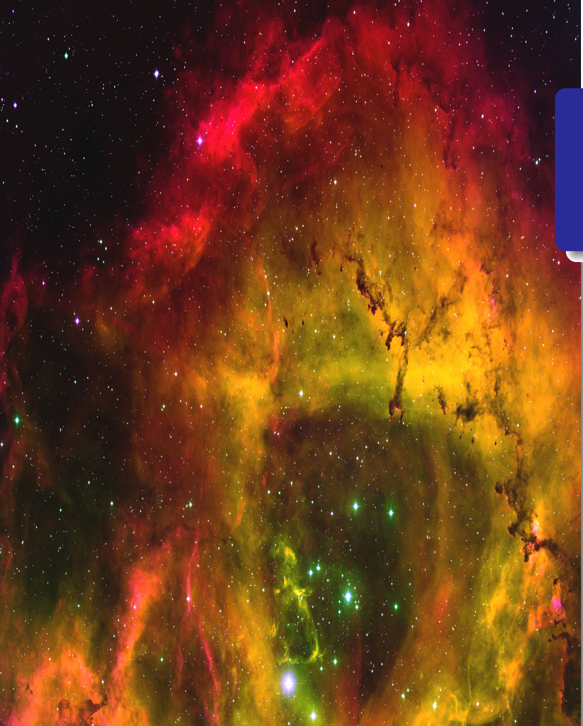


The Turbulent Interstellar Medium

Giuseppe Di Bernardo

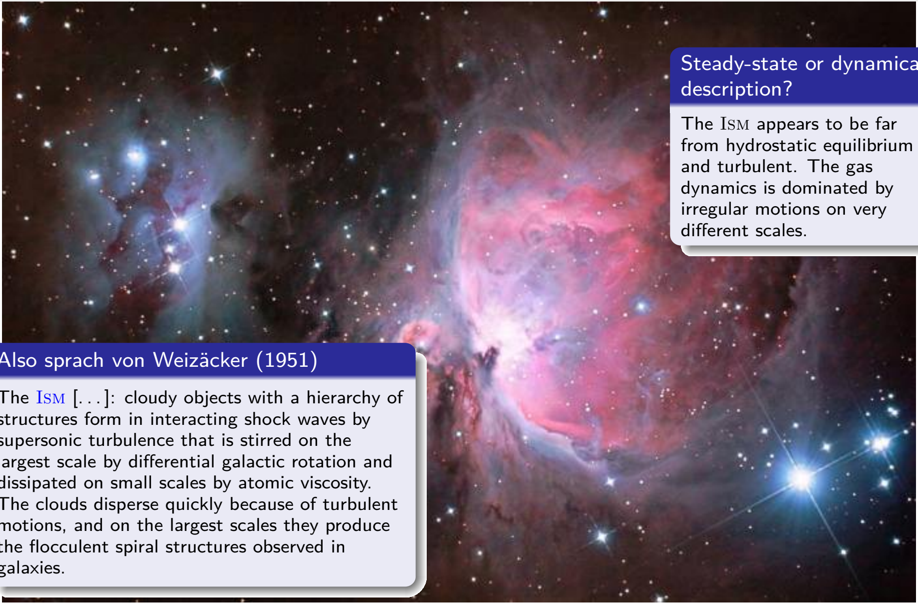
Coordinator:
Prof. Alessandro B. Romeo
University of Gothenburg
giuseppe.dibernardo@physics.gu.se

Göteborg, Dec 09, 2010

Steady-state or dynamical description?

The ISM appears to be far from hydrostatic equilibrium and turbulent. The gas dynamics is dominated by irregular motions on very different scales.

The Interstellar Medium
What is it ?



Steady-state or dynamical description?

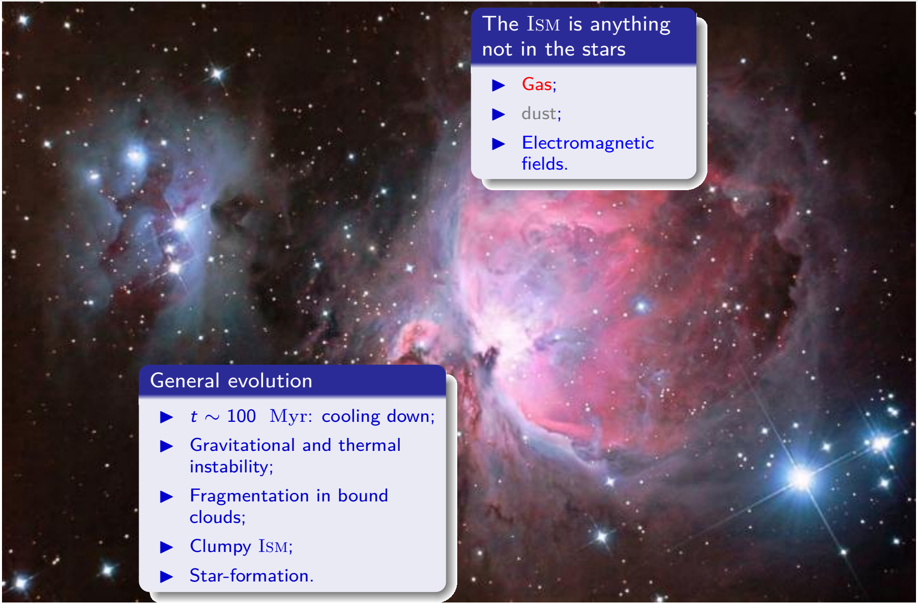
The Ism appears to be far from hydrostatic equilibrium and turbulent. The gas dynamics is dominated by irregular motions on very different scales.

Also sprach von Weizäcker (1951)

The Ism [. . .]: cloudy objects with a hierarchy of structures form in interacting shock waves by supersonic turbulence that is stirred on the largest scale by differential galactic rotation and dissipated on small scales by atomic viscosity. The clouds disperse quickly because of turbulent motions, and on the largest scales they produce the flocculent spiral structures observed in galaxies.

- Brief review of main aspects of ISM
  - physics of ISM
  - turbulence
- The driver of ISM turbulence
  - work of Agertz *et al.* 2009
- Conclusions

The Physics of ISM
The overall picture



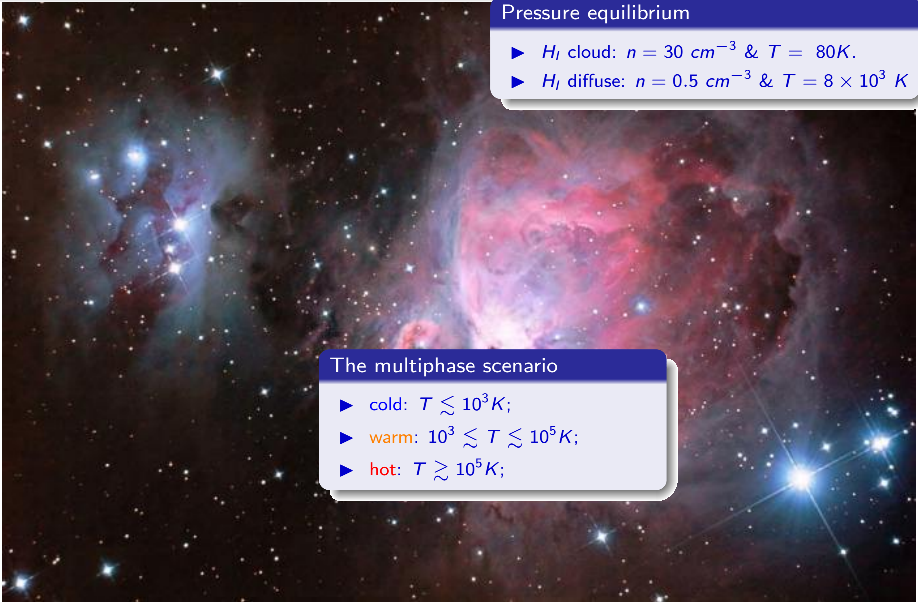
The ISM is anything not in the stars

- Gas;
- dust;
- Electromagnetic fields.

General evolution

- $t \sim 100\ \mathrm{Myr}$: cooling down;
- Gravitational and thermal instability;
- Fragmentation in bound clouds;
- Clumpy ISM;
- Star-formation.

The Physics of ISM
The overall picture



Pressure equilibrium

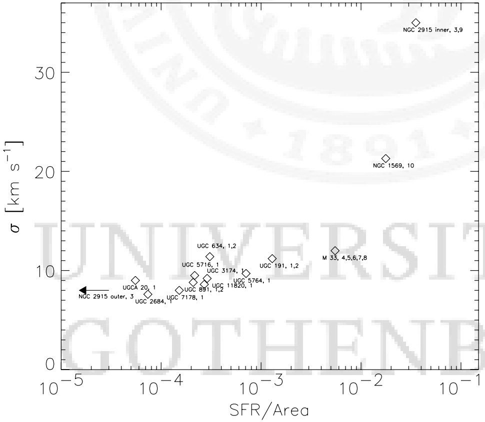
- H_I cloud: $n = 30\ cm^{-3}$ & $T = 80K$.
- H_I diffuse: $n = 0.5\ cm^{-3}$ & $T = 8 \times 10^3\ K$

The multiphase scenario

- cold: $T \lesssim 10^3 K$;
- warm: $10^3 \lesssim T \lesssim 10^5 K$;
- hot: $T \gtrsim 10^5 K$;

Turbulence in the diffuse ISM

- Irregular/turbulent gas motions;
- $f(v) = (1/\sigma\sqrt{2})\exp\left[-(1/2\sigma^2)(v - v_0)^2\right]$: H_I line profiles;
- $\sigma \sim 10\ \mathrm{km\ s^{-1}}$: not only thermal broadening.



Turbulence in the diffuse ISM

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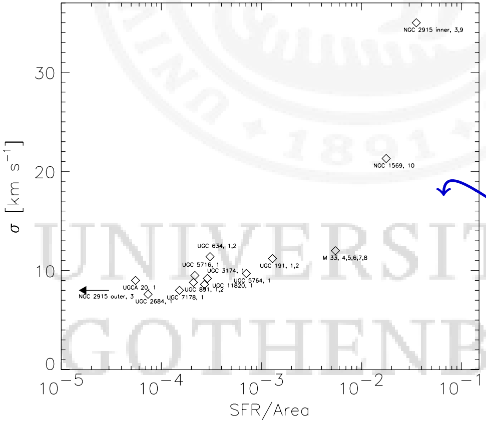


Typical velocity dispersions (see Dib *et al.*, 2006)

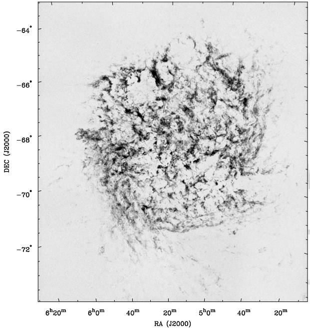
- Transition into active/starbursting galaxies;
- $\sigma \sim 12 \div 15\ \mathrm{km\ s^{-1}}$ in the inner regions, and $\sigma \sim 4 \div 5\ \mathrm{km\ s^{-1}}$ in the outer parts.
- small scale ($< 0.7\ \mathrm{kpc}$) bulk motions.

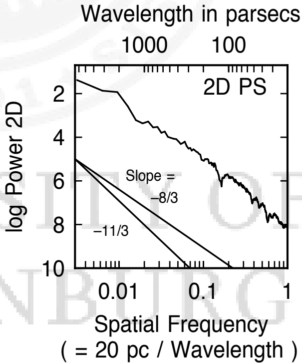
21 cm H_I in LMC

- H_I holes, filaments, shell and superbubbles;
- which origins ? SW, SNE ...;
- only a weak sign of ongoing stellar activity;
- ISM turbulence, thermal and gravitational instabilities ? (see e.g., Dib & Burkert, 2005).

$P(k)\ d^2k$ in LMC

- transfer of energy over 2 decades in lenght;
- $P(k) \propto k^{-3}$: good fit;
- Is it a 2D Kolmogorov spectrum ($P(k) \propto k^{-8/3}$) ?





The Basic Fluid Equations

Main ingredients of fluid equations

- $\mathbf{f}$: force per unit mass, due to e.g. self-gravity and magnetism $\rightarrow$ Poisson and induction equations;
- $\overleftrightarrow{\pi}$: shear-stress tensor;
- $-\frac{1}{\rho}(\nabla\cdot\overleftrightarrow{\pi}) \rightarrow \nu[\nabla^2\mathbf{u} + \nabla(\nabla\cdot\mathbf{u})/3]$, $\nu \sim 10^{20} c_5/n$ is the kinematic viscosity;
- ρ, P: $\rightarrow P \sim \rho^\gamma$ EoS.

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0$$

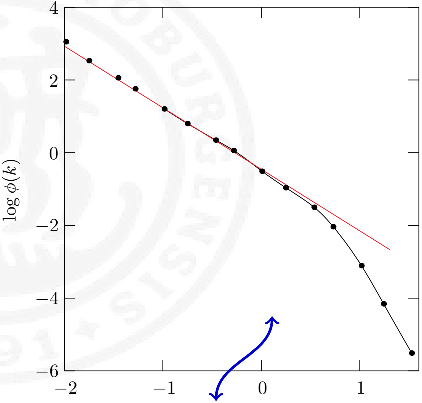
$$\frac{\partial \mathbf{u}}{\partial t} + \underbrace{(\mathbf{u}\cdot\nabla)\mathbf{u}}_{advective\ term} = -\frac{1}{\rho}\nabla P + \mathbf{f} + \underbrace{\frac{1}{\rho}\nabla\cdot\overleftrightarrow{\pi}}_{viscous\ term}$$

Several ways of solving the Navier-Stokes equatons

- analytically: a little bit difficult;
- AMR hydrodynamics codes: (e.g `RAMSES`, `PENCIL`, etc.) try to perform a more realistic multiphase ISM, in which one can disentangle the various contributing effects.

Power (large-scale) sources for ISM turbulence

- stellar origin: expanding H_{II} regions, stellar winds or SNe: unable to explain all H_I data;
- galactic rotation: shear coupled to gravitational and thermal instability;
- magnetorotational instability: significant in outer part of galaxies.



The Kolmogorov scaling relations

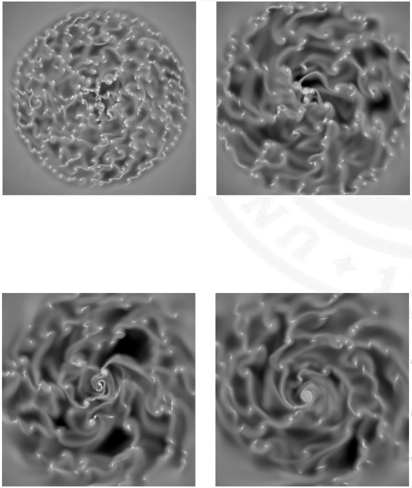
- $(\mathbf{u}\cdot\nabla)\mathbf{u}$: distorsions of the velocity field (*eddies*);
- Reynolds number: $R_e = \mathcal{U}\mathcal{L}/\nu \sim 3\times 10^3 M_a L_{pc} n$;
- Onset of turbulence: $R_e \gg 1$;
- Energy cascade process: $\dot{\varepsilon} \sim (u_l/l)^3$;
- Kolmogorov's law: $u_l \sim \mathcal{U}(l/\mathcal{L})^{1/3}$;
- *incompressible flows.*

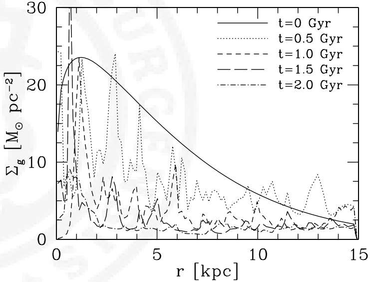
The inertial range

The energy fed into the largest eddies ($\mathcal{L}$) is progressively transferred via nonlinear interactions to eddies of smaller and smaller scale (l). The energy is dissipated at Reynolds scale l_ν at which the viscous terms exceed the advective one.

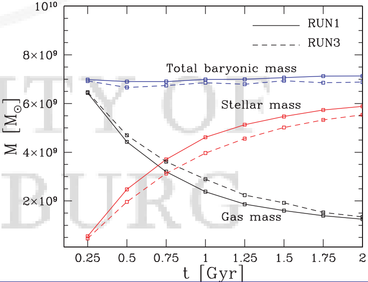
Results of Numerical Simulations

The simulated galaxy (see Agertz, O., *et al.* Mon. Not. R. Astron. Soc. **392**, 294-308, (2009))

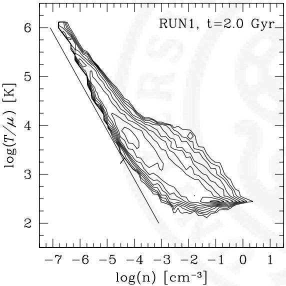




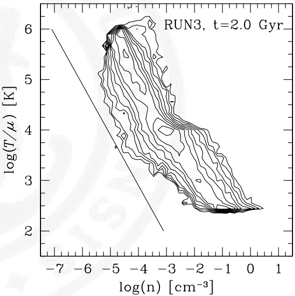
t=0 Gyr
t=0.5 Gyr
t=1.0 Gyr
t=1.5 Gyr
t=2.0 Gyr
Σ_g [$M_\odot$ pc^{-2}]
0
10
20
30
0
5
10
15
r [kpc]



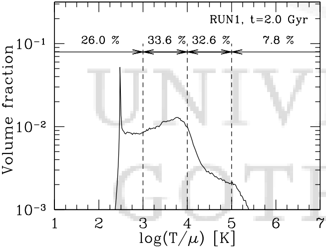
RUN1
RUN3
Total baryonic mass
Stellar mass
Gas mass
10^{10}
8×10^9
6×10^9
4×10^9
2×10^9
M [$M_\odot$]
0.25
0.5
0.75
1
1.25
1.5
1.75
2
t [Gyr]



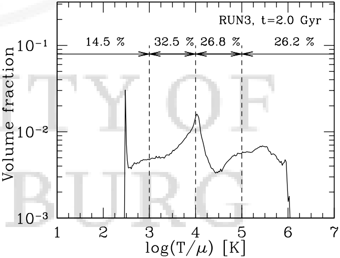
RUN1, t=2.0 Gyr
log(T/μ) [K]
log(n) [cm⁻³]



RUN3, t=2.0 Gyr
log(T/μ) [K]
log(n) [cm⁻³]



RUN1, t=2.0 Gyr
26.0 %
33.6 %
32.6 %
7.8 %
Volume fraction
log(T/μ) [K]



RUN3, t=2.0 Gyr
14.5 %
32.5 %
26.8 %
26.2 %
Volume fraction
log(T/μ) [K]

Local Stability of Differntial Rotating Disks.

- dispersion relation: $\omega^2 = \kappa^2 - 2\pi G\Sigma|k| + \sigma^2 k^2$;
- neutral stability: $\omega^2 = 0$;
- longest unstable wavelength in a zero-pressure disk: $\lambda_T = 4\pi G\Sigma/\kappa^2$;
- Toomre's stability criterion: $Q = \kappa\sigma/\pi G\Sigma > 1$.

Toomre's Q serves as a thermometer for galactic disks!

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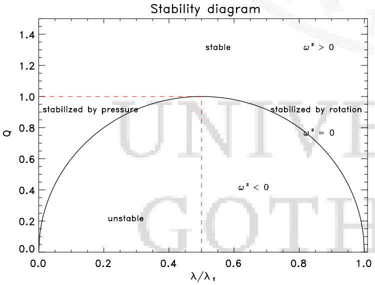

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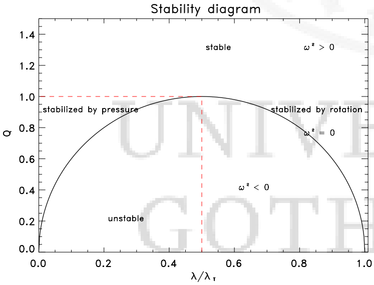

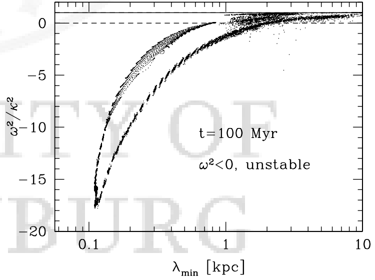

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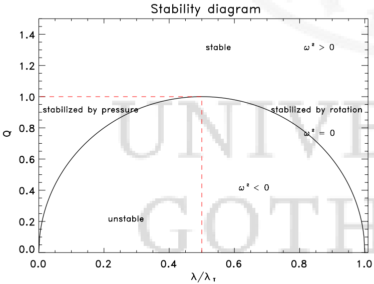
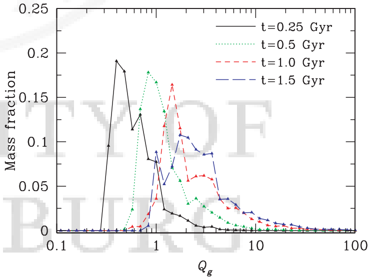
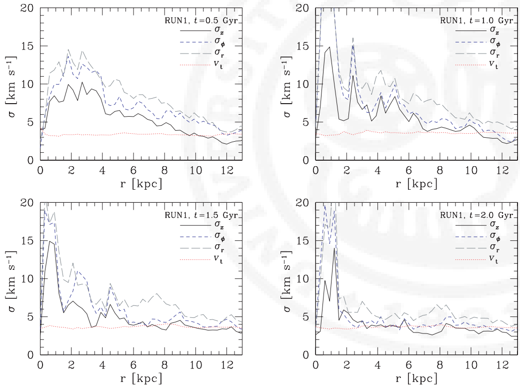




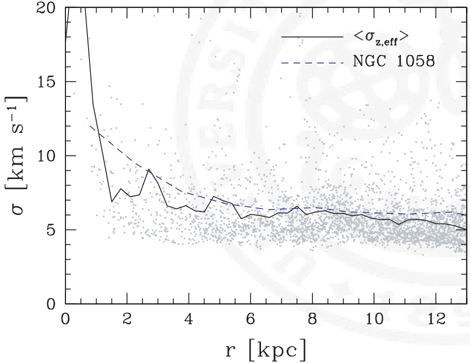
Results of Numerical Simulations
The velocity dispersions



Simulated velocity dispersions of the H_I gas (see Agertz, O., Mon. Not. R. Astron. Soc. 392, 294-308, (2009)).

- black solid line: vertical (σ_z) component;
- black dashed line: angular (σ_ϕ) component;
- black long-dashed line: radial (σ_r) component;
- red dotted line: thermal (v_t) component.

- Time evolution of radial behaviour of the velocity dispersion.
  - simulated velocity dispersions are comparable with observational data;
  - anisotropic velocity dispersion;
  - the thermal velocity becomes important as the turbulent at large radii.

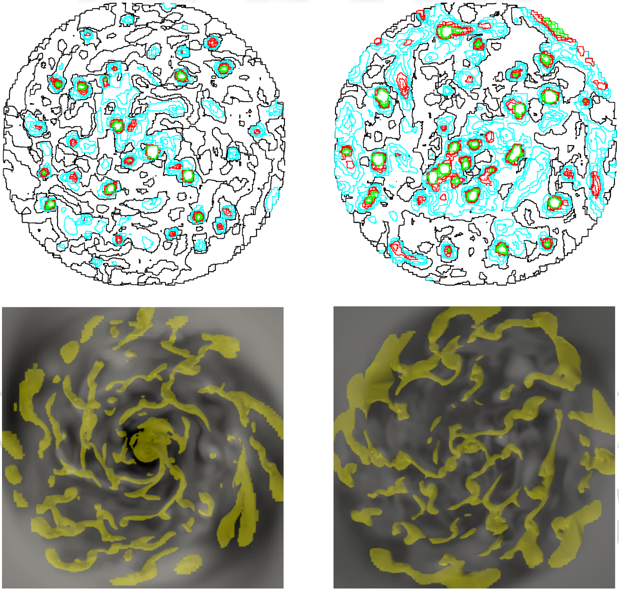


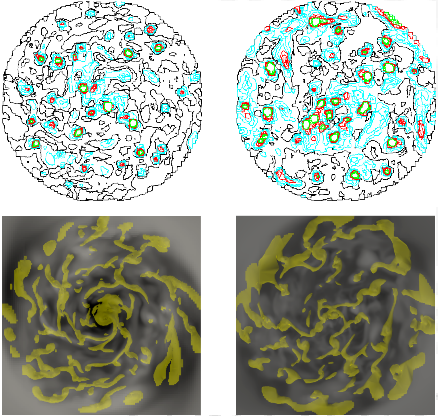
Comparison between simulations and the H_I data of the spiral galaxy NGC 1058 (see Agertz, O., Mon. Not. R. Astron. Soc. 392, 294-308, (2009)).

- black solid line: effective vertical dispersion ($\sigma_{z,eff}$) at $t = 1.5$ Gyr, computed numerically;
- blue dashed line: observed velocity dispersion of the face-on NGC 1058;
- gray dots: measured velocity dispersions in NGC 1058 (patchy peaks of $\sigma > 10$ km s^{-1}).

- Numerical simulation not only reproduces the magnitude of the velocity dispersion but also the declining radial shape.
  - NGC 1058 is comparable in size, surface density and peak rotational velocity to the simulated disc;
  - NGC 1058 is almost face-on galaxy ($i \sim 4^o \div 11^o$): it's possible to disentangle the vertical component from the planar;
  - NGC 1058 has a low SFR ($\sim 3.5 \times 10^{-2}$ $M_\odot$ yr^{-1}): no SNe feedback

Results of Numerical Simulations
The spatial distribution of vertical velocity dispersion

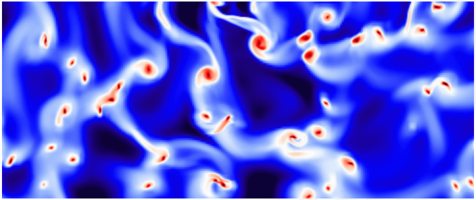




Contour levels of vertical velocity ($\mathrm{km\ s^{-1}}$; top panels) and density fields ($n > 0.2\ cm^{-3}$; bottom panels), calculated for the H_I gas.

- black contour: $\sigma_{z,eff} \sim 3 \div 5\ \mathrm{km\ s^{-1}}$;
- cyan contour: $\sigma_{z,eff} \sim 6 \div 8\ \mathrm{km\ s^{-1}}$;
- red contour: $\sigma_{z,eff} \sim 9 \div 11\ \mathrm{km\ s^{-1}}$;
- green contour: $\sigma_{z,eff} \sim 12 \div 14\ \mathrm{km\ s^{-1}}$.

- The high-density gas is distributed in a flocculant spiral structure.
  - the strongest peaks ($\sigma_{z,eff} > 10\ \mathrm{km\ s^{-1}}$) are associated with dense clouds;
  - mildly turbulent regions ($\sigma_{z,eff} \sim 6 \div 8\ \mathrm{km\ s^{-1}}$) correspond to intercloud/arm regions (strong shear).

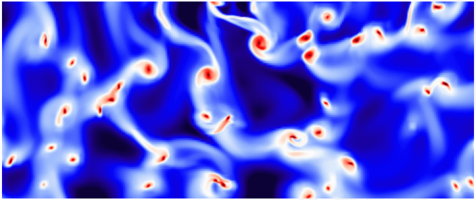


Gravity coupled with shear

- wide spectrum, by mass, of Q_g;
- $Q_g \sim 1.2$: marginal stable value ($\sigma \sim c_s$, Kim & Ostriker 2007);
- for $Q_g \gtrsim 1.2$: swing amplified turbulence;
- for $Q_g < 1$: full non-linear gravitational instability.

- In marginally stable disks ($Q_g \gtrsim 1.2$) the origin of turbulence is due to SWING amplification (Goldreich & Lynden-Bell, 1965).
  - spectrum of waves with intermediate levels of turbulence ($\sigma_{z,eff} \sim 6 \div 8 \ \mathrm{km\ s^{-1}}$);
  - a useful parameter: $X = (k_{crit} r / m)$, where $k_{crit} = \kappa^2 / 2\pi G \Sigma$;
  - $Q_g \gtrsim 1.2$ and $1 < X < 3 \rightarrow$ swing amplification;
  - in multicomponent disks ($m \gtrsim 4$) the swing amplification is very effective $\Rightarrow$ flocculant spiral structure !

What is the driver of ISM turbulence ?
Gravity and shear: goodfellas!



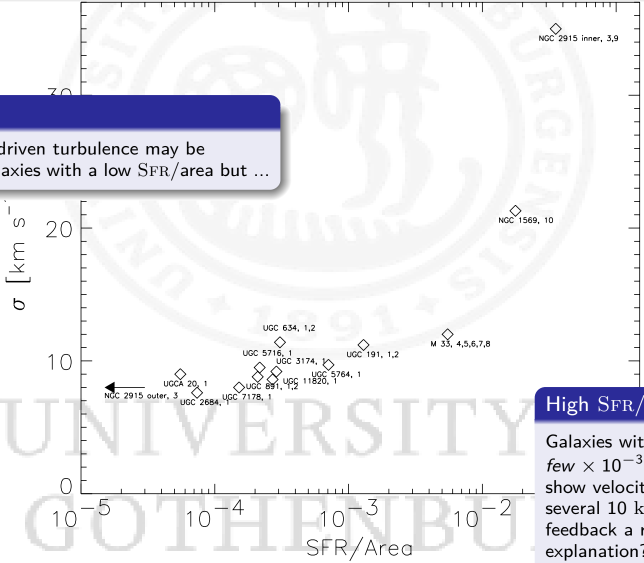
Coupling between gravity and shear

- wide spectrum, by mass, of Q_g;
- $Q_g \sim 1.2$: marginal stable value ($\sigma \sim c_s$, Kim & Ostriker 2007);
- for $Q_g \gtrsim 1.2$: swing amplified turbulence;
- for $Q_g < 1$: full non-linear gravitational instability.

- In completely unstable disks ($Q_g < 1$) the cold ($T \lesssim 10^3 K$) phase dominates the mass gas.
  - cloud as main local perturbers;
  - cloud merging and tidal interactions: stirring of the inter-cloud medium;
  - warm phase of ISM regulated by energy dissipation in shocks: $v_t \sim 4 \div 5 \text{ km s}^{-1}$;
  - shearing environment: wave and filaments associated with clouds;
  - leading waves excited by clouds: swing amplification.

What is the driver of Ism turbulence ?

We have still not a definite answer

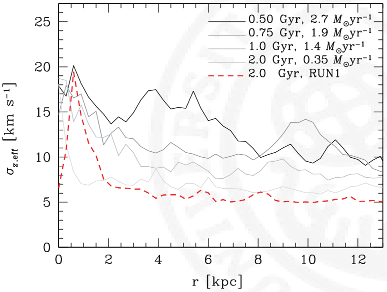


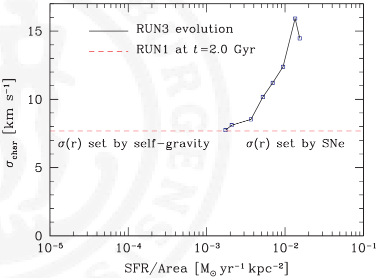
Low Sfr/area

The self-gravity driven turbulence may be important for galaxies with a low Sfr/area but ...

High Sfr/area

Galaxies with Sfr/area $\geq$ *few* $\times\, 10^{-3} M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$ show velocity dispersion of several 10 $\mathrm{km\ s}^{-1}$ $\rightarrow$ Is SNe feedback a reasonable explanation? (see Dib *et al.* 2006)





- The SN feedback could explain the transition into high SFR/area region:
  - the SFR decreases with time;
  - a lower stellar activity lowers the velocity dispersion;
  - at $t \sim 1.5$ Gyr the effect of SN feedback has saturated;
  - SFR/area $\sim 1 \div 2 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$ is the transition point;
  - Agertz *et al.* 2009 achieved a good agreement with the value observed for NGC 1058.

Conclusions

- A turbulent ISM naturally develops due to the coupling between gravitational instability and shearing motions. A multiphase medium develops in which cold dense clouds and filaments co-exist with a diffuse warm gas. When SNe feedback is implemented, a hot phase is present;
- At $SFR \leq 10^{-3} M_{\odot} yr^{-1}$ the gravity can provide alone the energy source for maintaining the observed level turbulence in the ISM of galaxies;
- At $SFR \geq 10^{-3} M_{\odot} yr^{-1}$ the SNe feedback becomes the dominant driver of the turbulence and the velocity dispersion increases with SFR;
- Thank you for attention.

Tack och hej . . .

UNIVERSITY OF GOTHENBURG