Gravitational collapse in a turbulent ISM.

Juan C. Ibáñez-Mejía

collaborators:
Mordecai-M. Mac Low (AMNH)       Ralf S. Klessen (ITA)
Christian Bazcynski (ITA)         Andrea Gatto (MPA)
Outline

• Introduction to computational astrophysics

• Introduction to star formation
  • Who controls star formation?
  • Giant molecular clouds and the environment

• The stratified box model

• Results
  • Cloud properties & 1D statistics
  • Tracking clouds & Accretion rates.
  • New parameterized low temperature cooling.

• Conclusions
Introduction

Computational Astrophysics.
lets talk about beer
So astronomy is like drinking beer.

**Beer**

- $T = 290\; \text{K}$
- $\lambda \sim 10\; \text{nm}$
- $s = 10\; \text{cm}$
- $s/\lambda \sim 10^7$
Introduction

Astronomy, beer and the fluid approximation

Beer
T = 290 K
\( \ell \sim 10 \text{ nm} \)
\( s = 10 \text{ cm} \)
\( s/\ell \sim 10^7 \)

molecular cloud
n = 100 cm\(^{-3}\)
T = 10 K
\( \ell \sim 10^{-6} \text{ pc} \)
\( s = 10 \text{ pc} \)
\( s/\ell \sim 10^7 \)

Orion Nebula, infrared image from WISE. Credit: NASA/JPL/Caltech

Youxue Zhang and Zhengjiu Xu 2008

Champagne flows in HII regions
Introduction

Why use a computational approach?

• Astronomy doesn't really have an experimental department, we can not create planets, stars, galaxies in a laboratory.

• We can turn on and off physics at our own discretion.

• Most of the astrophysical observations give us a snapshot in time and the time evolution of a system has to be reconstructed with statistics.

• We observe the universe in 2D.
Eulerian & Lagrangian codes

Mass conservation
\[ \left( \frac{\partial}{\partial t} + v \nabla \cdot \right) \rho = \frac{d}{dt} \rho = -\rho \nabla \cdot v \]

Momentum conservation
\[ \left( \frac{\partial}{\partial t} + v \nabla \cdot \right) \rho v = \frac{d}{dt} \rho v = -\nabla P + \rho g \]

+ conservation of energy + equation of state

Euler - Discretizes Space

\( v_y, b_y \)

\( T, \rho \)

\( v_x, b_x \)

Lagrange - Discretizes Mass

Credit: Volker Springel “High performance computing and numerical modeling” lecture
Eulerian & Lagrangian codes

Mass conservation

\[
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Euler - Discretizes Space

\[\text{v} \quad \text{v} \quad \text{T,} \quad \text{v} \quad \text{v}\]

Lagrange - Discretizes Mass

\[\text{Smoothing kernel}\]
Eulerian & Lagrangian codes

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Note: I am only referring to two implementation of numerical hydrodynamics codes. There are many more codes specialized for different problems.

- Spectral codes
- N-body codes
- Fluid solvers
- and many more …
Introduction

Grid & SPH codes Examples

Eulerian

Lagrangian
Introduction

New Generation of codes

- Arepo
- Gizmo
Introduction

Star formation theory
Introduction

Multi-scale & Multi-physics Process

M51, NASA and the Hubble Heritage Team

NGC 602 (Hubble)

HH 901, Carina Nebula (Hubble)

Sun (SOHO)

Spatial Scales

- Spiral galaxy: few 10s kpc
- Molecular clouds: few 10s - 100 pc
- Young cluster: \(~1\) pc
- Sun: \(~5 \times 10^{-9}\) pc

Density

- Interstellar medium: few particles per cm\(^3\)
- Molecular clouds: \ (~100s\) particles per cm\(^3\)
- Sun: \ (~1\) g/cm\(^3\)
Multi-scale & Multi-physics Process

Introduction

M51, NASA and the Hubble Heritage Team

NGC 602 (Hubble)

HH 901, Carina Nebula (Hubble)

Sun (SOHO)

- Smaller Scales
- Higher density

- Contracting Forces
  - Gravity

- Competing Forces
  - Thermal pressure
  - Turbulence
  - Magnetic Fields
  - Radiation pressure
  - Shear
The Model
Our Model

- **Physics included**
  - Static gravitational potential (Gas + Stars + DM).
  - Random & correlated supernova (SN & SB).
  - Parameterized heating & cooling.
  - Ideal magnetic fields.
  - Self-gravity.

- **Missing Physics**
  - Star Formation.
  - Wind & radiative feedback.
  - Rotation & shear.
Basic assumptions

Heating and Cooling the ISM.

Cold & Warm

Hot

Dalgarno & McCray 1972

Sutherland & Dopita 1993
Basic assumptions

Heating and Cooling the ISM.

Cold & Warm

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Dalgarno & McCray 1972

Sutherland & Dopita 1993
Heating and Cooling the ISM.

Basic assumptions

Cooling processes:
- Metal line cooling.
- Ly alpha cooling
- C+ fine structure cooling.

Heating processes:
- Photoelectric emission from dust $T < 10^4$ K.
- PdV work and shock heating

Net cooling:

$$n\Gamma - n^2\Lambda$$
Self-gravitating turbulent ISM

Developing the turbulent initial conditions.
Generating a turbulent ISM
The Action of Self Gravity
Self-gravity and power law tails.

$\frac{dV}{V}$

$t_{SG} = 4 \text{ Myr}$

Volume fraction $\frac{dV}{V}$

Column density $[\text{cm}^{-2}]$

Non-star-forming clouds

Star-forming clouds

Kainulainen et al 2009

Extracting the cloud catalog
Cloud definition

- Connected contours above a number density cut of 50 cm$^{-3}$
- Minimum 20 cells across. Min Mass of 250 $M_{\text{sun}}$
Mass distribution - My cloud catalog

Cloud mass Distribution

- $t_{SG} = 0$ Myr
- $t_{SG} = 4$ Myr

Number

$\log_{10}(\text{Mass})\,[M_{\odot}]$
Early Results

Cloud tracking

Cloud Following: Standard case

- Search radius
- Real Position $t_1$
- Predicted Position $t'_1$
- Tag 01
- Tag 11
- Mother 01
- Cloud $t_0$

Cloud Following: Merger

- Search Radius 02
- $t_2$
- Tag 07
- Tag 21
- Mother 01
- Mother 07
- $\Delta d$

Cloud Following: Formation

- No Mother cloud
- Tag 01
- Inmaculate conception

Cloud Following: Dissipation

- Search radius
- No cloud found
- Tag 02
- Tag 32
- Cloud $t_4$
- Tag Replacement
Early Results

Accretion rates

![Accretion rates graph](image-url)
Accretion rates

Accreted mass fractions per free fall time

\[ \int_{t_{\text{ff}}}^{t_{\text{ff}}'} \frac{\dot{M}}{M_0} \, dt \]

\[ M_0 [\text{Msun}] \]
Accretion rates - catching up with collapse.

Results
Early Results

Accretion rates - Environmental effects

$t_{ff} \gg 5 \text{ myr}$

$t_{ff} \sim 5 \text{ myr}$
Early Results

Accretion rates - Environmental effects

\( t_{ff} \gg 5 \text{ myr} \quad t_{ff} > 5 \text{ myr} \quad t_{ff} \sim 5 \text{ myr} \)
Cooling the warm & cold phases of the ISM
Heating and cooling the cold gas

Figure 30.1 Physics of the interstellar and intergalactic medium. Draine
Basic assumptions

Structure of the ISM - Density

New parameterized cooling curve

Old cooling curve
Basic assumptions

Structure of the ISM - Temperature

New parameterized cooling curve

Old cooling curve
Basic assumptions

Structure of the ISM - Phase Plots

New parameterized cooling curve

Old cooling curve

$log_{10}$ (number density) [cm$^{-3}$]

$log_{10}$ (Temperature) [K]
Limitations of our model

- Missing physics:
  - Self consistent star formation and correlated stellar feedback.
  - Radiation transport.
  - Galactic rotation and shear.
  - Non-equilibrium chemistry evolution.
  - Proper cosmic rays.
  - Intergalactic gas accretion.
  - Thermal conduction.
  - non-ideal MHD.
  - and more
Conclusions

- Numerical simulations are an amazing tool to study the physical processes in astrophysics.
- Different numerical methods have different strengths, choose wisely depending on the problem you want to investigate.
- The model assumptions have a strong impact in your results, be careful not to over-interpret your results.

- Clouds formed in a multiphase, turbulent ISM interact with their environment exchanging a significant amount of energy and mass in short timescales.
- Self gravity is necessary to explain the mass distribution and physical properties of molecular clouds, as well as mass accretion rates.