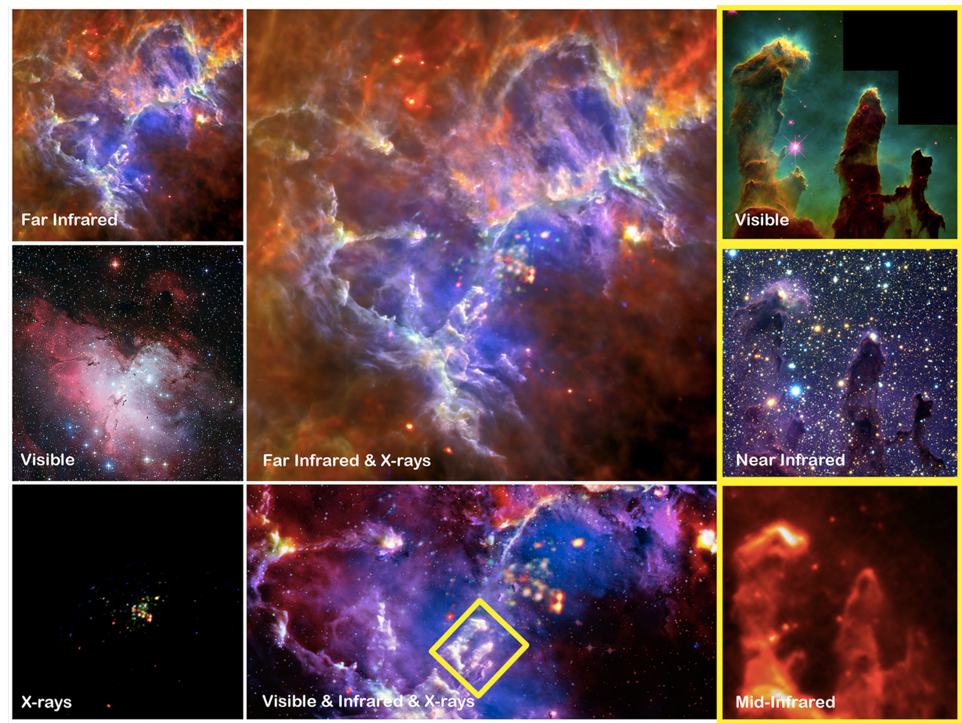
- **Internal processes:** important for maintaining the GMCs.

1. Proto-stellar outflows.
2. Stellar winds.
3. Ionizing radiation.

9.2 Self-regulated star formation

- In addition to turbulence, the overall star formation efficiency (SFE) of GMCs can also be influenced by star formation itself. This is called **self-regulation.**
- For example, feedback from proto-stellar winds are believed to regulate star formation efficiency of the stellar cores.
- GMCs as a whole are also believed to be ultimately destroyed by energetic feedback from massive OB stars (photo-evaporation by HII regions, stellar winds and supernova explosions).
- Star formation may also provoke star formation (positive feedback). Shock waves associated with supernovae, stellar winds and ionization fronts may compress neighbouring gas and thus induce star formation.

Triggered star formation due to photoevaporation: An example



- The pillars of creation in M16, ‘the Eagle Nebula’.

Formation and destruction of molecular hydrogen

- Understanding the formation of GMCs is closely linked to under-standing the formation of molecules. By far the most important and abundant molecule in interstellar space is H_2 which can form via two processes:

1. Via recombination of pairs of adsorbed H atoms on the surface of dust grains.
2. And directly via gas-phase reactions, which is much less efficient than the formation via dust-grains. The gas-phase formation of H_2 is only important in the absence of dust, e.g. the formation of the first stars in the Universe (Pop III stars).

- The main destruction mechanism of H_2 is photo-dissociation. An unattenuated radiation field would destroy the molecules rapidly. Need dense gas and self-shielding in the GMCs.

Star formation efficiency

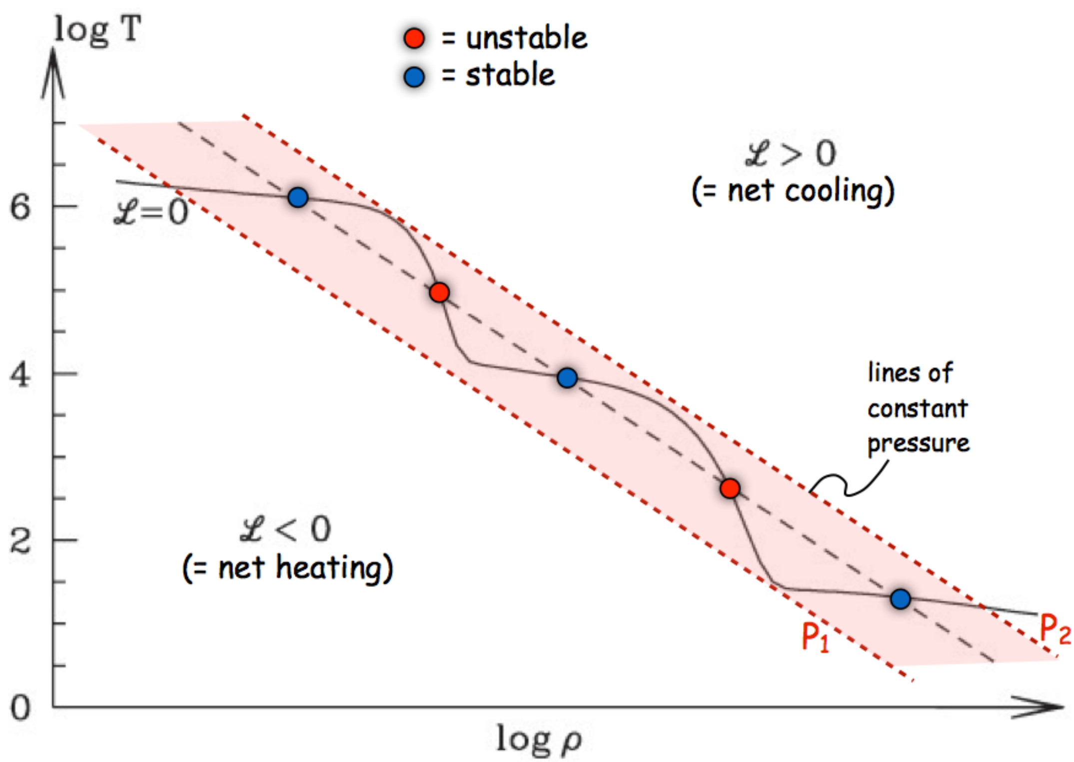
- The time scale for star formation can be simply defined as:

$$t_{\mathrm{SF}} = \frac{M_{\mathrm{gas}}}{\dot{M}_*}$$

- For disk galaxies t_{SF}~$(1\text{-}5)\times10^9$ yrs >> t_{ff}.
- For starburst galaxies t_{SF}~10^7-10^8 yrs~t_{ff}.
- Why is star formation quite inefficient in disk galaxies? Cooling is an isotropic process that conserves angular momentum. Conservation of angular momentum causes a spin up of the cooling and collpasing gas -> formation of disk galaxies. Thus not all of the gas ends in the centre.
- Part of the inefficiency is also due to inefficiency of forming GMCs, as stars only form from cold molecular gas.

Thermal instability

- A gas is in thermal equilibrium if L=(C-H)/ρ=0.
- Since both Cooling and Heating depend on n and T. Thermal equilibrium can be defined as a curve in the density-temperature plane.
- For pressures $P_1<P<P_2$ gas at multiple phases can coexist in pressure equilibrium. However, only three phases are stable.



Hot (T~10^6 K) low density phase.
Warm (T~10^4 K) medium density phase.
Cold (T~10-100 K) high density phase.

Gravitational instability

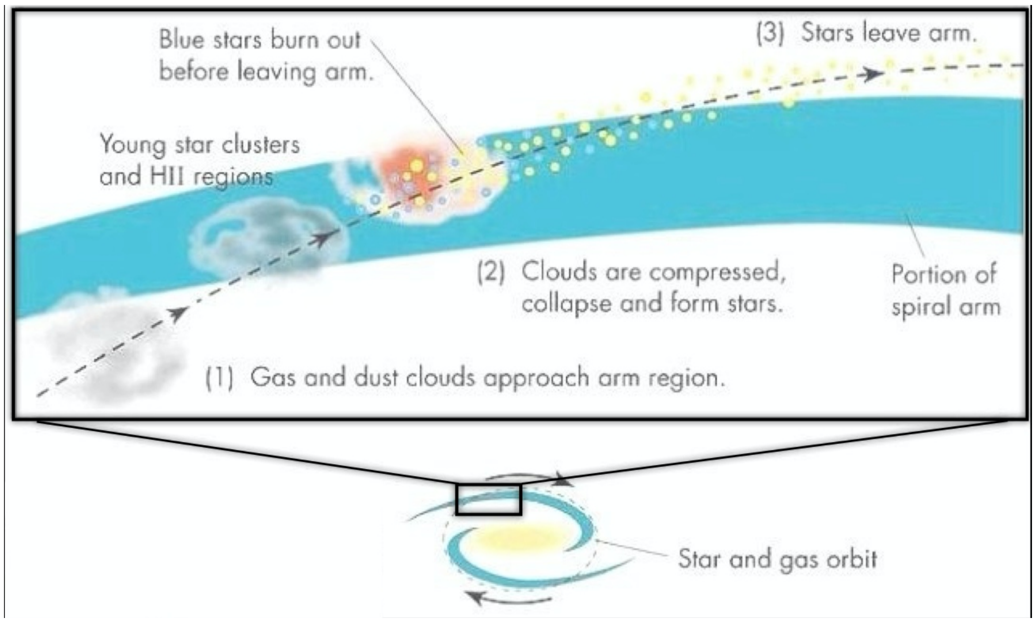
- In a disk galaxy with differential rotation the Jeans criterion is not the proper criterion for gravitational instability. The centrifugal force due to rotation provides additional support against collapse.
- The Toomre stability criterion can be derived for a rotating disk, where the velocity shear makes the disk stable against gravitational collapse, i.e. the disk is stable if Q>1:

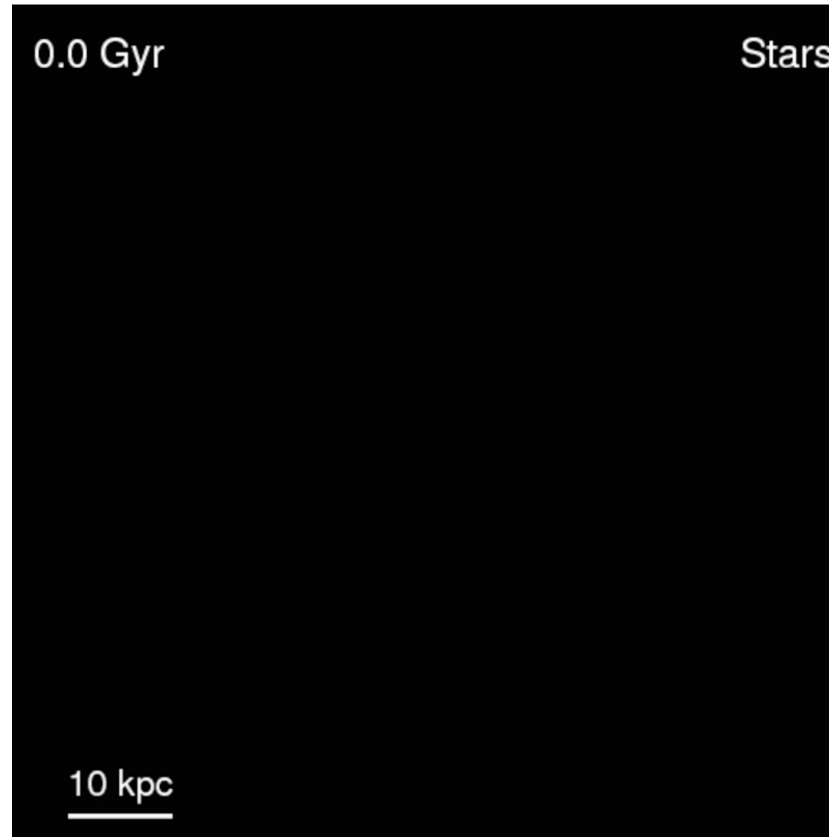
$$Q = \frac{c_s \kappa}{\pi G \Sigma}, \qquad \kappa = \sqrt{2}\left[\frac{v_c^2}{R^2} + \frac{v_c}{R}\frac{dv_c}{dR}\right]^{1/2}$$

- Here c_s is the sound speed, κ is the epicyclic frequency and Σ is the surface mass density. For Q<1 perturbations of the size λ_{crit} will grow:

$$\lambda_{\mathrm{crit}} = \frac{2\pi^2 G \Sigma}{\kappa^2}$$

Star formation triggered by spiral arms and galaxy mergers

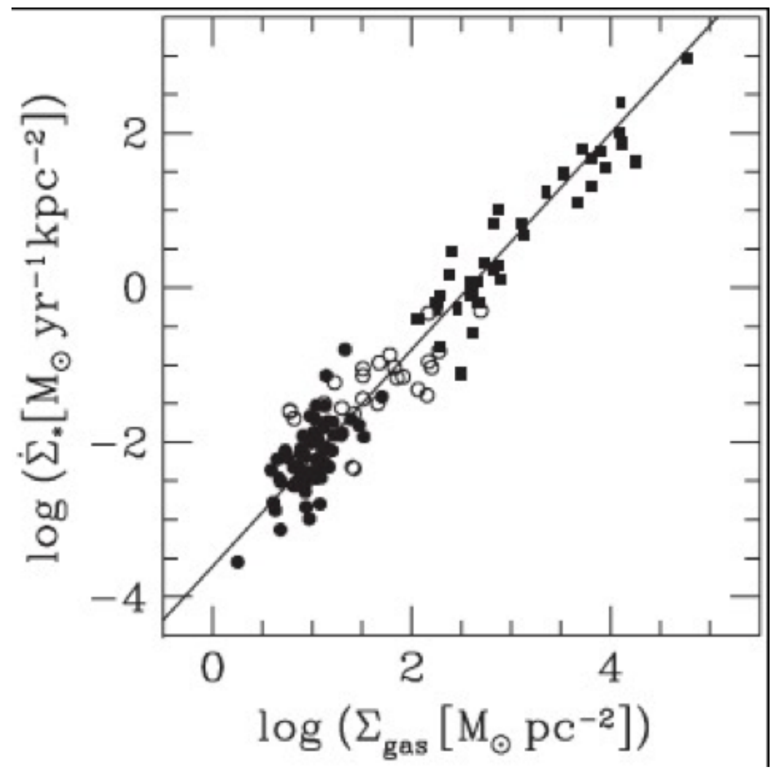




Movie credits: Phil Hopkins (Caltech)

9.3 Empirical star formation laws: Global relations I

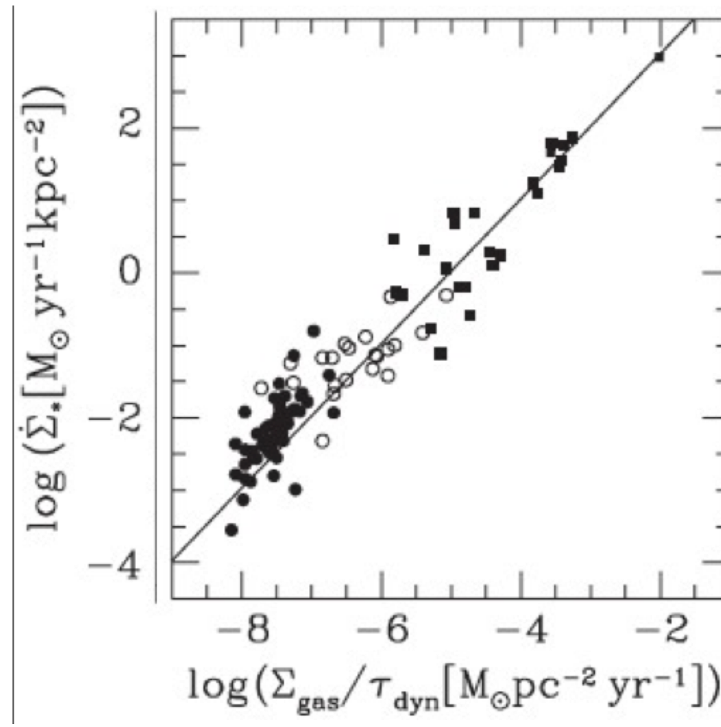
- In galaxy formation modelling it is in practise impossible to resolve the ~20 orders of magnitude relevant for star formation. Instead one typically resorts to empirical star formation laws, which are scaling relations between the SFR and global properties such as gas density, etc.
- The best known empirical star formation law is the Schmidt-Kennicutt law that relates the global averaged star formation density to the surface-gas density (atomic+molecular):



$$\dot{\Sigma}_* \simeq 2.5 \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{M_\odot {\rm pc}^{-2}} \right)^{1.4} M_\odot {\rm yr}^{-1} {\rm kpc}^{-2}$$

Global relations II

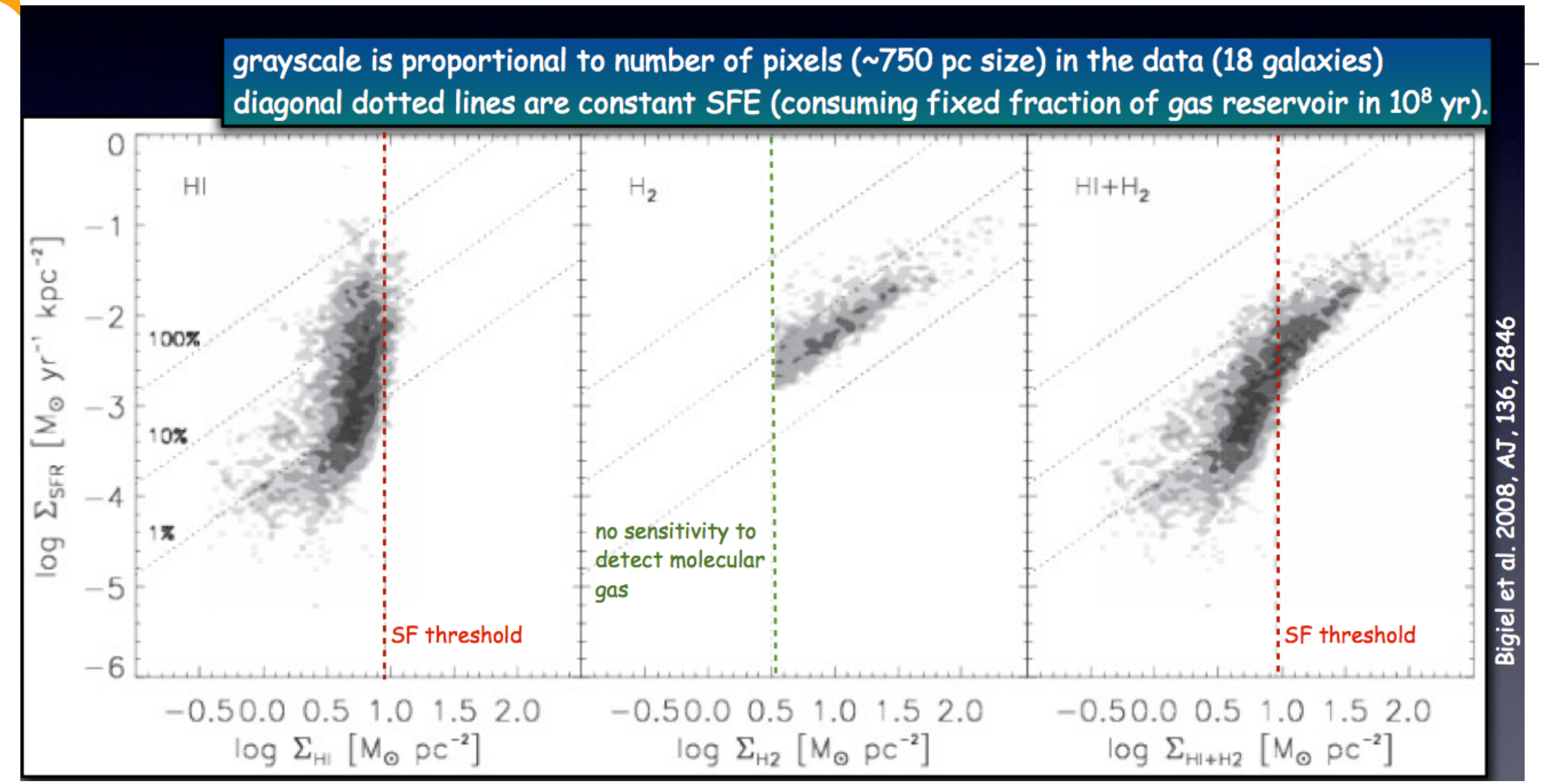
- A common interpretation of the KS-law is that the SFR is controlled by the self-gravity of the gas: $SFR=\varepsilon_{SF} \times \rho_{gas}/t_{ff} \propto \rho_{gas}^{1.5}$.
- However, $\varepsilon_{SF} \ll 1$ which indicates that simple self-gravity cannot be the entire picture.
- The KS-law also reveals a tight correlation between the surface SFR and Σ_{gas}/t_{dyn}, where $t_{dyn}=2\pi R/V(R)$ and R is the outer edge of the star-forming disk.



$$\dot{\Sigma}_* \simeq 0.017\Sigma_{gas}\Omega, \quad \Omega = V_{rot}(R)/R$$

Local relations I

Pixels ~750 pc in size.



- Instead of global measurements, we can measure the SFR, Σ_{gas} and Ω locally pixel by pixel. Observations show that locally the SF efficiency has little to do with the local orbital time, contrary to the global quantities.

Local relations II

- The high resolution measurements of the small-scale local data have revealed that an equivalent to the KS-law is valid with one modification. There is a pronounced break in the power-law behaviour near Σ_{gas}~10 $M_{\odot}pc^{-2}$.
- This threshold is interpreted as a star formation threshold. By splitting gas in atomic and molecular it is clear that this threshold coincides with the atomic-to-molecular transition.
- Atomic gas alone is a poor indicator of star formation, however, in the case of molecular gas there is a well defined Schmidt law, with slope n=1.0±0.2.

$$\dot{\Sigma}_* \simeq 7 \times 10^{-4} \left(\frac{\Sigma_{H_2}}{M_\odot \mathrm{pc}^{-2}} \right)^{1.0} M_\odot \mathrm{yr}^{-1} \mathrm{kpc}^{-2}$$

9.4 Supernova feedback

- One of the most important problems in galaxy formation is the overcooling problem discussed in lecture 8. Preventing overcooling requires some heat input.
- According to the current paradigm the main heating mechanisms are feedback from supernovae and AGN feedback from supermassive black holes (see Lecture 13).

Observed supernova feedback in M82

Supernova feedback: ejection

- To eject gas from a galaxy requires an energy of $E_{ej}=1/2 M_{ej} V_{esc}^2$, where V_{esc} depends on the total mass and mass profile of the galaxy and its dark matter halo.
- The energy available for supernova feedback is:

$$E_{\rm fb} = \epsilon_{\rm SN} \zeta M_* E_{\rm SN}$$

- $\varepsilon_{SN} \leq 1$= fraction of SN energy available for feedback (not radiated away)
- $\zeta=0.01\ M_\odot^{-1}$= number of SN produced per solar mass (IMF dependent)
- $E_{SN} \sim 10^{51}$ erg= energy supplied by SN.
- Equating the feedback energy with the required ejection energy from a NFW halo with concentration parameter c we get:

$$\frac{M_{\rm ej}}{M_*} \simeq 0.4 \epsilon_{\rm SN} \left(\frac{c}{10}\right)^{-1} \left(\frac{v_{\rm vir}}{200\ {\rm km/s}}\right)^{-2}$$

Supernova feedback: heating

- Rather than just ejecting gas from the halo, SN energy can also be used to reheat the gas: $E_{int}=3/2M_{gas}\,(k_BT/\mu m_p)$.
- Let us reheat gas from an initial temperature $T_{init}=10^4$ K to the virial temperature T_{vir}, this requires:

$$E_{\rm reheat} = \frac{3}{2} M_{\rm gas} \frac{k_B(T_{\rm vir} - T_{\rm init})}{\mu m_p} = \frac{3}{4} M_{\rm gas} V_{\rm vir}^2 \left(1 - \frac{T_{\rm init}}{T_{\rm vir}}\right)$$

- Equating the reheating energy to the ejection energy yields:

$$\frac{M_{\rm gas}}{M_*} \simeq 17\epsilon_{\rm SN} \left(\frac{v_{\rm vir}}{200\ {\rm km/s}}\right)^{-2} \left(1 - \frac{T_{\rm init}}{T_{\rm vir}}\right)^{-1}$$

- Reheating is more efficient than ejecting gas: $0.01<\varepsilon_{SN}<1$ and depends on the ISM and star formation conditions.

Mass loading and scaling relations

- The ratio η is called the mass loading factor of the wind and is an important parameter for galaxy formation: $\eta = \dot{M}_{\rm w}/\dot{M}_*$
- Since we lack proper, theoretical understanding of galactic winds and numerical simulations lack the spatial resolution and physics to treat SN feedback from first principles, a number of heuristic approaches have been used in numerical simulations and semi-analytic models:

1. Energy-driven winds: $v_w \propto v_{vir}$ $\eta \propto v_{vir}^{-2}$ (energy conserved).
2. Momentum-driven winds: $v_w \propto v_{vir}$ $\eta \propto v_{vir}^{-1}$ (momentum conserved).
3. Constant winds models: v_w=constant η=constant
4. Power-law wind models: $v_w \propto v_{vir}$ $\eta \propto v_{vir}^{-\alpha}$.

Supernova feedback in numerical simulations

1. **Thermal feedback:**

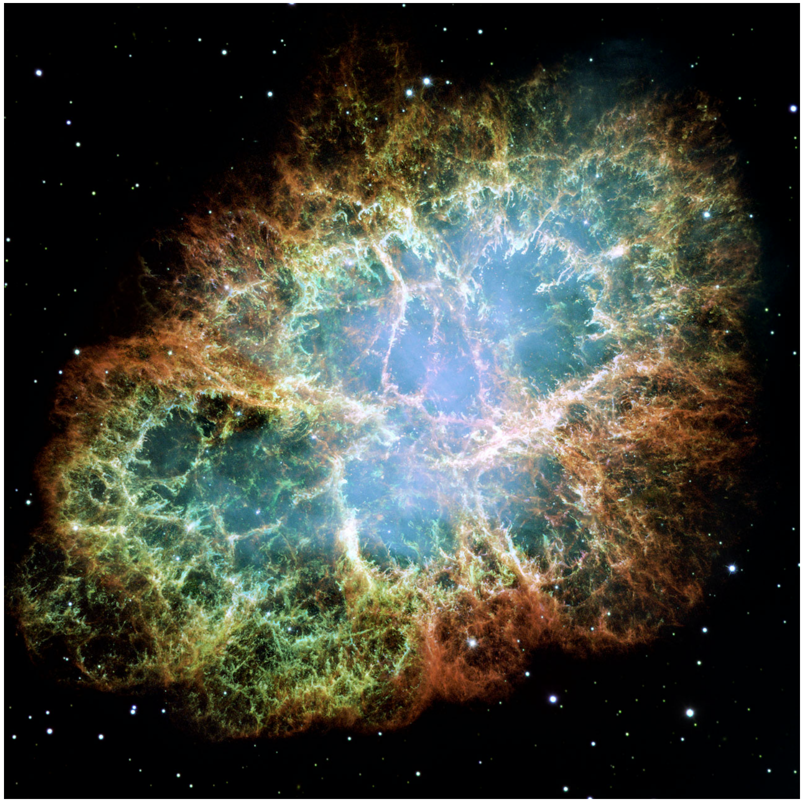
- A fraction $\varepsilon_{SN} \leq 1$ of the SN energy is given to neighbouring gas particles in the form of thermal energy. A problem with this approach is that the gas in star-forming regions is very dense resulting in rapid cooling and consequently most of the SN energy is rapidly radiated away. A solution is to turn off cooling for a time period Δt to allow the thermal pressure to disperse the gas.

2. **Kinetic feedback:**

- A fraction $\varepsilon_{SN} \leq 1$ of the SN energy is given to neighbouring gas particles in form of kinetic energy, the wind velocity has to be put in by hand. A problem is that the star-forming gas is dense preventing gas from escaping to large distances. A solution would be to turn off the hydrodynamics for wind particles for a time period Δt to allow the kinematic motion to disperse the gas.

Rayleigh-Taylor instabilities

- Realistic supernova winds are subject to Rayleigh-Taylor instabilities.
- This instability arises when lower density gas pushes higher density gas, i.e. when a hot bubble tries to disperse a shell of dense cold gas.
- Rayleigh-Taylor fingers appear that ultimately allow the hot gas to escape.
- If galactic winds consist of hot bubbles pushing shells of cold material outwards, mass loading factors are naturally restricted to $\eta \leq 1$.



Rayleigh-Taylor fingers in the Crab nebula supernova remnant.

What have we learned?

1. At high gas densities (Σ_{gas}>10 $M_{\odot}pc^{-2}$) conditions are such that self-shielding becomes important, and molecular gas forms.
2. GMCs are supported by supersonic turbulence and turbulent compression creates clumps and cores that are Jeans unstable.
3. Energy and momentum injection due to the star formation process itself is likely to be an important regulator of the star formation efficiency in GMCs.
4. Supernova feedback is an essential ingredient in galaxy formation models. It helps explaining why the star formation efficiency overall is low and why galaxy formation if less efficient in lower mass haloes. In the numerical modelling of supernova feedback many challenges still remain.