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Density, Alternative Determinant of Star Formation Efficiency of the Milky Way GMCs: Core Reason for Low Star Formation Efficiency

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Abstract: The overall efficiency with which Milky Way Giant Molecular Clouds (GMCs) is forming stars was determined by deriving an equation using density of cloud (i.e. stellar density/ total cloud density), which is the core parameter that determines star formation other than the mass of cloud, and comparing with mass (i.e. stellar mass/ total gas mass) as was propounded by previous researchers, to ascertain the reasons the observed star formation efficiency of Milky Way Giant Molecular Clouds (ϵ_{GMC}) is low. This will aid understanding the physical factors behind the formation of stars from interstellar gas and develop a predictive theory of star formation and evolution of galaxies. A total of 191 star formation complexes-giant molecular cloud (SFC-GMC) complexes was used in estimating the following cloud parameters: density as 93.8218 solar mass/parsec squared, average stellar density as 2.67872 solar mass/parsec squared, average luminosity as 9.87E24 solar luminosity, average effective temperature as 498,647 solar temperature, average stellar radius as 51.4522 parsec and average cloud radius as 325507 parsec as well as the total mass in stars $M_\star$ harbored by the individual clouds (20,831 solar mass), which was inferred from Wilkinson Microwave Anisotropy probe (WMAP) free-free. Finally, the overall efficiency with which Milky Way Giant Molecular Clouds is forming star gave 0.0289573 which is less than the previous estimate as 0.030849, showing that not all the masses of the cloud were present at the end of the star formation, and this reduction in mass are caused by magnetic field, supersonic turbulence, self-regulation and unbound states of its internal structure, which are the reasons the observed star formation efficiencies are low.

Keywords: Galaxies, Star Formation Efficiency, Cloud Density, Stellar Mass, Gas Mass

1. Introduction

Everything known about galaxy, such as its observations, definition etc. is through its stellar contents. Therefore, any theory of galaxy formation has to start by addressing how stars' form, the main processes that drive star formation and what mass fraction of a gas cloud can be converted into stars (star formation efficiency (SFE or ϵ)). Star formation on the other hand is the process by which interstellar medium of gas and dust collapse and form stars in its dense region known as molecular clouds or star-forming region [24].

"Lee et al and Murray N. defined star formation efficiency of the GMCs (ϵ_{GMCs}) as the fraction of the GMC that is converted into stars over the lifetime of the GMCs [16, 22]". Mathematically ϵ_{GMCs} is defined as the total mass in stars, produced over the life time of the GMC, divided by the overall GMC mass which also includes the total mass in those stars

$$\epsilon_{GMCs} = \frac{M_\star}{M_{GMC} + M_\star} = \frac{M_\star}{M_g} \tag{1}$$

where $M_\star$ is the total mass of the individual stars inside the clouds, M_{GMC} is the total mass of the remaining cloud that does not finally convert to star and M_g is the total mass of the cloud.

After thorough examination on this parameter (Mass) found in equation (1), it was found that using mass to calculate the efficiency of clouds in forming stars cannot provide the exact value for the prescribed efficiency because some of these masses of the clouds have been destroyed by both internal and

external forces such as magnetic flux of the internal structure of the clouds [7, 13], supersonic turbulence and self-regulation, over a long period of time [4, 12 20,] (i.e. from the time of gravitational collapse to the time the cloud is ready to form stars). Hence, making M_g of these clouds not ideal for ϵ, rather Σ_g [20].

$$\epsilon_{GMCs} = \frac{\Sigma_\star}{\Sigma_{GMC} + \Sigma_\star} = \frac{\Sigma_\star}{\Sigma_g} \qquad (2)$$

Grudic et al defied SFE, as the fraction of the gas mass that is converted to stars across the entire life time of a cloud [11]:

$$\epsilon_{int} = \frac{M_{\star(t=\infty)}}{M_{gas(t=0)}} \qquad (3)$$

where $M_\star$ is the total mass in stars formed and M_{gas} is the total gas mass. ϵ_{int} is of particular interest because it is sensitive to the details of stellar feedback physics, as eventually a sufficient number of massive stars will form to expel the gas. ϵ_{int} ultimately determines the mapping between the GMC and star cluster mass functions in a galaxy, and dictates the fraction of stars remaining in a gravitationally bound clusters after gas expulsion. The inferred gas mass will also vary over the lifetime of the cloud: while the effect of gas consumption might be negligible if overall efficiencies are small, molecular gas will also be destroyed and ejected by stellar feedback, so towards the end of a cloud's star forming lifetime the inferred efficiency might be biased upward [10].

As already known [23], dense gas ($\geq 10^5$ cm^{-3}) has a great impact on star formation in molecular clouds. At times, cores of very dense gas resist the disruptive forces of winds and radiations from nearby newly-formed stars and they help to maintain their ongoing star formation even in hostile environments. Therefore, the sample of the dense region of these clouds is generally small compared to the total masses of these clouds.

Many works have been done on SFE (e.g. [17, 19] etc.) of the Giant Molecular Clouds (GMCs) and it has been found that these ϵ are so low and the reasons behind this are yet concluded.

This research work was carried out to ascertain the reasons for low star formation efficiencies of the GMCs and is organized as follows: section 2 focused with the internal and external forces responsible for the destruction of the cloud masses, section 3 is the methodology used in the estimations, section 4 results are presented, section 5 discussions of results, and finally, section 6, conclusion and our contribution to knowledge.

2. The Disruptive Forces

There are so many forces responsible for the low star formation efficiencies, and these forces affects the masses of the clouds in a greater percentage than densities which is the core determinant, necessary for a cloud to form star (s). These forces such as forces of stellar winds and radiations from newly formed stars, (stellar feedback), magnetic flux, supersonic turbulence etc. [2, 8, 10], etc. are part of the

reasons the star formation efficiencies are so low and at the same time sources of trigger for star formation.

2.1. Stellar Feedback

Stellar Feedback may not only be important for promoting star formation under certain conditions. For instance, star formation in one place may be induced by the feedback of star-formation activity in other places, which is called an "induced" star formation, i.e. the density and velocity structure of the ISM, are actually produced by stars themselves. Even if the large-scale star formation environments are produced by the other processes described above, compression by energy feedback from nearby stars may play an important role in triggering star formation in pre-existing clouds [9]. Sellar Feedback may also terminate or prevent star formation; it also destroys some parts of the already existing cloud thereby reducing the M_g of the cloud.

2.2. Self-Regulation

The third mechanism that may be important for regulating the overall ϵ_{GMCs} is self-regulation that is the actual process of star formation itself which destroy the molecular clouds, and hence regulates the ϵ_{GMCs}; in particular. Feedback from protostellar winds is believed to play an important role in regulating the overall ϵ_{GMCs} of protostellar cores [18].

2.3. Supersonic Turbulence

In a self-gravitating turbulent medium, the collapse of gas clouds can be affected by turbulence in two different ways. First, because turbulent motion increases the effective velocity dispersion of the gas can delay or suppress gravitational collapse. Second, shocks produced by the supersonic flow in a turbulent medium can promote gravitational collapse by increasing the gas density.

2.4. Magnetic Flux

A major question to understand the role of the magnetic field in molecular cloud evolution is how it correlates with the other fields and in particular with the density, [12]. Owing to that he stated that the mean magnetic intensity is independent of gas density, n, for values up to about 300 cm^{-3}. At higher densities, that is to say at least up to 10^{6-7} cm^{-3}, the mean magnetic intensity has been found to increase with n broadly like a power-law, that is $B \simeq n^k$. The exact value of k is still a matter of debate. Earlier works [5] obtained k=1/2 but more elaborated Bayesian analysis led to k $\simeq$ 0.65 [6]. Finally, the mass to magnetic flux ratio, M/Φ, can be estimated by combining the column density of the observed component along the line of sight and the observed magnetic intensity, leading to the conclusion that the atomic and diffuse molecular gas is subcritical, that is to say dominated by the magnetic field, while dense regions, such as dense cores, are generally supercritical.

Prior, to our understanding of galaxy formation, the cold gas in a star-forming galaxy is assembled hierarchically through the cooking and accretion of gas in merging dark matter halos. This process produces high levels of turbulence

in the gas. Also cosmological numerical simulations of galaxy disk formation show that gravitational instabilities can generate high level of turbulence [3, 14, 20].

3. Methods

The first step in the calculation of ϵ_{GMC} is to identify the host GMCs of the SFCs, [15]. The cloud catalog provides the Σ_{GMC} (cloud density) estimate, and is presented partially in table 1 and fully in appendix A.

3.1. Estimation of Stellar Mass from Free–Free Flux

The average mass of stars associated with each cloud is evaluated from the WMAP free–free fluxes. For a given WMAP free–free source (the large ~1°–2° wide regions identified by their peak free–free flux in WMAP; see [21] for more detail), aperture photometry was first performed to compute the total free–free flux F_v. The total flux is divided into constituent star formation complexes ((SFCs) and by extension, constituent SFC-GMC complexes), proportional to the relative SFC 8μm fluxes computed from Spitzer GLIMPSE and MSX images. The mass of "live" stars is given by the formula

$$M_\star = Q/(\langle M_\star\rangle/\langle q\rangle) \qquad (4)$$

$$where \; (\langle M_\star\rangle/\langle q\rangle) = 6.3 \times 10^{46}s^{-1}M^{-1}$$

Having assigned fluxes F_v to each SFC, kinematic distance D was used to calculate the free–free luminosity

$$L_v = 4\pi D^2 f_v \qquad (5)$$

emitted by that region, and the rate

$$Q = 1.37 \times 10^{26}L_v s^{-1} \qquad (6)$$

Q is the ionizing photons emitted by each source per second required to power the observed free–free [21].

Following [25], the rate of ionizing photons (Q) was increase by a factor 1.37 to account for the fact that some of those photons are absorbed by dust, and hence do not contribute to the free–free emission detected by *WMAP*. The live stellar mass was then calculated using Equation (4) above.

3.2. Estimation of Stellar Densities from Free–Free Flux and Other Clouds Parameters

At the same time, stellar density of the individual cloud was calculated using mass-density relation, given as:

$$\Sigma_\star = \frac{M_\star}{V_\star} \qquad (7)$$

Where $V_\star$ is the volume of the individual stars, and is given as $\frac{4}{3}\pi R_\star^3$.

The effective temperature T_{eff} was estimated using temperature-luminosity relation given as $T = (L_v^{br}/4\pi R^2 \sigma_{SB})^{0.25}$, and finally, the radius of the individual stars ($R_\star$) and clouds (R_{cloud}) was estimated using $R = M^{0.7}$ as shown in table 1, where σ_{SB} is the Stephan-Boltzman constant $= 5.6696 \times 10^{-8}\, kgs^{-3}K^{-4}$. Finally, having selected the GMCs and calculated its cloud parameters, the ϵ_{GMC} was then estimated by substituting into equation (2).

4. Results

The results of 191 selected GMCs were presented, with their cloud properties such as: total gas masses (M_g), average stellar masses ($M_\star$), Luminosities (L_v), Effective Temperature (T_{eff}), Cloud Radius (Rad), total densities (Σ_{GMCs}) and star formation efficiencies ($\in$) of the selected GMCs which we presented partially in table 1 and fully in appendix A.

Table 1. 191 Selected GMCs Efficiencies and its Estimated Cloud Parameters.

S/N	GMCs no	Q s^{-1}	M_g $M_\odot$	M_g $M_\odot$	Σ_{GMC} $M_\odot/pc^2$	Σ_{GMC} $M_\odot/pc^2$	M_{GMC} $M_\odot$	L_v ergs$^{-1}Hz^{-1}$	Rad pc	T $T_\odot$	SFE M_g GMCs	SFE DEN GMCs
1	1726	3.64000E+05	577778	947000	6.31E+01	0.757098	369222	2.73684E+26	15256.2	1133405	0.610114	0.110260
2	1761	1.65000E+52	261905	8490000	1.61E+02	1.198825	8228095	1.24060E+26	70833.0	431604	0.030849	0.047974
3	26	9.50000E+51	150794	2970000	2.23E+02	3.027471	2819206	7.14286E+25	33957.0	542998	0.050772	0.019571
4	279	8.28000E+51	131429	3510000	2.18E+02	2.381247	3378571	6.22556E+25	38169.4	494860	0.037444	0.319713
5	440	7.24000E+51	114921	2330000	1.51E+02	2.093327	2215079	5.44361E+25	28651.6	552322	0.049322	0.003108
6	171	7.00000E+51	111111	769000	1.13E+02	2.410169	657889	5.26316E+25	13187.1	807296	0.144488	0.015906
7	388	6.25000E+51	99206	933000	7.36E+01	1.034809	833794	4.69925E+25	15097.9	733405	0.106330	0.016665
8	583	6.04000E+51	95873	3430000	1.88E+02	2.085155	3334127	4.54135E+25	37558.3	461040	0.027951	0.222916
9	1054	5.81000E+51	92222	1240000	8.71E+01	1.999706	1147778	4.36842E+25	18424.5	651897	0.074373	0.038168
10	678	5.79000E+51	91905	2690000	2.34E+02	3.327404	2598095	4.35338E+25	31683.0	496694	0.034165	0.019557

Efficiencies of Milky Way star-forming complexes and their host GMCs. (Column 2) GMCs number of Lee et al., (2016). The rest of the columns give star formation complex properties; (Column 3), ionizing photons emitted per second Q (Column 4), stellar mass $M_\star$ (Column 5), GMC mass M_g (Column 6) cloud densities, (column 7) the mass of GMCs that does not form stars M_{GMC}, (column 8) free–free luminosity L_v, (column 9) GMC radius Rad pc, (column 10) effective Temperature T_{eff} and (column 11 and 12) GMC efficiency $\in$.

5. Discussion

This work was aimed at estimating the overall efficiency with which Milky Way GMC form stars and the factors

responsible for low SFE of Milky Way GMCs.

From these result, the overall ϵ_{GMC} is 0.024832, with standard deviation equal 0.05613, then comparing this result with the one gotten from $M_\star/M_g$, and it was found that their outcome are closely related, which means one can also

calculate the ϵ_{GMC} by using both equations or expressions as illustrated in [1], they considered "all the gas above the transition density to be dense "self-gravitating gas" and all the gas in the lognormal portion to be "diffuse unbound molecular gas". They also predicted that self-gravitating gas fraction (f_{dense}) can then be related to a star formation efficiency which tells that the overall fraction of gas mass available for star formation at a given time based on the slope of the density PDF and the cloud environment".

The graph of $M_{\star}$ against M_g and $\Sigma_{\star}$ against $\sum_g$ see figures (1 and 2 respectively) were plotted to check if our results are consistent with the results of the previous researchers and it was found that majority of these efficiencies clustered at a low scale between zero (0) to 100,000 M on $M_{\star}$ axis and zero (0) to 2,000,000M on M_g axis (figure 1) and between zero (0) to 5 M /pc^2 on $\Sigma_{\star}$ axis and between zero (0) to 200 M /pc2 on $\sum_g$ axis (figure 2) showing the low efficiencies of GMCs to form star.

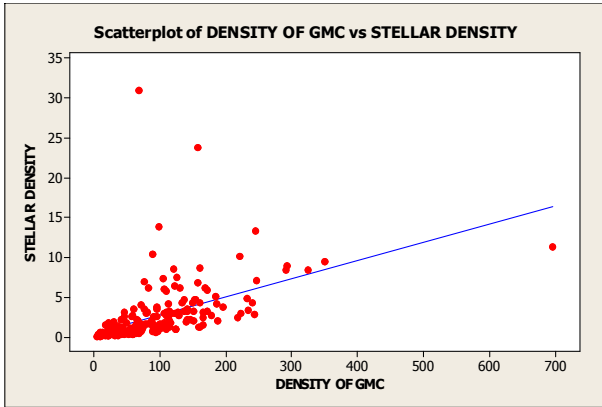*Figure 1. The scatter plot of the calculated $M_{\star}$ vs M_g of the GMCs in Milky Way.*

Figure 2. The scatter plot of $M_{\star}$ vs $\sum$ of the selected GMCs in Milky Way.

It was also found that the $\in_{GMC}$ does not depend on M_g, as shown by the Asymptotic decay curve of our plot on Figure 3, (this means that at an interval of zero (0) to about 1,000,000 solar mass on a horizontal axis of M_g, the ϵ_{GMC} increases and above this mass it decays exponentially) rather, it depended on $M_{\star}$ which in turn depended on the $\sum_g$ as shown in Figures 4.
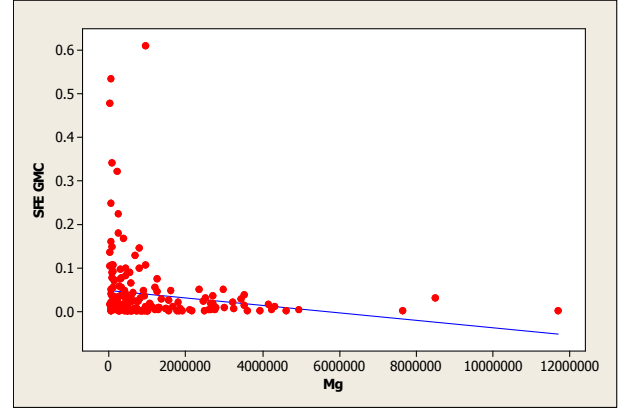

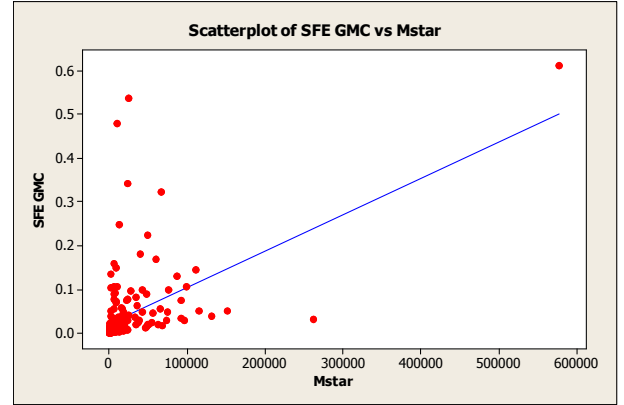*Figure 3. The scatter plot of SFE-GMC vs M_g of the selected GMCs in Milky.*

Figure 4. The scatter plot of SFE-GMC vs M_g of the selected GMCs in Milky.

This is in line with [4] who said that the unbound clouds can naturally result in lower SFEs than their bound (dense) counterparts, simply because the gas is unable to rid itself of the excess kinetic energy and achieve a bound state. It was concluded that what determines the state and the efficiency of a cloud to form star is its density.
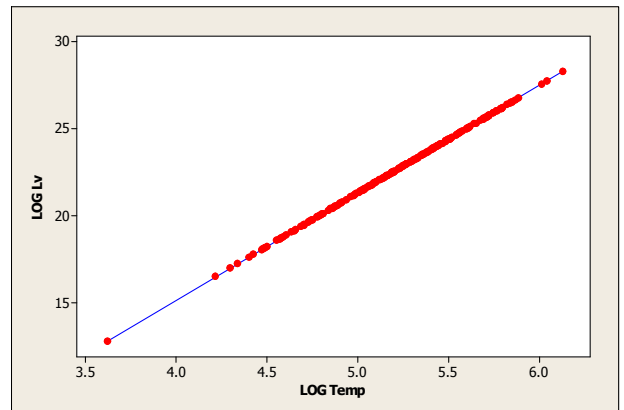

Figure 5. The scatter plot of Luminosity vs Temperature of the selected GMCs in Milky Way.

Other cloud parameters such as $\log L_v$ vs $\log T_{eff}$ Figure 5, $\log L_v$ vs $\log Rad$ Figure 6 etc was plotted. to check the correlation of parameters toward another. This was to ascertain if some of the formulae used here relate to another or not, but the outcome shows tight correlations: i.e. mass-

luminosity relation (L= $M^{3.9 \approx 4}$), mass – radius relation (R= $M^{0.7}$) and luminosity-temperature relation $\left(T = \left(\frac{L_{CO}}{4\pi R^2 \sigma_{SB}} \right)^{0.25} \right)$ whose results are presented in Table 1 and in appendix A.
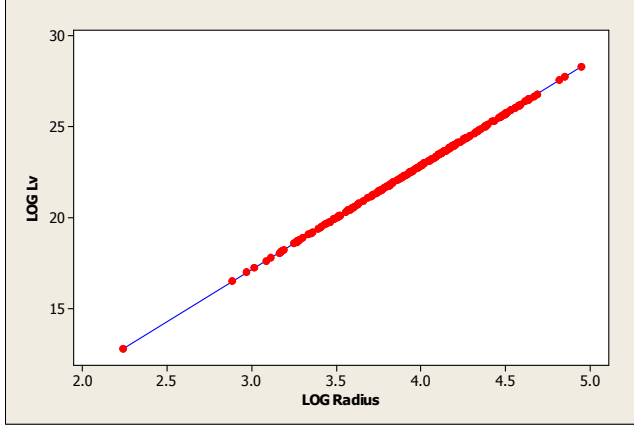

Figure 6. *The scatter plot of Luminosity vs Radius of the selected GMCs in Milky Way.*

Finally, it was also found that $\sum_g$, $M_\star$ and L_v have a direct relationship and can be determined from the given correlations, (i.e. they are in direct proportion to each other).

On the search to know why the observed star formation efficiency is so low led comparing the above results with the results of [4, 20] and concluded that the reasons why the observed star formation efficiency is so low are: magnetic field, supersonic turbulence, self-regulation and Variations in the initial kinematic state of the cloud or star-forming region.

6. Conclusion

The overall efficiency with which the Milky Way GMC form stars has been estimated from our derived equation and the factor responsible for low SFE of Milky Way GMC have been outlined. One can conclude that: the ϵ_{GMC} can be calculated/estimated, if the average ($\Sigma_\star$) and the $\sum_g$ of the cloud are known (which is present as $\epsilon_{GMC} \equiv \Sigma_\star / \sum_g$) other than the relation given [16, 22], the ϵ_{GMC} declined as the M_g increases and increases as the $\sum_g$ increases, the M_g determines the collapse of cloud as described by Jean 1902, the low ϵ_{GMC} lies upon the densities of the GMCs as it determines the state of the cloud, the unbound states of internal structure are caused by magnetic field, supersonic turbulence and self-regulation, and finally, this density determines 1. the number of stars that will be formed over the life time of the GMC 2. the state of cloud`s internal structure (whether a cloud is in bound state or in unbound state (i.e., anything that can affect the density of cloud automatically can also affect the efficiency of that cloud)).

7. Contributions to the General Knowledge

The importance of star formation efficiency cannot be over emphasized. Yet the general problem of astronomers is no longer how stars form, but what mass fraction of a gas cloud can be converted into stars, what controls the star formation efficiency and reason why the observed efficiencies of GMCs are low.

This study on Milky Way GMCs has shown that unbound state of the internal structure determined by the density of GMCs caused by magnetic field, supersonic turbulence and self-regulation are the core mechanisms behind the observed low star formation efficiency of the Milky Way GMCs. And finally, that one can make better estimate of star formation efficiency using density or our derived equation.

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