OVERVIEW OF STAR FORMATION

- Motivations
- The problem
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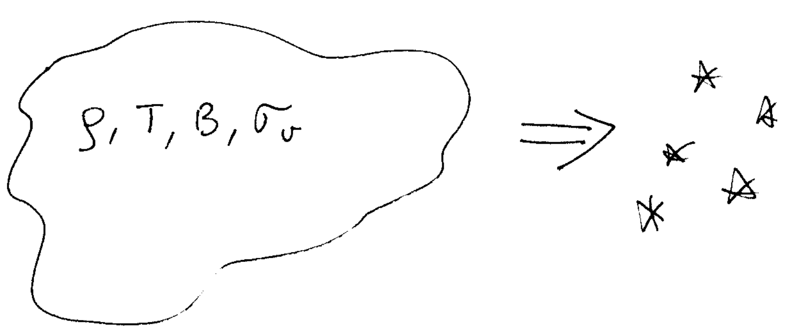
- Magnetically supported clouds
- Turbulent Fragmentation
- Current debates

Motivations

Stars provide :
- energy sources to the interstellar medium (winds, ionisation, supernovae)
- enrichment of heavy elements
- formation of planet
- re-ionization of the universe

The theoretical problem

gas exists in galaxies at a wide range of temperatures and densities. Stars are formed only in dense and cold gas → "dark clouds"



Rate of star formation
Mass distribution of stars

Gravitational Collapse

Under the force of its own gravity, a uniform sphere of gas, without any pressure support (very cold gas) collapses in a free-fall time:

$$\tau_{ff} = \sqrt{\frac{3\pi}{32\, G\, \rho}}$$

With the support of internal pressure, the sphere can collapse if the free-fall time is shorter than the sound crossing time:

$$\frac{R}{\sigma_{th}} \sim \tau_{ff}$$

Linear instability analysis (Jeans 1902):

$T = T_0$, $\rho = \rho_0$, $B = 0$, $u = 0$

Density perturbations $\Rightarrow \lambda_J = \left(\frac{\pi\, \sigma_{th}^2}{G\, \rho_0}\right)^{\frac{1}{2}}$ $\lambda > \lambda_J \rightarrow$ collapse

$M_J = \frac{4}{3}\pi \left(\frac{\lambda_J}{2}\right)^3 \rho_0 \sim \rho_0^{-\frac{1}{2}}\, T_0^{\frac{3}{2}}$ (Jeans mass)

What is the predicted stellar mass?

The answer depends completely on the initial density perturbations (like in Cosmology)

Example: If arbitrarily small perturbations are present, then you can get "gravitational fragmentation" down to a very small mass set by opacity (Hoyle 1953)

During the collapse, $\rho \nearrow \Rightarrow M_J \searrow$, if the temperature stays constant. The temperature is constant only if the cloud can radiate energy away faster than it gains from gravity:

$$4\pi R^2 \sigma T^4 > \frac{GM^2}{R\,\tau_{ff}} \quad \text{(assuming Black-Body radiation)}$$

One finds $m_{min} \simeq 0.01\,M_\odot$

Problems: - $m_{min} \ll$ most common stellar mass ($\sim 0.2\,M_\odot$)
- Clouds do not appear to collapse as a whole
- Clouds do not turn all their mass into stars in a time of order τ_{ff}

$\Rightarrow$ Gravitational fragmentation does not explain star formation.

We could consider magnetic support. The critical mass would then be defined by:

Magnetic Energy = Gravitational Energy

$$\frac{B^2}{8\pi}\,\frac{4}{3}\pi R^3 = \frac{3}{5}\,\frac{GM^2}{R} \quad \text{(uniform sphere)}$$

$$\Rightarrow M_{critical} = 0.168\,\frac{BR^2}{G^{1/2}}$$ (almost exactly the same for infinite sheet $\perp \vec{B}$)

So there is a critical value of the mass to flux ratio:

$$\left(\frac{M}{\Phi}\right)_{critical} = \frac{0.168}{G^{1/2}}$$

This can be reexpressed in terms of B and ρ:

$$M_{critical} \simeq 10^3\,M_\odot \left(\frac{n}{10^3\,cm^{-3}}\right)^{-2}\left(\frac{B}{30\,\mu G}\right)^3$$

(Mestel and Spitzer 1956)

But the fractional ionization is very low ($\sim 10^{-7}$), and ambipolar drift (Mestel and Spitzer 1956) can rapidly diffuse the magnetic energy out of the cloud.

So it is not clear that the magnetic critical mass defines a typical stellar mass.

Observational Constraints

Stars :
- Most common stellar mass : $\sim 0.2\, M_\odot$
- Power law mass distribution for $m > 1\, M_\odot$
- Most stars are clustered in space
- Low star formation efficiency : $SFE \equiv \frac{M_*}{M_{TOT}} \sim 0.01$

Star-forming clouds :
- Hierarchical distribution
- (example:) $10^6\, M_\odot$, $10\,K$, $M_J \simeq 3\, M_\odot$
- No large scale collapse $\Rightarrow SFR \ll \frac{M_{cloud}}{\tau_{ff}}$
- Large density fluctuations, filamentary
- Large B variations : $B \approx 10\mu G \left(\frac{n}{10^3 cm^{-3}}\right)^{\frac{1}{2}}$
- Supersonic random velocities:

$$E_K \gtrsim E_g >> E_{th}$$
$$\uparrow \qquad\qquad \uparrow$$
$$E_B \;?\quad E_B\;?$$
(Padoan, Nordlund 1999)

- Scaling of velocities :

$$\delta v(\ell) \simeq 1 \frac{Km}{s} \left(\frac{\ell}{1pc}\right)^{0.4}$$ (Larson 1981)
($1\,pc = 3\times 10^{18}\,cm$)

- Reynolds number $\sim 10^8$

$$Re = \frac{U_o L_o}{\nu} = 10^6 \left(\frac{U_o}{1Km/s}\right)\left(\frac{L_o}{1pc}\right)\left(\frac{n_o}{100\,cm^{-3}}\right)\left(\frac{T_o}{10K}\right)^{-\frac{1}{2}}$$

How do we predict properties of stars from cloud properties?

Magnetically Supported Clouds

The "traditional" picture of star formation focuses more on E_B than E_K. It assumes that star forming clouds are magnetically supported ($B \sim 30-100\,\mu G$).

The observed random velocities are interpreted as Alfvén waves:

$$\sigma_v \sim \sigma_A = \frac{B_0}{\sqrt{4\pi\rho_0}}$$

Clouds are not in free-fall. They evolve on a timescale set by ambipolar drift, τ_{AD}.

$$\tau_{AD} >> \tau_{ff} \Rightarrow \text{quasi-static evolution} \Rightarrow \text{low SFR}$$

But this picture offers no prediction of the stellar mass distribution, so it cannot be tested against the most important constraint.

Furthermore, the picture of quasi static evolution contradicts the very dynamic nature of clouds (the observed supersonic turbulence)

Turbulent Fragmentation

Since supersonic turbulence is so ubiquitous, and $E_K \gtrsim E_g >> E_{th}$, it cannot be neglected.

We need to understand supersonic magneto-hydrodynamic (MHD) turbulence in order to understand star formation.

But there is no general theory of turbulence!

How can we get a theory of star formation without a theory of turb.?

We don't need a general theory of turbulence (what's that anyway?). We only need to discover the statistics of u, ρ, B in supersonic turbulence, which can be achieved with the aid of large computer simulations.

Turbulence statistics are universal flow properties $\Rightarrow$ statistical theory of star formation.

then turbulence is a useful tool, rather than a complication.

$$\delta v(\ell) \simeq 1 \, \frac{km}{s} \left(\frac{\ell}{1pc} \right)^{0.4} \qquad (1pc = 3 \times 10^{18} cm)$$

$$\sigma_{th} \simeq 0.2 \, \frac{km}{s}$$ $\Rightarrow$ Highly supersonic velocity fluctuations on the scale of a cloud, 10 pc.

The turbulence appears to be fed on very large scale:

$$L_0 \gg L_{cloud} \gg \lambda_J$$

The motions are macroscopic; they cannot be viewed as a type of internal energy ~~to~~ providing support against the gravitational collapse.

The main effect of supersonic turbulence is to cause strong compressions through isothermal shocks:

$$HD: \ \rho/\rho_0 = M_s^2 \quad ; \quad MHD: \ \frac{\rho}{\rho_0} = M_A = \frac{v_{shok \perp B}}{v_A}$$

where the Alfvén velocity is $v_A = \frac{B}{\sqrt{4\pi\rho}}$.
Strong density contrasts and filamentary morphology of clouds is naturally explained.

What determines the typical stellar mass?

We must abandon the concept of M_{Jeans}, due to the strong nonlinearities.
An alternative way to compare pressure support and selfgravity, not based on linear instability analysis, is to consider the hydrostatic equilibrium of an isothermal sphere bound by an external pressure (Ebert 1955; Bonnor 1956):

$$M_{BE} \simeq \frac{\sigma_{th}^4}{G^{3/2} P_{th,0}^{1/2}} \simeq \frac{\sigma_{th}^3}{G^{3/2} \rho_0^{1/2}} \simeq 1 M_\odot \left(\frac{T}{10K}\right)^{3/2} \left(\frac{n}{10^3 cm^{-3}}\right)^{-1/2}$$

$$M_{BE} \simeq M_J/2.47 \quad ; \quad \rho_{center} \simeq 14 \rho_{surface}$$

This is the largest stable mass (or density contrast).

This is a nonlinear configuration, and, more importantly, it allows to distinguish between internal support and external pressure.

We can model the turbulent compressions as a source of external dynamical pressure, and use M_{BE} to estimate the typical stellar mass in the presence of supersonic turbulence:

$$P_0 = P_{th,0} + P_{dyn,0} \simeq P_{dyn,0} \simeq \rho_0 \sigma_v^2$$

$$\Rightarrow M_{BE,t} \simeq \frac{\sigma_{th}^4}{G^{3/2} P_{dyn,0}^{1/2}} = \left(\frac{\sigma_{th}^3}{G^{3/2} \rho_0^{1/2}} \right) \left(\frac{\sigma_{th}}{\sigma_v} \right)$$

$$M_{BE,t} = M_{BE} \mathcal{M}_s^{-1} \simeq 0.2 \; M_\odot$$

which is the observed value of the most common stellar mass, and makes a prediction for its dependence on physical parameters.

Why a range of stellar masses?

Why a power law mass distribution $> 1 M_\odot$?

Turbulence is a scale-free process for scales, ℓ, within the inertial range: $\eta < \ell < L_0$, where η is the Kolmogorov dissipation scale (where turbulent motions are dissipated into heat by viscosity) and L_0 is the outer scale of the turbulence (roughly speaking the scale where the energy is injected).

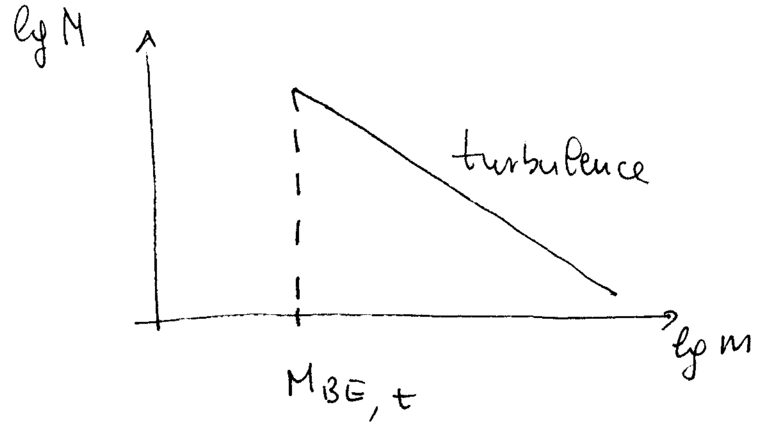
In star-forming clouds:

$$\begin{cases} \eta \lesssim 10^{13} \text{ cm} \\ L_0 \gtrsim 100 \text{ pc} \simeq 3 \times 10^{20} \text{ cm} \end{cases} \qquad \begin{cases} L_{cloud} \simeq 10 \text{ pc} = 3 \times 10^{19} \text{ cm} \\ r_{BE} \simeq 0.1 \text{ pc} \simeq 3 \times 10^{17} \text{ cm} \end{cases}$$

$\Rightarrow$ Star formation is within the inertial range of turbulence

Scale-free physics $\Rightarrow$ Power law mass distribution

One can work out the mass distribution from the scaling of velocity fluctuations (velocity power spectrum or velocity structure function) under some assumptions. For example, assuming that protostars are pieces of postshock sheets, so their size scales like the thickness of the postshock sheets, one derives a mass range that covers all stellar masses ($0.01 - 100\ M_\odot$), simply from the inertial range velocity fluctuations with $\delta v > \sigma_{th}$.



But the cutoff cannot be so sharp, because the P_{dyn} has strong fluctuations in the turbulent flow.

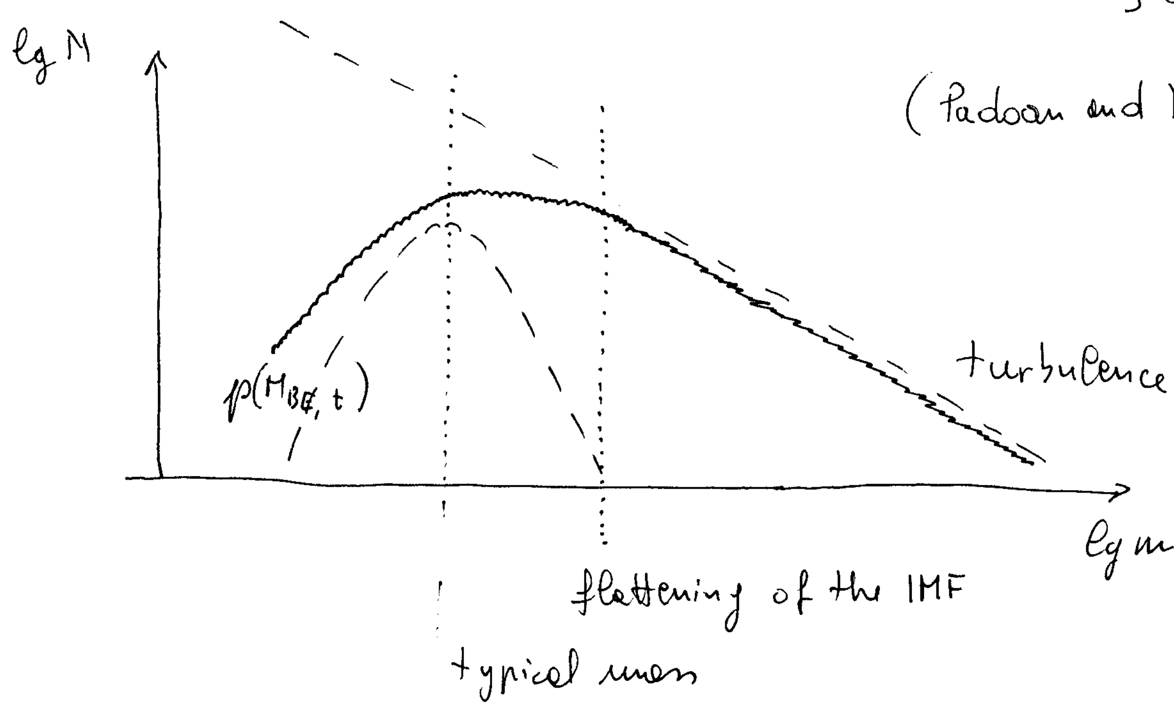
To estimate the distribution of $M_{BE,t}$, we can use the probability density function (pdf) of gas density, which is the direct consequence of the dynamic pressure of the turbulence.

We know from numerical simulations and from first principles that the pdf of density is a Lognormal, with standard deviation depending only on the rms Mach number (isothermal E.O.S.).

We can therefore derive the distribution of $M_{BE,t}$ from the distribution of ρ, if we define $M_{BE,t}(\bar{x})$ in analogy to M_{BE}:

$$M_{BE} = \frac{\sigma_{th}^3}{G^{3/2}\rho_0^{1/2}} \longrightarrow M_{BE,t}(\bar{x}) = \frac{\sigma_{th}^3}{G^{3/2}\rho(\bar{x})^{1/2}}$$

(Padoan and Nordlund 2002)



Why low star formation efficiency?

At any given time, only a small fraction of the mass is in regions dense enough and with little enough turbulence that they can collapse. These are regions of stagnation of the flow, behind shocks or intersections of shocks. The rest is moving around and cannot collapse ($E_K \gtrsim E_g$).

"Star formation as the process of turbulence dissipation (followed by gravitational collapse) in a supersonic flow"

Universal statistics of turbulence (velocity scaling, pdf of ρ_{gas})
$\Rightarrow$ Statistical theory of star formation

Current debates

- Magnetic Field Strength (observations + theory)
- Lifetime of Clouds and SFR (observations)
- Turbulence driving mechanism (observations + theory)
- Origins of the smallest stars (theory)
- Origins of the largest stars (theory)

(Thankyou for reading this)