# ON WHY WE NEED A GOOD THEORY OF STAR FORMATION

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In this conference we have had good lead speakers who have produced fine summaries of what has been achieved. Rather than summarise these summaries I have decided to ask how the type of work discussed here will influence the rest of astronomy. By comparing what we now know about star formation with what other parts of astronomy need from us, we shall see what is still needed and put in perspective what has been achieved.

There are three great areas of astronomy to which a theory of star formation is vital:

I. The formation and evolution of galaxies.
II. The understanding of the properties and evolution of all those fascinating objects that can be classed as nebular variables or nebular objects.
III. The origin of the solar system.

What do each of these subjects need from a theory of star formation?

I. When we model a galaxy falling together out of the intergalactic medium(1), (2), (3) we need to know the rate at which the gas is converted into stars. Too small a star formation rate will lead to the energy of collapse being lost via shocks and radiation; the resulting cold galaxy would no doubt fragment and shrink into a dense rotationally dominated flat structure. It seems unlikely that elliptical galaxies could be made. Too fast a rate of star formation would lead to galaxies of very low density with very little contraction from the pregalactic state. Such diffuse systems would be dominated by random motions and flat Galaxies probably would not be formed. It is the star formation rate which determines the density at which energy conserving stellar dynamics takes over from dissipative gas dynamics. The laws of star formation are vital to any understanding of what makes the difference between a spiral Galaxy and an elliptical. How does the rate of conversion of gas into stars per unit volume depend on the gross physical state? This rate $\mathcal{R}$ probably depends on gas density $\rho_g$, gas sound speed $c_s$, shock frequency $\omega_s$, shock strength $V_T/c_s$, gas rotation $\Omega$ and shearing rate A, the magnetic field

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strength $|\underset{\sim}{B}|$, the gas metal abundance Z and possibly the background star density $\rho_*$. Thus

$$\mathcal{R} = \mathcal{R}\,(\rho_g, c_s, \omega_s, V_T/c_s, \Omega, A, |\underset{\sim}{B}|, Z, \rho_*).$$

However if we knew the true functional form of $\mathcal{R}$ and offered it to a galaxy builder he would probably tell us "Oh, go and jump in the lake, that's far too complicated". Thus galaxy builders need oversimplified average laws like Schmidt's suggestion $\mathcal{R} = C\,\rho^2$.
Can we yet proffer a better simplified law? In dimensions $[\mathcal{R}] = [\rho][\omega]$. It is reasonable to choose the $\rho$ to be $\rho_g$ since there can be no star formation with no gas, thus our choice is really reduced to the choice of the rate $\omega$. Larson[3] has experimented with the most rapid growth rate of perturbations $\omega = (4\pi G\rho_g)^{\frac{1}{2}}$ but finds that a stronger dependence on $\rho_g$ gives better looking galaxies in the collapsing phase. Also a slower rate is needed in the disc phase of spiral galaxies to agree with observations of Hamajima & Tosa[4], Madore[5] and others in external galaxies. Lindsey Smith[6], Talbot[7],[8] and others have tried incorporating ideas from the density wave picture into proposed laws but the known data on star formation do not yet deserve much more than the simplest parameterisation, and as Lequeux[9] pointed out it is not yet so certain that departures from Schmidt's idea are needed[10]. Nevertheless more data and more work of the type Lindsey Smith described could give us vital clues by discovering semi-empirically which are the factors that $\mathcal{R}$ depends on most heavily. One might attempt to test hypotheses like $\mathcal{R} \propto \rho_g\,(\omega_{max}^2 + \omega_s^2)^{\frac{1}{2}}$ where $\omega_{max}$ is the maximum growth rate of the modes of the dispersive relation for the gas and $\omega_s$ is the frequency of shock encounters by a gas element. Note that for rotating systems $\omega_{max}$ becomes zero when the surface density drops below $\kappa c_s/\pi G$ so only shock induced star formation would occur in flat systems if such a law held unless $c_s$ became very low. Talbot has been working in this area[8]. The modifications to the dispersion relations when a magnetic field is present are known[11], but with our present knowledge such complication is probably more of a hindrance than a help. The dependence of $\mathcal{R}$ on the metal abundance in the gas is also important for chemical evolution and any empirical evidence for such dependence might put the metal enhanced star formation theory on a less shaky foundation. A study of the relative rates of star formation in the Small and Large Magellanic Clouds might be a reasonable test of the dependence of $\mathcal{R}$ on Z. One result of this conference that is reasonably clear is the great importance of shock waves in star formation and it is gratifying that one of the first models to take this idea seriously, Elmergreen & Lada's[12] is already making sense of Blaauw's[13] studies of chains of associations.

The initial mass function with which stars are formed is vital to theories of the chemical evolution of galaxies. Does the average mass function depend on the average conditions in each ring of a galaxy or is it of a universal Salpeter form $N(m) \propto m^{-2.35}$ ? The high mass end determines the element production in the galaxy, the 1 $M_\odot$ range determines the giants that produce the light of the elliptical galaxies and central bulges, while the low mass end contains most of the mass and thus

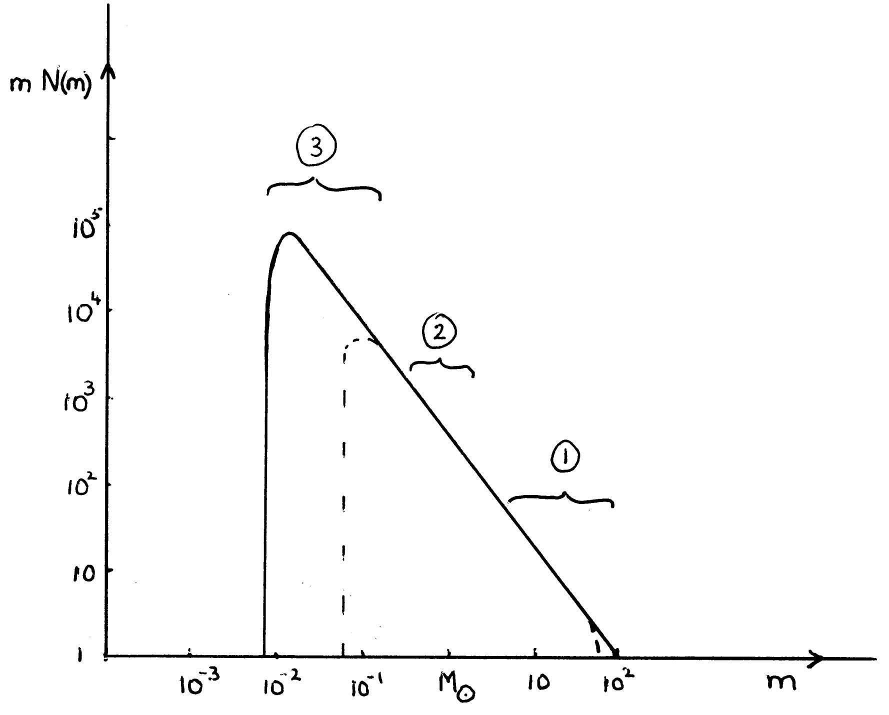


Figure 1

The initial mass function at birth, after Salpeter. Conventionally this has a lower cut-off of 0.06 $M_\odot$ below which stars cannot burn hydrogen but opacity limited fragmentation theory leads to a lower cut-off near 0.01 $M_\odot$. (Low & Lynden-Bell, MNRAS 176, 367, 1976.)

Stars in mass range ① give metal production. The yield of element production per gram of star formation is determined by the ①/③ ratio while the mass to light ratios of old populations are determined by the ② / ③ ratio.

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determines how much mass is locked away for ever after star formation. Thus the detailed form of the average mass function is crucial.

There is evidence that the mass function does change from cluster to cluster[(14),(15)] and an important question for research is: What are the conditions that give mass functions deficient in low mass stars and what conditions give rise to mass functions with no high mass stars? If we knew the answer for systems in our vicinity we could then assess whether the average mass function should be expected to vary from centre to edge in other galaxies. By and large I have been impressed with how well the concept of a universal Salpeter law can be made to explain the abundance gradients in spirals and, with the aid of some concentration of metals to the middle, the colours of ellipticals. Thanks to Larson's[(16,17)] idea that the gas mass was initially small as the Galaxy was being formed, so that the initial metal production rapidly raised the abundances to half solar, I[(18)] no longer find Schmidt's G dwarf numbers a problem. Presently the only result I know of that stands out against a universal average mass function is Faber's impressive correlation between total colour and total luminosity of the massive E galaxies[(19)]. This gross difference which almost certainly reflects a higher metal abundance in the more massive galaxies cannot be explained without a bias towards more massive stars being formed there. However determination of the mass to light ratios of the cD supergiants in Coma suggests that they are larger than for normal galaxies which favours many low mass stars.

Some years ago Professor McCrea asked the important question: "How does a mass of gas over 100 $M_\odot$ know that it is too heavy to form a star?". In a similar vein I would like to ask: "How does a mass of gas in a very massive galaxy know the mass of the galaxy it is in?". If Faber's colours are to be explained in terms of different mass functions, the star formation has to know - perhaps the strength of the shocks or even the background temperature of the new giant elliptical itself change the mass function's shape. Can a shock strength versus slope correlation be found in our Galaxy? One possibility is that the minimum mass cut off c the Salpeter function is raised by the higher background temperature of the massive galaxies at the time of their formation? Such a picture would fall in line with Silk's idea on how the mass spectrum is formed in a star cluster.

I now turn to the Nebular Variables and Nebular Stars. To many of us the combined data from CO and the infra-red has been the real highlight of this conference and there can be few of us who do not believe that most stages of star formation are represented in the ensemble of data. To theoreticians it is wonderful that at last Jeans unstable objects have been found and local collapse rather than overall collapse of the whole cloud seems to demonstrate the fragmentation of the large mass into what must become protostellar clouds.

The great important of living dangerously and working out exactly what should be seen from one's models was well illustrated. Larson's beautiful work on the early stages of star formation and mass accretion

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now seems in serious conflict with observations by Cohen[21], Strom[22] and Herbig[23] on the T Tauri stars which indicate that the accretion is stopped much earlier than Larson envisaged. It is grand to see theory and observation so well in contact that they can have a real argument! This causes the observers to fret about their spectral types and infra-red colours and the theorists to worry about their physics and their computational schemes. This is most healthy for both sides but here there is an added worry that it is our lack of a full understanding of coronal heating and stellar winds that may be causing all the trouble.

Of the excellently prepared and delivered reviews I found Penzias's remark that he was not sure if anything else much was added to the CO results by the other molecular lines the most refreshing, but the review by Strom[22] threw out many fascinating ideas for identifying the place of the different stellar and near stellar objects in the evolutionary sequence. I found the idea that most Herbig Haro objects were reflections of searchlight beams especially fascinating. Herbig's objections that the two outer objects of three in a line have large and parallel proper motions is open to a check. If the high proper motions are accompanied by suitably high radial velocities then the searchlight idea is wrong, but if the radial velocities are small, then the searchlight idea formed by holes in an opaque screen near the star is very likely to be correct after all.

Less secure were Strom's[22] arguments about the colours of T Tauri stars during variation. If the dimming is caused by objects of near stellar size in orbit, then the objects may be totally opaque to radiation so that the variation of light is a superposition of many partial eclipses. It is not then necessary to have $A_V/E(B-V)$ near 3, much larger values are possible. More work needs to be done on the origin if the veiling radiation and the reasons why it varies at all. This is no doubt tied up with the mysterious cause of the violently outflowing stellar wind. A point that Larson and others emphasised is important. Simultaneous inflow and outflow is a very natural phenomenon, as anyone who has tried to balance a heavy liquid on top of a light one will agree. Sometime in the evolution of a nebula a relatively cold enveloping cloud will have to be supported on a hot envelope about the star which is trying to make a wind. In this configuration opaque tongues of the cold heavy material might well fall down to the photosphere while the hot wind that was supporting it escaped. Only if both infalling and outflowing material are equally observable will no net flow be deduced. I am biassed to think that if inflowing tongues are opaque then they may be hard to see in the spectrum. By contrast the outflowing wind may be easier. Could such phenomena explain both the outflow and the variability because collisions of the tongues with the atmosphere would cause variable shock heating? The observers are convinced of the violent outflow from T Tauri stars. Levine has proposed that the solar corona is heated by magnetic flux reconnection[24]. The very strong K line strengths in the T Tauri stars would indicate very strong magnetic activity, very strong coronal heating, and very strong winds would result. The floating of the magnetism out of the newly formed star involved in such a mechanism is rather attractive as an idea, but since the phenomenon is so poorly understood even in the Sun it will be difficult to give a good basis for such a theory of T Tauri winds.

Such violent magnetic activity associated with the solar nebula might well give excess cosmic ray flux during the formation of the solar systems. The model by Gahm et al[25] for R U Lupi is especially attractive in that it ties into solar system models so naturally. I feel it deserves more discussion than it has had at this conference.

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