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On the origin of stellar aggregates in molecular clouds

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A method which provides the possibility to connect the global characteristics of the interstellar medium with that of the young stellar population of the Galaxy is proposed.

Es wird eine Methode vorgeschlagen, die die Möglichkeit bietet, die globalen Eigenschaften des interstellaren Mediums mit denen der jungen Sternpopulation unserer Galaxis zu verknüpfen.

Key words: Interstellar matter — giant molecular clouds — star formation.

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At present it is evident that the process of star formation in the Galaxy is closely connected with the giant molecular clouds (GMC) (Turner 1984). Young stars and GMC's reveal very similar space distributions (Sanders et al. 1984). In this article I will discuss the relation between some physical characteristics of the GMC's and young stars of the Galaxy. In Tables 1—4 the general observational characteristics of the GMC's and the population of young stars are given (Sanders et al. 1984, Silk 1980, Iben and Tutukov 1983, Mezger and Smith 1977, Elmegreen 1983).

During the last 10^{10} years the star-formation rate in the Galaxy has remained constant. This makes us search for a feedback mechanism in the star-formation process. A balance between the energy and momentum of photons and particles injected into the interstellar medium from OB stars and supernovae usually is regarded as such a mechanism (Franco and Shore 1984, Surdin 1984). Here I must note one very important link of the feedback circuit — the destruction of the GMC in the process of star formation. We can represent the binding energy of a GMC as the sum of the gravitational energy of the cloud and the chemical energy of the H_2 molecules. Although, as we can see from Table 3, the chemical energy always exceeds the gravitational one, a complete destruction of the cloud as a self-gravitating object is necessary to stop star forma-

Table 1
Individual characteristics of GMC

Characteristic	Mean value	Range of values
Mass ($M_\odot$)	$5 \cdot 10^5$	$5 \cdot 10^4$—$5 \cdot 10^6$
Radius (pc)	20	10—50
Mean density (H_2/cm^3)	300	10^2—10^3
Temperature (K)	10	5—30
Gravitational binding energy GM^2/R (erg)	10^{51}	10^{50}—10^{52}
Energy of dissociation of molecular hydrogen (erg)	$2 \cdot 10^{52}$	$3 \cdot 10^{51}$—10^{53}
Surface escape velocity (km/s)	15	10—20
Turbulent velocity with in the cloud (km/s)	9	2—17
Lifetime (years)	10^8	10^7—10^9
Magnetic field (G)	$5 \cdot 10^{-5}$	$(2—10) \cdot 10^{-5}$

Table 2
Characteristics of the population of molecular clouds of the Galaxy

Total mass $M(H_2 + He)$		$3 \cdot 10^9 M_\odot$
Mass ratio $M(H_2)/M(HI + HII)$ for the whole Galaxy ($R \leqq 15$ kpc)		1
Mass spectrum	$dN/dM \propto M^{-1.55 \pm 0.10}$ total	
Number of clouds	total	$20 \cdot 10^3$
	$(M \geqq 10^5 M_\odot)$	$6 \cdot 10^3$
	$(M \geqq 10^6 M_\odot)$	$1 \cdot 10^3$
Mass ratio of the warm ($t_{kin} \geqq 10$ K) and cold subsystems of the clouds		1:3
Total velocity dispersion		10 km/s
Mean frequency of encounters		10^{-8} yr^{-1}

Table 3
Structure and physical parameters of GMC

Physical parameter	Structural level				
	Little compressions	Smale-scale condensations	Large-scale condensations	Main body	HI envelope
Mass ($M_\odot$)	1	10^2—10^3	10^4	10^5—10^6	10^5
Radius (pc)	0.1	1	1—10	10—100	50
Temperature (K)	20	20	20	10	50
Density (H_2 cm^{-3})	10^4—10^5	10^4	$5 \cdot 10^3$	300	100 H cm^{-3}
Gravitational energy (erg)	10^{42}	10^{45}—10^{47}	10^{48}—10^{49}	10^{50}—10^{51}	10^{49}
Dissociational energy $H_2 \rightarrow 2$ H (erg)	10^{47}	10^{49}—10^{50}	10^{51}	10^{52}—10^{53}	—
Free-fall time (yr)	$(1$—$4) \cdot 10^5$	$4 \cdot 10^5$	$5 \cdot 10^5$	$2 \cdot 10^6$	$5 \cdot 10^6$

Table 4
Some characteristics of the population of young stars in the Galaxy

Star formation rate	$\dot{M} = (3$—$4) M_\odot \text{ yr}^{-1}$
Formation rate of star clusters	$\nu_C = (2$—$4) \cdot 10^{-4} \text{ yr}^{-1}$
Formation rate of associations	$\nu_A = (2$—$4) \cdot 10^{-4} \text{ yr}^{-1}$
Mass range of young stellar aggregates (open clusters and associations)	$M_{YSA} = (10^2$—$10^4) M_\odot$
Number of supernovae per unit mass of young stars	$\beta = 10^{-2} \text{ SN} M_\odot^{-1}$

tion in it. If we assume that for destructing the cloud its gravitational energy must be equal to the total energy liberated by young stars via supernovae explosions, we have

$$\frac{GM^2}{R} = \mu \cdot E_0 \cdot \beta \cdot M_{YSA} \tag{1}$$

Here, E_0 is the energy of a supernova explosion, μ is the fraction of this energy conserved in the hot gas of the supernova remnant. β is the number of supernovae per unit mass of young stars, M and R are the mass and the radius of the GMC, and M_{YSA} is the mass of young stellar aggregate (YSA) which will be formed in the inner part of the GMC by the moment of its destruction. For $E_0 = 10^{51}$ erg, $\mu = 0.1$, and $\beta = 10^{-2} \cdot M_\odot^{-1}$ (LARSON 1974) we have

$$M_{YSA} = 4 \cdot 10^3 M_\odot \cdot (M/10^6 M_\odot)^{5/3} \cdot (n/300 \text{ H}_2 \text{ cm}^{-3})^{1/3} ,$$

where n denotes the mean density of the GMC. We can estimate the mass because it is almost independent of the density. For the massive clouds of the "warm" subsystem associated with the process of star formation ($10^5 M_\odot \leqq M \leqq 4 \cdot 10^6 M_\odot$), the range of the YSA mass is $10^2 M_\odot \leqq M_{YSA} \leqq 4 \cdot 10^4 M_\odot$. This range is in good agreement with the observations. The efficiency of star formation in the GMC as a whole is not large: $M_{YSA}/M = (0.1 - 1)\%$, agreeing with the observations, too (DUERR et al. 1982, CARLBERG 1985).

If we assume that the mass function of the GMC is $dN/dM \propto M^{-3/2}$, we obtain as the expected value of the star-formation rate:

$$\dot{M} = \frac{1}{\tau} \cdot \int_{M_{min}}^{M_{max}} M_{YSA} \cdot \frac{dN}{dM} \cdot dM = \frac{M_\odot}{2 \cdot \tau} \cdot \left(\frac{M_{max}}{M_\odot}\right)^{7/6} \tag{2}$$

Here, τ is the lifetime of the GMC and M_{max} is the maximum value of its mass. The latter is well known from the observations: $M_{max} = 4 \cdot 10^6 M_\odot$. But we cannot determine the value of τ so precisely. If we consider the GMC's from the "warm" subsystem associated with the spiral arms, the time of their free-fall contraction give us a lower limit of τ ($5 \cdot 10^6$ years). An upper limit is found by the time a GMC needs to cross a spiral arm ($3 \cdot 10^7$ years). Thus, Eq. (2) predicts a star-formation rate $\dot{M} = (1$—$5) M_\odot$/yr, which is in good agreement with the observations. Depending on the specific conditions for the star formation in the inner or outer parts of a GMC, after its destruction the YSA can become a gravitationally bound open cluster or an expanding association. Condensations in the inner part of a GMC with masses $\leqq 10^4 M_\odot$ have a short time of free-fall contraction resulting in a high efficiency of star formation and consequently the formation of gravitationally bound clusters.

This method also provides the possibility to determine the frequency of the formation of YSA in the Galaxy. Assume that after $\tau = (0.5-3) \cdot 10^7$ years one YSA is formed from each GMC with a mass $M \geqq 10^5 M_\odot$. Then we find as YSA-formation rate $\nu_{YSA} = N/\tau = 6{,}000/(0.5-3) \cdot 10^7$ yr $= (2-12) \cdot 10^{-4}$ yr^{-1}. The observed formation rate of clusters and associations in the Galaxy is, in keeping with this value, $\nu_c + \nu_A = (4-8) \cdot 10^{-4}$ yr^{-1}.

The present star-formation rate in the Galaxy as well as the formation rate and the range of masses of open clusters and associations can be quantitatively explained by means of assuming a simple connection between the gravitational energy of the GMC's and total energy set free by the YSA formed within them. Probably for the first time we have a theoretical method at hand which offer the possibility to relate global characteristics of the interstellar medium and the population of young stars in our Galaxy. We hope that this proceeding has good prospects because no free parameters are used and our propositions are quite plausible. The application of this method is not restricted to our Galaxy and the present time.

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