An evolutionary model for the Star Formation Rate and Efficiency in collapsing Molecular Clouds.

Manuel Zamora-Avilés, Enrique Vázquez-Semadeni & Pedro Colín

Centro de Radioastronomía y Astrofísica, UNAM, Campus Morelia, México.

ABSTRACT: **We present a semi-analytical model for the regulation of the Star Formation Rate (SFR) and Efficiency (SFE) in a Giant Molecular Cloud (GMC) undergoing global gravitational collapse, rather than supported by any agents. The SFR regulation is accomplished by erosion of the cloud caused by massive-star feedback. The behavior of the model is shown to correctly reproduce 1) the physical properties of the OMC-1 molecular cloud; 2) the stellar age dispersion in clusters; 3) the location of individual molecular clouds in the Kennicutt-Schmidt diagram; 4) the age/mass sequence of GMCs in the LMC, and 5) the SFR-mass relationship for dense gas in external galaxies.**

I. The General Model.

We assume that the cloud is formed by the collision of two cylindrical streams (Fig. 1). The newly formed cloud begins to collapse and to form stars. The most massive of these ionize part of the cloud through HII regions. Fig. 2 is a sketch of the competition between accretion and consumption of the cloud by star formation (SF) and ionization.

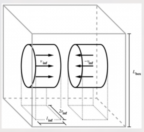


Fig. 1: Model used in Vázquez-Semadeni et al. 2007.

The evolution equation for the cloud's mass is:

$$M_C(t) = \int_0^t \dot{M}_W(t')dt' - M_S(t) - M_I(t)$$

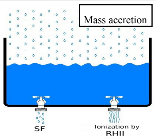


Fig. 2: Regeneration vs cloud destruction sketch.

where M_C is the cloud mass, M_w the mass accretion rate of the WNM, $M_S(t)$the total mass in stars, and $M_I(t)$ the ionized mass. We assume that $M_W(t)=\rho_W v_W A_C(t)$ with ρ_W and v_W being the density and velocity dispersion of the WNM. Also, We assume that the SFR is given by the ratio of the gas mass in the high-density tail ($n > n_{SF}$) of the density distribution produced by the turbulence in the cloud, to its local free-fall time. Therefore, the mass in stars is:

$$M_S(t) = \int_0^t SFR(t')dt' = \int_0^t f \frac{M_C(t')}{t_{ff}(\rho_{SF})} dt'$$

We consider that only the gas with number density higher than a critical value n_{SF} is participating in the SF process. For this, we also consider that the level of supersonic turbulence is constant, and the density is characterized by a lognormal PDF. The mass fraction that forms stars is:

$$f = \int_{s_C}^{\infty} e^s P_s(s)ds = \frac{1}{2}\left(1 - erf\left[\frac{\ln(s_C) - \sigma_s^2/2}{\sqrt{2}\sigma_s}\right]\right)$$

PDF: $P_S(s) = \frac{1}{\sqrt{2\pi\sigma_S^2}} \exp\left[-\frac{(s-s_p)^2}{2\sigma_S^2}\right]$

Where $s = \ln(n/n_0)$,
$s_p = \ln(n_p/n_0)$ and
$\sigma_S = [\ln(1+b^2M^2)]^{1/2}$
For only compressive modes b=1, and
Mach number $M=v_{RMS}/c_S$

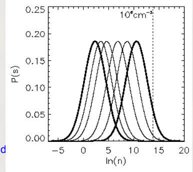
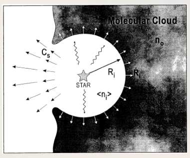


Fig. 3 **As the cloud collapses, its average density (<*n*>) grows, and the distribution peak moves to higher densities.**

Finally, to model the cloud evaporation by massive stars, we use the results from Franco et al. (1994). These authors found that the cloud evaporation rate by a massive star near the cloud surface is:

$$\dot{M}_I(t) \approx 2\pi R_{S,0}^2 m_H c_{S,I} < n > \left(1 + \frac{5c_{s,I}t}{2R_{S,0}}\right)^{1/5}$$



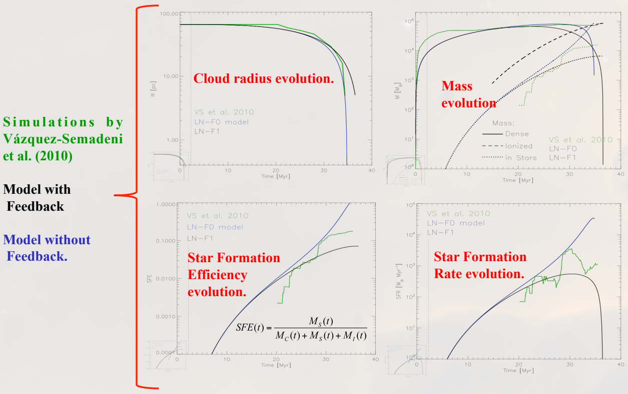
where t is the age of the massive star, c_S is the sound speed in the ionized gas, <n> is the mean number density of the MC, and $R_{S,0}$ is the initial Stromgren radius of the massive star in the cloud. Thus, to get the total ionized mass we integrate this equation over the lifetime of each massive star formed.

II. Calibration.

We calibrate the model by matching it to the numerical simulation by Vázquez-Semadeni et al. (2010).

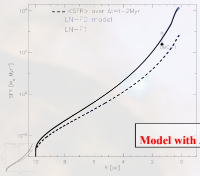
Common parameters:
n_{inf} = 1 cm^{-3}
R_{inf} = 64 pc
n_{SF} = 10^6 cm^{-3}

Parameters that best fit the simulations:
v_{inf} = 4.5 km s^{-1} (7.5 km s^{-1} in the simulations)
Mach = 3
f_L = 1.7 (Larson, 1969)



$$SFE(t) = \frac{M_S(t)}{M_C(t) + M_S(t) + M_I(t)}$$

III. Model vs. Observations.



a) Good agreement with OMC-1:

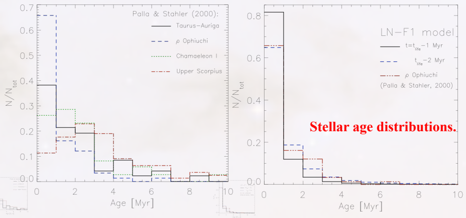
	n (cm^{-3})	Size (pc)	Mass in stars (M$_\odot$)	Stellar age (Myr)	<SFR> (M$_\odot$ yr^{-1})
OMC-1*	1.5 x 10^4	1.3	500	~2	2.5×10^{-4}
Model	1.5 x 10^4	1.9	200	2	10^{-4}

*from Vázquez-Semadeni et al. (2009).

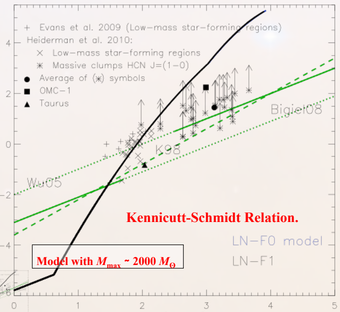
We make the comparison at the time when the density in our model is the same as that of OMC.

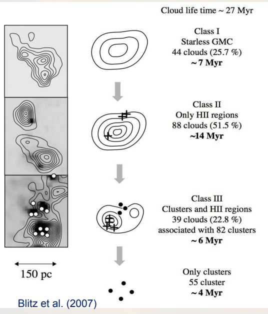
b) The stellar age histogram 2 Myr before the end of our model's life resembles those of Palla & Stahler (2000).

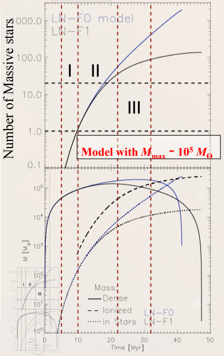
➔ SFR increases over time!!!



c) Cloud-scale observations occupy a well-defined locus in Σ_{gas}–Σ_{SFR} space in the Kennicutt-Schmidt diagram, which can be compared with our model (Fig. at right). We choose a model's mass of $M_{max} \approx$ 2000 $M_\odot$ (cf. to Evans et al's. (2009) and Heiderman et al.'s (2010) samples). The model (thick solid line) evolves from low to high values of both Σ_{gas} and Σ_{SFR}. The massive clouds from Heiderman et al. (2010) are shown with an upward-pointing arrow indicating the likely underestimation of the SFR due to the methods they used. We also plot the data from OMC-1 (from Vázquez-Semadeni et al. 2009) and Taurus (see, e.g., Heiderman et al. 2010).







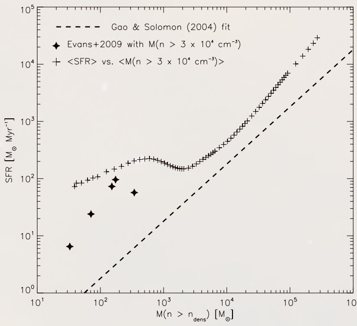
d) Comparison with the cloud types defined by Kawamura et al. (2009). We define cloud types in our model by the number of massive stars N_{mass} as follows:

Type I: $N_{mass} < 1$;
Type II: $1 < N_{mass} < 20$;
Type III: $20 < N_{mass}$.

We see that the model cloud (with M_{max} ~ 10^5 $M_\odot$) spends ~5 Myr as a Type I, ~12 Myr as a Type II, and ~10 Myr as a Type III, in agreement within a factor of 2 with Kawamura et al.'s (2009) classification.

e) Gao and Solomon (2004), in a sample of LIGs, ULIGs and spiral galaxies, found a linear relationship between the IR and HCN luminosities, which results in the star formation law in terms of dense molecular gas ($n > 3\times10^4$ cm^{-3}) content with a power-law index of 1.0 (see Fig. at right).

The *SFR* and the dense gas mas (M_{dens}) averages, in the modeled massive clouds (M_{max} > 10^4 $M_\odot$), follows the Gao and Solomon (2004) relationship, while the less massive ones occupy the locus of those observed by Evans et al. (2009) in the *SFR*-M_{dens} diagram.



IV. Conclusion.

With this simple model we obtained realistic GMC properties. This suggests that the scenario of global cloud collapse, with the SFR regulated by massive star-feedback is plausible.

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