PHYSICAL PROCESSES IN MASSIVE STAR FORMATION

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SUMMARY: The gravitational fragmentation theory of star formation is reviewed. Theoretical arguments are presented which suggest that the lower stellar mass cut-off to the IMF in giant HII regions may be as high as 10 $M_{\odot}$. Mechanisms for bimodal star formation are described in the context of a coagulation model for formation of the giant molecular clouds, and application is made to starbursting galaxies.

I. INTRODUCTION

Star formation is poorly understood, despite the fact that modern observational techniques can probe the very cores of nearby molecular clouds in which stars currently are forming. The reason is simply that a large number of physical parameters are involved in determing the fate of a collapsing cloud. Apart from specifying the cloud mass and initial geometry, these include gas density, temperature, turbulent velocity field, magnetic field, rotation, ionization, dust grain properties, molecular and heavy element abundances. One must also consider feedback from the presences of newly formed stars, and global effects, such as the effect of the environment or the molecular cloud. Different (and occasionally even the same) authors have argued at various times that different subsets of these parameters play a dominant role. Not even fully three-dimensional numerical computations, now or in the foreseeable future, seem capable of unravelling these many complexities. Hence it is perhaps presumptuous to attempt to even speak of star formation theory. Rather, there are certain observational facts, some secure, others less so, from which one can try to reconstruct a theoretical framework within which one can seek to test various speculations involving collapse and fragmentation. That is the philosophy underlying this review, in which I shall examine some aspects of massive star formation.

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To commence, I discuss the fragmentation of collapsing clouds, and argue for the existence of a critical mass scale (§II). I show that this leads in a natural way to a reasonable form for the initial mass function, and that the lower stellar mass cut-off may increase in giant HII regions (§III). The mechanism of secondary star formation is described in §IV, where I argue that this naturally leads to bimodal star formation. The observational evidence for bimodality is summarized, and then in §V, I describe the role of giant molecular cloud formation in initiating starbursts. A final section draws implications for future research, both theoretical and observational.

II. FRAGMENTATION

A popular view of star formation is that it occurs via the hierarchical fragmentation of a collapsing gas cloud. Hoyle (1953) originally proposed that during the isothermal contraction phase characteristic of a diffuse cloud, the Jeans mass M_J would decrease and lead to fragmentation on decreasing scales. This mass scale is the mass contained within a sphere of diameter equal to the critical wavelength for gravitational instability in an infinite uniform medium, namely the Jeans length $\lambda_J \equiv \pi V_s(G\rho)^{-1/2}$. A more sophisticated analysis in a uniform, isotropically collapsing cloud (Hunter 1962) confirmed this result in linear perturbation theory: all wavelengths exceeding λ_J are unstable to small perturbations in densities

However these simple analyses in linear theory have been seriously questioned (Layzer 1963; Tohline 1980). Fluctuations acquire angular momentum by tidal torques and may undergo disruptive interactions. The level of initial fluctuations δ is crucial to the outcome of the instability, which has a secular growth rate. In spherical collapse, the mean density must increase by a factor of order δ^{-2} (Mestel 1965) and in aspherical collapse by a factor δ^{-1} (Silk 1982), before fragmentation can occur. Growth only commences on a given scale once this scale exceeds the instantaneous value of the Jeans length.

Numerical simulations have not hitherto had adequate resolution to verify whether fragmentation indeed occurs in the dynamic collapse phase. Collapses subject to large amplitude initial perturbations are found to fragment (Rozyczka 1983). Most hydrodynamical simulations study the effects of initial pressure and rotation. Typically, collapse occurs to a quasi-equilibrium sheet or ring which subsequently fragments (Bodenheimer *et al.* 1980). In essentially all numerical studies, the fragments contain many Jeans masses, but this is undoubtedly an artifact of the low resolution obtainable because of grid limitations (Tohline 1982).

It seems plausible that some combination of thermal pressure, rotation and magnetic support will greatly slow the clouds from free-fall collapse. Observational studies strongly suggest that clouds are not in free-fall collapse, otherwise, given the observed efficiencies of star formation, far too high a rate of star formation would ensue. In view of the unacceptably low resolution of hydrodynamical three-dimensional studies, it is therefore useful to pursue an analytical treatment. The stability of thin, self-gravitating sheets of gas has been extensively studied, including pressure support, rotation and magnetic fields. A general conclusion from linear stability analyses is the following, shown most simply for an infinite isothermal sheet, but characteristic of more general conditions (Larson 1985). The dispersion relation for the growth of exponential perturbations $exp(\omega t - i\underline{k}.\underline{x})$ is

$$\omega^2 = V_s^2 k^2 - 2\pi G\mu k, \tag{1}$$

where the first term on the right hand side represents the pressure force and the second the self-gravitational force for a sheet of surface density μ. Equation (1) explicitly demonstrates that $\omega(k)$ has a maximum value at k_c, corresponding to the most rapidly growing mode: $k_c \approx (2H)^{-1}$, where H is the scale-height of the sheet. The corresponding mass-scale may be written

$$M_c = 2.4\ T^2 \left[\mu(M_\odot pc^{-2})\right]^{-1}\ M_\odot \tag{2}$$

To apply equation (2) to the interstellar medium, one may note that $\mu \approx 100 - 200 M_\odot pc^{-2}$ over a wide range of clump or cloud masses. The empirical relation $n \propto \ell^{-1}$ is satisfied over scales from ~ 0.1 to $\sim 30pc$ (Larson 1982). Gas temperatures span the range $\sim 5K$ to $\sim 100K$, so that $0.3M_\odot \lesssim M_c \lesssim 200M_\odot$.

Since M_c is derived from linear perturbation theory, it is important to examine the non-linear criterion for a fragment to collapse. This is best understood for an isothermal gas sphere embedded in a medium of pressure P (Ebert *et al.* 1960). If the surface pressure on the spherical cloud exceeds a critical value, it will collapse. Hence for newly formed fragments to be unstable and collapse, one requires

$$P/k > P_{crit}/k = 10T^4 M^{-2}\ cm^{-3}K, \tag{3}$$

where the cloud mass M is in units of $M_\odot$. For the previously cited temperature and mass ranges (if $M = M_c$), the critical pressures inferred from (3) are common in molecular clouds.

Once fragments do collapse, they are likely to form stars with high efficiency. This is because magnetic field lines thread gas fragments to the surrounding cloud. Magnetic torquing enforces approximate corotation as the fragments collapse (Mestel 1965; Mouschovias and Paleologou 1979), and this outward transfer of angular momentum enhances the efficiency of star formation: essentially all of the mass in a fragment should be able to contract to high density. This argument presupposes that magnetic fields are well coupled to the molecular gas. Ionization studies, as well as indications that ionizing X-ray photons are produced by protostellar flares deep within molecular clouds, suggest that the magnetic field diffusion time-scale (for ions and charged grains which carry the field and slip relative to the neutrals) is at least 10^7 *yr* (Langer 1984). The inefficiency in exhausting the gas supply of a molecular cloud lies rather in the existence of stable, non-collapsing fragments.

The preceding results for critical mass and pressure are exceedingly sensitive to temperature. This motivates the ensuing discussion: heat input is a crucial ingredient in determining the protostellar mass range.

III. THE INITIAL MASS FUNCTION

Suppose that for some set of initial conditions determining surface density and temperatures, fragments form protostars of specified mass M. Now not all of the cloud will fragment simultaneously. Either in a reasonably chaotic collapse or because of magnetic support, occasional dense cores will run away in density, while there will be a continuing reservoir of gas that is capable of ongoing collapse and fragmentation. Hence once the first protostars form, their subsequent energy output can affect the energy balance in the cloud. In general, one might plausibly expect that more massive stars form as the cloud heats up, but decreasingly smaller numbers of stars are formed because the heat input per star will rise with increasing mass.

It is possible to estimate in a schematic way the shape of the resulting initial stellar mass function. Suppose that the luminosity of a protostar scales as $L \propto M^{1+\beta}$, and that the dust grain emissivity varies as $T_d^{4+\alpha}$ when integrated over the spectral energy distribution. Here T_d is the grain temperature, and α depends on the specific grain properties: typically $1 \lesssim \alpha \lesssim 2$. Then suppressing all coefficients, the fragment mass spectrum satisfies

$$N\frac{dL}{dM} - L\frac{dN}{dM} = \frac{d}{dM}\left(T_d^{4+\alpha}\right) = \frac{d}{dM}M^{2+\alpha/2},$$

whence

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$$\frac{dN}{dM} = M^{-2-\alpha/2-\beta}. \tag{4}$$

Now one expects that $\beta \approx 0$ for massive protostars, and one therefore infers an IMF with slope about -2.5. A more detailed treatment with allowance for gas-grain coupling was given by Silk (1977). This derivation does assume that all masses form with similar efficiency: hence one can convert from gas fragment to stellar masses. It is encouraging that (4) approximates the observed IMF, but the comparison does not merit being taken too seriously.

A more quantitative comparison with stellar data may be made by focusing on the lower mass cut-off of the IMF. When a cloud begins to form its first stars, the proto-stellar masses are likely to be inhibited below a particular value M_* that coincides with the critical mass corresponding to fragments that can collapse at pressure P_{crit}. Lower mass stars would require larger pressure at given T and μ or ρ to have contracted from newly formed fragments, whereas all fragments more massive than M_* would have collapsed. Suppose the fragments which are just going non-linear have the same temperature as the surrounding gas. Then since $M_* \propto T^2\ P_{crit}^{-1/2}$, we infer that the critical gas density to form stars more massive that $M_{10} \equiv M_*/10M_\odot$ is

$$\rho_{crit} = 6000\ T_{100}^3 M_{10}^{-2}\ M_\odot\ pc^{-3}, \tag{5}$$

where $T_{100} = T/100K$.

It is of interest to compare this theoretical prediction with the stellar density observed in the cores of the most compact clusters of massive stars. The comparison is valid provided that the stellar density observed now reflects that at birth: a necessary condition for this is that the relaxation time for core collapse be at least comparable to the hydrogen-burning lifetime of massive stars. This condition is satisfied for R136a in 30 Doradus, which contains at least 8 massive stars within a region 0.25 pc across (Weigert 1985). The core collapse time-scale is $\sim 7 \times 10^6\ M_{10}^{-1/2}\ yr$, and the stellar mass density is $\sim 3 \times 10^4\ M_{10}^{-1/2}\ M_\odot\ pc^{-3}$, where the IMF has been assumed to have slope $dN/dM \propto M^{-2.5}$ and to cut off below mass $M_{10} \sim 1$ (Moffat *et al.* 1985). Comparison with the prediction (5) suggests that $M_* = 13(T/200K)^2\ M_\odot$ in R136a. Application to the even more compact stellar core HD 97950 in NGC 3603 is not so clear-cut, since the core collapse time-scale is only $10^6\ yr$ in this object.

The previous discussion is not self-consistent, since an arbitrary value has been adopted for the temperature, which admittedly is likely to exceed 100 K

for dust grains in R136a. To improve this, let us assume that dust and gas temperatures are well coupled. Then for grains with emissivity inversely proportional to wavelength, the dust temperature $T_d^5 \propto \rho_*$, where ρ_* is the star density and it has been assumed that O stars dominate the contribution to the local radiation field. The approximate normalization of this equation is

$$T_d = 3(1+\rho_*)^{1/5} \quad degrees \quad K, \tag{6}$$

where ρ_* is measured in units of $M_\odot\ pc^{-3}$. To apply this, we use equation (2) which expresses the critical stellar mass-scale in terms of only one parameter, namely T_d, if we make the observationally motivated assumpion that all potentially star-forming fragments have a universal surface density, taken to be 150 $M_\odot\ pc^{-2}$. Combining (6) and (2), and identifying M_{crit} with the lower mass cut-off M_*, then yields

$$M_* = 0.1(1+\rho_*)^{2/5}\ M_\odot. \tag{7}$$

Note that ρ_* is a weak function ($\propto M_*^{-1/2}$) of M_*. This is the desired relation for M_*: it yields $M_* \approx 7M_\odot$ for R136a. This should correspond to a peak in the IMF.

IV. SECONDARY STAR FORMATION AND BIMODALITY

Hitherto, only radiative heating by newly formed massive stars has been shown to provide sufficient feedback to ensure continuing massive star formation. However dynamical effects may play an even greater role. Ionization fronts and stellar winds can compress ambient condensations as well as induce the agglomeration of larger condensations by sweeping up molecular gas fragments (Silk 1985). For compression of gas clumps by shock propagation to result in gravitational instability and collapse of an initially stable configuration, it is necessary that the compression be quasi-three-dimensional. A one-dimensional compression is stable, since the pressure gradient is proportional to R^{-1} but the gravitational restoring force is constant. Only three-dimensional compression (with the gravitational force proportional to R^{-2}) is guaranteed to destabilize ambient clumps. Numerical simulations of destabilization of clumps embedded in an HII region have been performed by Klein *et al.* (1983). In order to have such three-dimensional effects play an important role, it is necessary for a number of massive stars to simultaneously be present in a molecular cloud. This requirement poses a minimum mass requirement on the cloud. If a mass fraction f of a cloud forms O stars within a cloud lifetime t_{cl}, then for a number N of O stars to be present, one needs

$$M_{cloud} > 5 \times 10^4 (N/10)(f/0.1)(t_{cl}/3 \times 10^7)\ yr\ M_\odot. \tag{8}$$

Massive molecular clouds are therefore likely to undergo much more pronounced bursts of star formation than low mass clouds: star formation becomes self-reinforcing once a number of O stars are present.

This means that any remaining low mass globules should be triggered into forming stars. Even the lower mass stars are known to drive winds during their pre-main-sequence evolution. A dramatic consequence of the dynamical interactions will be that the molecular cloud is disrupted. HII regions, wind interactions, and supernovae can destroy a molecular cloud within a few tens of millions of years (Whitworth 1979; Norman and Silk 1980). All of this is greatly compounded by the argument given in the previous section, namely that continuing fragmentation, once a few massive stars have already formed, produces exclusively more massive stars because of the increase in M_*. In a low mass molecular cloud, however, where $M_* \sim 0.1\ M_\odot$, the typical star will be of low mass, the heating effects will be negligible apart fom dynamical wind interactions, and low mass star formation should continue until the gas supply is exhausted. The occasional massive star may form but only if the cloud accretes sufficient mass can enough O stars form to stimulate a star formation burst.

This suggests the following model for galactic star formation. The interarm regions contain small molecular clouds (SMC), which form stars with an IMF extending down to $\sim 0.1\ M_\odot$. Individual SMC make very few O stars, hence there is negligible feedback. Coagulation of the SMC as they orbit around the galaxy is enhanced by the spiral density wave, and giant molecular clouds develop predominantly in the spiral arms (see following section). A GMC forms many O stars, feedback is important, and the low mass cut-off increases to a few $M_\odot$ for newly forming fragments. At the same time, some lower mass stars form by implosion of existing globules. This distinction between the character of star formation in SMC and GMC favors a bimodal origin for low mass and massive stars.

Observational evidence for bimodality is well known. Herbig (1962) originally cited T associations as sites of exclusively low mass star formation, and argued that this must precede a phase of massive star formation. Observations of the Pleiades open cluster show that while the nuclear age inferred from the main sequence turn-off is $\sim 3 \times 10^7\ yr$, low mass star formation must have been continuing to occur for $\sim 10^8$ *yr* (Stauffer 1984). That young as well as old mass stars are present is inferred from the presence of both rapid and slow rotators (Stauffer *et al.* 1984). A study of the Pleiades IMF using a complete sample from proper motion studies shows that there is no detectable turn-over in the IMF: stars appear to have formed down to $\sim 0.1\ M_\odot$. A similar conclusion is reached from isochrone fitting of NGC 2264, where there is evidence that low mass star formation occurred over a longer period than the recent phase of massive star formation, and that the rate of massive star formation appears to be increasing with time (Iben and Talbot 1966; Adams *et al.* 1983; but see Stahler 1985 for a different interpretation).

Other arguments suggest that there are regions which can form predominantly massive stars. A study of the diffuse galactic thermal radio emission suggests that this is true for the spiral arms, as opposed to the interarm regions (Güsten and Mezger 1983). Studies of starburst regions strongly indicate that these regions are forming only stars above a few solar masses (Rieke *et al.* 1980). This follows from the observed ratio of far infrared luminosity, which measures the mass in OB stars, to the available stellar mass, together with independent constaints on the minimum duration of the starburst (for example, from the presence of spectral features associated with giants or supergiants).

Bimodal star formation is taken here to mean that one can in some regions form almost exclusively low mass stars, and in other regions almost exclusively massive stars. The same gas clouds could be involved, and make the transition from one mode to another. Indeed the general mix in open clusters of low mass and massive stars suggests that stars of all masses form in the same site. Bimodality argues that they have not formed coevally, however.

V. STARBURSTS

The coagulation theory for the origin of the GMC provides a natural mechanism for understanding starbursts, not merely of the mild variety encountered in our galaxy but also in much more active galaxies. An early difficulty encountered in the coagulation theory was that the time-scale for GMC formation was too slow, taking in excess of 2×10^8 *yr* (Scoville and Hersh 1979, Kwan 1979). It was pointed out, however, that the inelastic response of cloud-cloud collisions to the spiral density wave gives a considerable boost to the coagulation rate and also favors GMC formation in the spiral arms. (Cowie 1980; Norman and Silk 1980; Kwan and Valdes 1983). Detailed computations show that up to 30 percent of all molecular gas clouds can coagulate into GMC within a fifth of a galactic rotation period (Tomisaka 1984).

The cloud mass spectrum that results from coagulation of many SMC should evolve self-similarly according to simple coagulation theory (Nakano 1976; Silk and Takahashi 1979). The only scale is the characteristic mass M_{char}, determined by the product of the mean number of collisions and the mean initial cloud mass, and the resulting self-similar spectrum has the form

$$\frac{dN}{dM} \propto M^{-\nu}\ exp(-M/M_{char}). \tag{9}$$

Unfortunately, the theoretical investigations, involving either analytic studies or numerical simulations (Pumphrey and Scalo 1983), cannot constrain the power-law index ν of the low mass spectral tail to better than

$$1 \lesssim \nu \lesssim 3.$$

It is noteworthy that $\nu = 2$ is a critical value that distinguishes two regimes. If $\nu > 2$, one has most of the mass being stored in low mass clouds, whereas if $\nu < 2$, most of the mass is stored in the most massive clouds.

This has the following implications. If $\nu < 2$, one might expect that since the massive clouds are most rapidly eroded by OB star formation according to our earlier discussion, one would have a series of bursts of massive star formation and use up essentially the entire gas reservoir within the GMC build-time, roughly the time spent of time between spiral arms, or $\sim 10^8\ yr$. On the other hand, if $\nu > 2$, the mass would mostly be stored in the long-lived SMC, and there would be a relatively uniform star formation rate.

The mass spectrum of molecular clouds in our galaxy has been determined observationally, and corresponds to $\nu > 1.5$ (Sanders *et al.* 1985; Dame 1983). Most of the molecular gas is therefore stored in the most massive clouds. Hence our galaxy should be subject to bursts of star formation. Another prediction of a coagulation origin for the GMC is that they should be in equipartition: this is precisely what is observed for clouds of mass in excess of $\sim 10^5\ M_\odot$ (Stark 1983). The empirically determined collision time between GMC ($0.6/kpc, \sigma_r \sim 3km\ s^{-1}$) is $\sim 2 \times 10^8\ yr$, but this is considerably decreased within the spiral arms. GMC disruption occurs when enough OB stars have formed.

The observed efficiency of OB star formation is estimated to be $\sim$ 0.3 percent in the λ Orionis OB associations and the surrounding molecular shell (Duerr *et al.* 1982). It will take a GMC of $3 \times 10^5\ M_\odot$ at least one free-fall time or about 10^7 yr to even commence forming OB stars. For winds to develop, the stars must evolve past hydrogen burning, and this takes an additional 3×10^6 yr for a massive star. With enough O stars forming, disruption of a GMC should occur by propagation of the ionization front within $\sim (1 - 2) \times 10^6$ yr. This would be the case for a giant HII region. For a more typical galactic cluster, one might have to wait until B stars have evolved, and produced supernovae before disrupting a GMC. This could take up to $\sim 4 \times 10^7$ yr. In fact, Bash (1979) has used a ballistic model of cloud trajectories to analyze the galactic CO distribution, and he infers a phenomenological lifetime of $\sim 4 \times 10^7$ yr.

These two time-scales for GMC formation and disruption are the principal ingredients for an estimate of the star formation rate in a starbursting galaxy. If M_H is the reservoir of gas and ξ denotes the efficiency at which it is converted into stars of all masses, then the star formation rate can be expressed as

$$\begin{aligned} \dot{M}_* &= M_H \xi \left[max(t_{disrupt},\ t_{form})\right]^{-1} \\ &= 4 \left(\frac{\xi}{0.2}\right) [M_H/4 \times 10^9\ M_\odot]\ M_\odot\ yr^{-1}, \end{aligned} \tag{10}$$

The efficiency ξ has been set equal to 20 percent in order to give the known galactic star formation rate, and t_{form} has been set equal to 2×10^8 yr. Note that far infrared observations indicate an efficiency of 20 - 40 percent for effective cloud lifetimes. Observations of cold cloud cores directly show that an efficiency of $\xi \gtrsim 0.1$ is attainable in forming solar mass stars (Wilking and Lada 1983). Equation (10) is consistent with the hypothesis that our galaxy is a mini-starbuster, about to effectively tap its gas reservoir over the GMC formation time-scale.

Now one can immediately rescale equation (10) to infer the star formation rate in more active galaxies. The star formation rate per unit mass of gas is sensitive to the efficiency factor. However there is no obvious reason why it could be significantly larger than the value inferred for our galaxy. The remaining freedom is in the ratio of cloud formation to disruption times. A tidal interaction with a close companion or a merger could greatly reduce t_{form}. Toomre (1981) has found that even small ($\sim 1 - 2$percent) tidal perturbations of a cold disk galaxy amplify by a factor of ~ 20 over 4 rotation periods. His calculations did not include any allowance for inelastic gas cloud interactions, and one could readily imagine that the response of molecular clouds would be far stronger. However saturation of the star formation rate is reached if $t_{form} < t_{disrupt}$. Hence, allowing for uncertainty in ξ, one would expect the star formation rate per unit mass of gas to increase by up to a factor of 10 in closely interacting galaxies.

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Far infrared observations of starbursting galaxies seem to be in accord with this prediction. The ratio of far infrared to blue luminosity L_{IR}/L_B measures the ratio of star formation rate to the total stellar mass. For our galaxy this ratio is approximately unity. Galaxies with high values of L_{IR}/L_B are generally found to be interacting galaxies or have close companions (de Jong 1986). One of the most extreme cases known is Arp 220, with $L_{IR}/L_B \sim 100$. Our model predicts that the maximum enhancement in star formation per unit stellar mass expected is $(5-10) \times$ (gasfraction/0.03) $\sim 150-300$. Provided that the GMC properties are similar to those in our own interstellar medium, a higher ratio is not possible, unless the galaxy is genuinely young and lacks a gravitationally dominant old star population, that is to say, unless $M_* << M_H$.

VI. CONCLUSIONS

The low mass cut-off in the IMF is sensitive to heat input from massive stars because the critical mass above which molecular cloud fragments collapse and form stars depends sensitively on the temperature. A simple model suggests that in the stellar cores of giant HII regions, the low mass cut-off may be increased from ~ 0.1 to $\sim 10\ M_\odot$. An extension of the argument suggests that positive feedback from continuing massive star formation can account for the approximately power-law slope of the IMF.

Feedback effects are especially important in GMC, where a number of massive stars simultaneously coexist. Dynamical interactions of ionization fronts and winds will further stimulate star formation: The outcome is a star formation burst, destroying the GMC after about $4 \times 10^7\ yr$. In SMC, massive star formation is relatively infrequent, feedback effects will be unimportant, and one may expect low mass star formation to continue until continuing coagulation between SMC produces a GMC after $(1-2) \times 10^8\ yr$. The mass spectrum of molecular clouds in our galaxy shows that starbursts can occur over $\sim 2 \times 10^8\ yr$. The star formation per unit mass rate in an active galaxy undergoing vigorous bursts of star formation will be enhanced by up to a factor of 100 due to the increased gas content relative to our galaxy, and to the enhancement in rate of SMC coagulation triggered by tidal interaction with a close companion galaxy.

A search for the low mass IMF cut-off in R136a and 30 Doradus and in other giant HII regions would help confirm some of the ideas presented here.

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Discussion : SILK.

WALBORN :

I was interested by the application to 30 Doradus suggesting a lack of lower mass stars, because one argument that had been advanced against a cluster with many very high mass stars was that the normal IMF would then predict an improbable number of lower mass stars, whereas I never saw any reason to expect that a normal IMF should apply to a region like 30 Dor.

SREENIVASAN :

An important qualitative aspect that must be considered is shown in the interstellar medium. Fortunately, the Jeans' criterion is still valid, so your discussion may hold. But, Jeans' criterion is only a necessary condition when shear is present. A sufficient condition is that field lines have to be sheared much more efficiently perpendicular to the axis of a protostar than parallel to it. This makes for a slightly higher density in the Jeans' criterion.

One can thus have star formation only in those regions where the shear is favourable.

ZINNECKER :

I don't understand your claim that hierarchical fragmentation is not important. After all, observations show that there are filaments or sheets which contain dense knots of gas which in turn contain young stellar objects.

SILK :

Numerical collapse simulations suggest that multiple fragmentation during dynamical collapse is rather rare. The sheets and filaments seem to form first and then fragment and form protostars.

McGREGOR :

Gatley, Jones and Hyland have found at least four massive protostars near 30 Dor where there is no large molecular cloud and the dust temperature is much higher than in galactic star formation regions.

SILK :

It would be interesting to see quantitatively if this result provides evidence for heating by the nearby O stars.

APPENZELLER :

I fully agree that the suppression of the formation of low mass stars after high mass stars have formed may lead to different IMF's in different associations. However, I am not quite convinced that this must lead to a bimodal distribution. From data on young associations of low mass stars, we know e.g. that in the Lup dark cloud we observe only very low mass stars, in Orion also medium and some high mass stars, and in other associations a mix between the Lup and Orion IMF. Could there not simply exist a smooth transition from massive-star-poor to massive-star-rich associations?

SILK :

In the solar neighbourhood, molecular clouds appear to quiscently form low mass stars for 10^7 yrs or longer. I agree that the data you mention suggests these clouds subsequently form OB stars. This may well be a stochastic effect: a very large cloud should be able to form more OB stars than a small cloud, and the strong heating associated with these massive stars is what I have argued will induce a starburst of primarily more massive stars. Such giant clouds are found in the inner galaxy and presumably they are also responsible for such giant HII regions as 30 Doradus.

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