Mon. Not. R. astr. Soc. (1992) **256**, 641–646

Towards understanding the stellar initial mass function

Richard B. Larson
Yale Astronomy Department, Box 6666, New Haven, CT 06511, USA

Accepted 1992 January 6. Received 1991 November 11; in original form 1991 July 15

SUMMARY

It is suggested that the stellar initial mass function (IMF) is closely related to the geometrical structure of star-forming clouds, and that the power-law form of the upper IMF results from accretion processes in hierarchical groupings of forming stars. If the stars in these groupings form from linear cloud structures such as filaments or strings of clumps, and if the overall structure of star-forming clouds is sheet-like or two-dimensional, then the mass of the most massive star that can form in each grouping is predicted to increase as the square root of the group mass; this in turn implies an IMF with a slope of $x=2$, in acceptable agreement with observations. More generally, if star-forming clouds have fractal structures, and if stars form with masses proportional to the linear dimensions of the basic cloud structures from which they form, as might be expected if these structures are isothermal filaments, then the predicted slope x of the IMF is equal to the cloud fractal dimension, which has been estimated by several studies to be about 2.3. The fragmentation of such filaments is also predicted to yield a minimum stellar mass of the order of $0.1\,M_\odot$.

Key words: accretion, accretion discs – stars: formation – stars: luminosity function, mass function – interstellar medium: clouds.

1 INTRODUCTION

A major goal of studies of star formation is to understand the spectrum of masses with which stars are formed, since the initial mass spectrum plays a fundamental role in determining the observed properties of stellar systems and their evolution with time. The observational evidence concerning the stellar IMF has been reviewed extensively by Scalo (1986). While it may show some variability, particularly for low-mass stars (Larson 1982; Scalo 1986; Myers 1991), the observed IMF nevertheless seems to have the same basic form everywhere; its essential features are a characteristic stellar mass of the order of $1\,M_\odot$ and a power-law tail of apparently universal slope toward higher masses. These basic features might result from the existence of a characteristic scale for cloud fragmentation and from accretion processes that build up a high-mass tail on the IMF, as reviewed by Larson (1986, 1989, 1991). In addition to the Jeans length, which determines the basic scale of fragmentation, the numerically similar 'Alfvén length', or minimum scale on which magnetic effects can act, may also play a role in setting the characteristic stellar mass (Mouschovias 1990). Further reviews discussing these and other possible ways of accounting for the stellar IMF have been given by Elmegreen (1985), Zinnecker (1987, 1989), Cayrel (1990), and Ferrini (1991).

If stars form in relative isolation, it is possible that they will continue to gain mass almost indefinitely by accretion until other effects such as stellar winds intervene to stop the accretion (Shu *et al.* 1988). However, the extensive data yielded by recent infrared surveys suggest that most stars do not form in relative isolation but in dense groups or clusters (Lada & Lada 1991; Evans 1991). The efficiency of star formation in these clusters is observed to be fairly high, typically 20 to 40 per cent, and therefore most of the stars in these clusters cannot grow indefinitely by accretion; only a small fraction of the stars present can attain much larger masses in this way. Massive stars have in fact long been known to form in clusters or associations (Blaauw 1964), and there is even a possible tendency for the most massive stars to form in the dense cores of large clusters, suggesting that accretion processes in cluster cores may indeed play an important role in the formation of massive stars (Larson 1982).

The formation of massive stars by accretion can readily account, at least schematically, for an upper IMF of power-law form. The simplest possibility is that stars accrete gas from an infinite uniform medium, as in classical accretion theory; this predicts an upper IMF of power-law form with roughly the correct slope (Zinnecker 1982). However, such a model is clearly oversimplified for stars forming in clusters, where the gas is clumpy and the total amount available for accretion is limited; in such a situation the runaway growth predicted by classical accretion theory cannot occur, and interactions among the clumps or forming stars may play an important role (Silk 1978; Larson 1982, 1990). If most of the gas in a forming cluster is in clumps, an accreting object may gain mass mainly by accreting these clumps; the total mass that it can attain will then depend on the number of clumps with which it can interact, and this will depend in turn on the size of the cluster.

It is also possible that the power-law form of the upper IMF results from a tendency for stars to form in a self-similar hierarchy of clusters and subclusters (Larson 1978, 1991). The probable importance of hierarchical clustering for star formation is suggested by the presence in star-forming clouds of complex hierarchical and perhaps even fractal structure (Scalo 1985, 1988, 1990; Falgarone 1989; Dickman, Horvath & Margulis 1990; Lada, Bally & Stark 1991; Falgarone & Phillips 1991; Falgarone, Phillips & Walker 1991), and also by the fact that many young star clusters appear to contain subclusters (Elson 1991). Within each subsystem, accretion processes may be expected to produce a spectrum of stellar masses extending up to a maximum mass that, in general, increases with the size of the system because of the increasing amount of material available for star formation. Observationally, a dependence of the maximum stellar mass on the total mass of a system is suggested by the fact that in regions of star formation, the mass of the most massive star present increases systematically with the mass of the associated molecular cloud (Larson 1982; Stacy *et al.* 1988). If the efficiency of star formation is approximately the same in different regions, as is suggested by the evidence (Evans & Lada 1991), then a similar correlation is implied between the maximum stellar mass and the total mass of stars in each region.

If the mass $M_{\rm max}$ of the most massive star that can form in a stellar system increases as some power $n<1$ of the mass of the system, i.e. if

$$M_{\rm max} \propto M^n_{\rm system}, \qquad (1)$$

and if all of the stars belong to a clustering hierarchy in which the mass of the most massive star in each subsystem is related in the same way to mass of the subsystem, then the stars making up the hierarchy will have a power-law distribution of stellar masses m given by

$$dN/d\log m \propto m^{-x}, \qquad (2)$$

where $x=1/n$ (Larson 1991). This follows because each star of mass m in such a hierarchy is, by assumption, the most massive star of a subgroup whose mass is proportional to $m^{1/n}$; since the number of such subgroups is inversely proportional to their mass, the number of stars of mass m in the hierarchy is also inversely proportional to the subgroup mass, that is, it is proportional to $m^{-1/n}$. Each level of the hierarchy corresponds to a fixed logarithmic interval in mass, so this proportionality also holds for the number of stars per unit logarithmic mass interval. Thus, for example, the observed IMF slope of $x=1.7\pm0.5$ (Scalo 1986) could be reproduced if n were equal to $1/x=0.6\pm0.2$, which within the uncertainties is consistent with the value $n\sim0.43$ suggested by observations of regions of star formation (Larson 1982). In the present paper, this approach to accounting for the form of the stellar IMF will be pursued further, and a possible simple origin for power-law relations like (1) and (2) will be suggested.

2 THE FORMATION OF MASSIVE STARS AND THE ORIGIN OF THE UPPER IMF

If massive stars are formed by accretion processes in groups or clusters, and if the accreted material is mainly in the form of clumps, then the maximum mass that a star can attain will be limited by the number of clumps with which it can interact. The accretable mass will also be limited by the fact that many of the clumps are likely to be collapsing into stars, so that the gas available for accretion is exhausted after only a few collapse times. Thus, while the accumulation processes involved in building up massive stars may resemble those postulated in clump coagulation models for the origin of the IMF (Nakano 1966; Arny & Weissman 1973; Silk & Takahashi 1979; Pumphrey & Scalo 1983), the existence of a limit on the total amount of mass that can be accreted introduces an important modification to such a picture.

The amount of time available for the growth of a massive star in a forming stellar system may be comparable to the crossing time of the system, and the maximum mass that the star can acquire may be of the same order as the amount contained in all of the clumps that it could encounter and accrete in traversing the system. If the system has a diameter l, and if it fragments into contiguous subregions or clumps of diameter d, then the maximum number of such clumps that could be encountered by an object traversing the system is of the order of l/d. If the accumulation of gas occurs not as a result of the motion of the object but rather as a result of an overall collapse of the system predominantly in one dimension (Larson 1985), the maximum number of clumps that could be accumulated into one object will again be of the order of l/d. A third, perhaps more realistic possibility to be considered in Section 3 is that the cloud fragments into filamentary strings of clumps which eventually accumulate into dense cores; again, the largest number of clumps that can be accumulated into one object will be of the order of l/d, where l is here the filament length. Thus, in all of these cases, it is plausible that the maximum stellar mass varies approximately as l/d, and so increases roughly linearly with the size of the system.

If the maximum number of clumps that can be accreted by a forming star in a system of size l is of the order of l/d, and if the average mass of these clumps is approximately the Jeans mass $M_{\rm J}$, then the mass of the most massive star that can form in the system is roughly

$$M_{\rm max} \sim (l/d)\, M_{\rm J}. \qquad (3)$$

The total mass of the system is just the total mass of all the clumps contained in a region of size l, and this depends on the geometry of the system. For example, if the cloud is basically sheet-like or two-dimensional, the number of subregions of diameter d in a region of diameter l is approximately $(l/d)^2$, and the mass of the system is approximately $(l/d)^2 M_{\rm J}$. The mass of the most massive star that can form in the system is then roughly the geometric mean of the clump mass and the system mass, i.e.

$$M_{\rm max} \sim (M_{\rm J} M_{\rm system})^{1/2}. \qquad (4)$$

As was noted by Larson (1991), this implies a power-law IMF with a slope $x=2$, which is in acceptable agreement with the observations. If the system is basically three-dimensional rather than two-dimensional, the relation between maximum stellar mass and system mass will still be given by a relation of the form (1) but with $n=1/3$ rather than 1/2, resulting in an IMF with a slope $x=3$, which is larger than is observed. The fact that the value of x predicted in the two-dimensional case agrees better with observations is consistent with theoretical expectations that fragmenting clouds should be more nearly two-dimensional than three-dimensional (Larson 1985). The dependence of the IMF on the geometry of star-forming clouds suggests that a fractal description may be useful, and such a description will be considered further in Section 3.

The above argument relating the maximum stellar mass to the mass of the system assumes that a growing massive object will accrete clumps only if they are encountered within a distance comparable to the clump size d. This is obviously true for the simple coalescence model, but the validity of this assumption is less apparent in the case where a star has already formed and is continuing to accrete matter gravitationally, since the star can in principle accrete gas from a greater distance. However, if the gas being accreted is clumpy, accretion is efficient only for a direct collision between the star and a gas clump. This is because the angular momentum of the gas passing on one side of the star must approximately cancel that of the gas passing on the other side; otherwise, for example in a grazing encounter where the gas has a strong density gradient, the accretion rate is greatly reduced (Fryxell & Taam 1988). Thus, there may still be an effective accretion radius that is comparable to the clump size, just as in the simple coalescence model.

Another important assumption made above is that gas is accumulated primarily by motions in one dimension. In addition to the possibilities mentioned above, this might be the case if the gas were constrained to move along magnetic field lines. In general, however, motions in more than one dimension could also be involved. An extreme case might be that a central object in each system gains material by a radial collapse of the system as a whole; the most massive star might then acquire a larger fraction of the total mass, and a smaller IMF slope might be predicted. In the limit, the most massive star in each system might always acquire the same fraction of the total mass, regardless of the size of the system; this would imply $n=1$ and $x=1$. A better understanding of accretion processes in forming stellar systems will be needed before the possible importance of such effects can be evaluated more quantitatively, but meanwhile it seems significant that the smallest and largest values of x obtained in the limiting cases considered here are 1 and 3, since nearly all of the values of x derived from observations do, in fact, lie in this theoretically most plausible range (Scalo 1986).

3 A FRACTAL DESCRIPTION

Evidently, the initial stellar mass spectrum depends on the way in which gas accumulation processes are organized in star-forming clouds, and this depends in turn on the detailed structure of these clouds. Hierarchical structure, if present, will clearly play an important role, and the slope of the IMF will also depend on the basic dimensionality of these clouds. As reviewed by Scalo (1985, 1988, 1990), there is indeed considerable evidence that molecular clouds have complex hierarchical structures, and also that they are typically wispy or filamentary in shape. Theoretical reasons for expecting star-forming clouds to have sheet-like structures have been discussed by Larson (1985), and reasons for expecting such sheets to fragment into filaments which finally break up into clumps have been discussed by Miyama, Narita & Hayashi (1987a, b). Such a picture is supported by numerical simulations of the collapse of rotating clouds, which show that the disc formed by the collapse first breaks up into filaments, and that dense knots then form in these filaments and grow by accreting matter from them (Miyama, Hayashi & Narita 1984; Monaghan & Lattanzio 1991). Observational evidence that stars often form in filaments is provided by the fact that the cloud cores in which stars form are typically elongated, and often appear to be parts of filaments (Schneider & Elmegreen 1979; Myers *et al.* 1991).

The results of the detailed simulations of Monaghan & Lattanzio (1991) also resemble the results of simulations of cosmological large-scale structure which show the formation of intricate fractal-like networks of filaments (Park & Gott 1991; Kates, Kotok & Klypin 1991; Beacom *et al.* 1991). In these cosmological simulations, the material in the filaments eventually accumulates into dense clumps at the nodes of the network. If star-forming clouds also contain complex networks of filaments, the material in these filaments may accumulate in a similar way into dense cores, and stars may form in these cores. If such clouds are in fact fractal in structure (Scalo 1990; Dickman *et al.* 1990; Falgarone *et al.* 1991), then the stars will form in a hierarchy of groupings and subgroupings, and if the filaments fragment into strings of clumps, then the more massive stars will form by the accumulation of clumps, in which case this picture becomes identical to the clump accretion model discussed in Section 2. However, with a fractal description, greater generality is possible because the structure of the system can be characterized by a dimension that need not be an integer. A fractal description of star-forming clouds was earlier proposed by Henriksen (1986), although with somewhat different assumptions from those adopted here.

A fractal structure is one that is made up of substructures similar to the whole, and it can be characterized by a fractal dimension D which is such that the distribution of the linear sizes l of the substructures is given by

$$dN/d\log l \propto l^{-D} \tag{5}$$

(Mandelbrot 1977, 1982). If a star-forming cloud can be approximated as a fractal structure, then the relevant substructures are those regions of the cloud that form stellar groupings and subgroupings. For example, if the cloud contains a fractal network of filaments, the relevant star-forming regions would be the various branches of this network. The fractal dimension D of any structure may be regarded as a measure of how much of space is filled by it; for example, a network that uniformly covers a two-dimensional sheet will have a fractal dimension $D=2$ (an example is shown on page 61 of Mandelbrot 1977), while one that fills up a larger region of space, such as a convoluted sheet or a sponge, will generally have a larger fractal dimension.

If each fractal region of size l contains, say, one filament of length l, then equation (5) also gives the distribution of filament lengths in the cloud. If the filaments all have the same mass per unit length, their mass distribution will have the same form as this length distribution. A constant mass per unit length is in fact expected for filaments formed by the fragmentation of an isothermal sheet, since such filaments are predicted to have line densities comparable to the critical value,

$$m/l=2c^2/G, \tag{6}$$

appropriate for an equilibrium isothermal cylinder with sound speed c (Miyama *et al.* 1987a). Filaments of any origin should have line densities comparable to this critical value as long as they are significantly gravitationally bound and are not highly transient, since filaments with larger or smaller lines densities would quickly collapse or disperse. If filaments with a constant line density and a length distribution given by equation (5) condense efficiently into stars, then the predicted spectrum of stellar masses m will be

$$dN/d\log m \propto m^{-D}. \qquad (7)$$

This result is identical to equation (2) if $x=D$; thus, under the above assumptions, the predicted IMF slope is just the fractal dimension of the star-forming cloud.

This result may also be obtained from the general property of fractals that the mass contained in a substructure of size l is proportional to l^D if all points in the fractal set have the same mass. This relation will hold, in particular, for the branches of a fractal filamentary network if all of the filaments have the same mass per unit length. If the mass of the most massive star that can form in a region of size l is proportional to l, as suggested above and in Section 2, then this maximum stellar mass will also be proportional to a power $1/D$ of the total mass in the region, i.e. equation (1) will hold with $n=1/D$. Thus, since $x=1/n$, it follows that $x=D$.

The projected boundaries of molecular clouds appear to be fractal curves with dimensions of about 1.2 to 1.4 (Scalo 1990; Dickman *et al.* 1990; Falgarone *et al.* 1991), which suggests that the surfaces of these clouds may be fractal surfaces with dimensions of about 2.2 to 2.4. There is not necessarily any simple relation between the fractal dimension of the surface of a cloud and that of its internal structure (Scalo 1988), nor does it even necessarily follow from this evidence that the internal structure of molecular clouds can be described in fractal terms. However, if molecular clouds have very open structures in which most of the matter is concentrated into thin dense substructures occupying only a small fraction of the volume (Stutzki *et al.* 1991; Falgarone *et al.* 1991), it is possible that much of their internal structure is directly reflected in surface features. For example, in a cloud with the structure of a convoluted sheet or an open sponge in which all parts are close to the surface, each internal structural feature might correspond to, or be observable as, as surface feature of the same size; the fractal dimension measured for the surface might then apply approximately to the cloud as a whole. If molecular clouds can thus be characterized at least roughly as having fractal structures of dimension $D\sim 2.3$, and if stars form with masses proportional to the linear sizes of the basic structural elements as suggested above, then the predicted IMF slope is $x\sim 2.3$.

This value of x is similar to that found by Miller & Scalo (1979) for massive stars, and it also agrees with the value of x inferred from the observed relation between maximum stellar mass and cloud mass (Larson 1982), which since $n\sim 0.43$ implies $x=1/n\sim 2.3$. However, most of the values of x compiled by Scalo (1986) are somewhat smaller than this, and fall in the range 1.7 ± 0.5. It is not certain that this difference is significant, but two effects might reduce the predicted IMF slope. A smaller value of x would be predicted if stars form only in parts of molecular clouds that constitute a subset having a smaller fractal dimension than the cloud as a whole. A smaller value of x would also be predicted if stars form with masses proportional to a power higher than unity of the linear sizes of the basic cloud structures in which they form; this might be the case, for example, if the larger structures tend to have higher temperatures.

4 FURTHER DISCUSSION AND IMPLICATIONS

4.1 The origin of fractal structure in clouds

The above way of accounting for the form of the upper IMF depends on the assumed presence of hierarchical structure of some sort in star-forming clouds, but the origin of this structure and such detailed properties as whether all of the subunits are gravitationally bound have been left unspecified. It is not crucial for the above picture whether the accumulation processes that occur in the subsystems are caused by self-gravity or by other effects. However, the hierarchical structure itself probably must be created mainly by the dynamical processes that form and shape molecular clouds and not by the subsequent action of self-gravity, since gravity can only amplify existing density fluctuations and cannot create new ones. This is also suggested by the fact that the hierarchical structure found in the numerical simulations of cloud fragmentation of Larson (1978) apparently originated mostly from density fluctuations that were present initially, since less substructure was found when smoother initial conditions were assumed.

The most obvious possible source of hierarchical density fluctuations in interstellar clouds is turbulence. Falgarone (1989) and Falgarone & Phillips (1991) have noted that the fractal dimension of molecular cloud surfaces is similar to the fractal dimension of $\sim 2.35\pm 0.05$ that characterizes various interfaces in turbulent flows (Sreenivasan & Méneveau 1986; Sreenivasan 1991), and they suggest that this may reflect the presence in molecular clouds of turbulence similar to laboratory and atmospheric turbulence. Some similarity in structure between the densest parts of molecular clouds and the regions of strongest energy dissipation in turbulent flows might be expected if turbulence is important in compressing the gas in these clouds (Larson 1981). Turbulence is usually generated by instabilities in shear flows, and this may be the case also in molecular clouds; several well-studied clouds have strikingly comet-like structures with irregular filaments whose appearance suggests the presence of turbulence generated by interaction with energetic external gas flows (Bally *et al.* 1991). Numerical simulations of compressible turbulence often produce filamentary structures, and in the presence of self-gravity, these structures are also clumpy (Tajima & Leboeuf 1980; Passot, Pouquet & Woodward 1988; Léorat, Passot & Pouquet 1990; Pouquet, Passot & Léorat 1991). Thus it is possible that turbulence can account for at least some of the structural properties of molecular clouds. However, the dynamical processes involved must be very complex, and much remains to be learned about them. For example, it will be necessary to understand better whether there is indeed a relation between the intermittency of turbulence and the fractal structure of molecular clouds, as has been suggested by Falgarone & Phillips (1990, 1991).

4.2 The minimum stellar mass

Whatever the origin of the hierarchical structure in molecular clouds, there is presumably a minimum size for any cloud structures that can form stars, given by the minimum length-scale on which self-gravity is important. For example, filaments that originate from the fragmentation of a sheet will have a minimum length that is approximately the Jeans length for sheet fragmentation, or $2c^2/G\mu$ where μ is the surface density. If the filaments have a mass per unit length comparable to the critical value (6), then the minimum filament mass is approximately $4c^4/G^2\mu$, which is essentially the Jeans mass for sheet fragmentation (Larson 1985). Smaller clump masses might result if the filaments become much thinner before breaking into clumps (Miyama *et al.* 1987b), but simulations of the fragmentation of collapsing cylinders show that the maximum number of clumps that can be formed is only about 4 times the number predicted from the initial Jeans length (Bastien *et al.* 1991); this suggests that there is a minimum clump mass which is roughly one-quarter of the Jeans mass, or approximately $c^4/G^2\mu$. Since the Jeans mass in typical dark clouds is of the order of $1\,M_\odot$ (Larson 1986), the minimum clump mass is then predicted to be of the order of $0.25\,M_\odot$.

If such clumps collapse into stars with reasonably high efficiency, as is expected theoretically (Larson 1984) and as is observed to be the case at least in clusters, a minimum stellar mass of the order of $0.1\,M_\odot$ is predicted. This prediction may be compared with the fact that, at least according to some determinations, the IMF has a peak at about $0.25\,M_\odot$ and declines steeply toward lower masses (Scalo 1986). The lower end of the IMF remains very uncertain, but even if the IMF does not drop steeply toward lower masses, it appears unlikely that there can be much mass in stars less massive than about $0.1\,M_\odot$ (Larson 1991). Thus, the picture of star formation in fractal filamentary clouds that has been suggested here may be able to account not only for the slope of the upper IMF but also for the turnover of the IMF at low masses and for a possible minimum mass of the order of $0.1\,M_\odot$.

This minimum mass is predicted to depend on cloud properties, especially the temperature (Larson 1985), so that the lower IMF might be expected to differ in regions where the clouds have systematically different properties. As reviewed by Myers (1991), there is indeed evidence for differences in the typical masses of T Tauri stars observed in different regions, and these differences appear to correlate with the properties of the associated molecular clouds; larger clouds, which tend to be warmer, also appear to form T Tauri stars with higher typical masses, in qualitative agreement with theoretical expectations.

5 CONCLUSIONS

In this paper it has been suggested that the stellar IMF depends on the geometrical structure of star-forming clouds, and in particular that the power-law form of the upper IMF results from the presence of hierarchical or fractal structure in these clouds. An IMF in reasonable agreement with observations is predicted if star-forming clouds have fractal structures and if stars form with masses proportional to the linear dimensions of the basic star-forming cloud structures; the slope of the IMF is then the same as the cloud fractal dimension, which is suggested by observations to be about 2.3. If the basic star-forming structures are isothermal filaments, the fragmentation of these filaments is also predicted to yield a minimum stellar mass of the order of $0.1\,M_\odot$.

The assumption of hierarchical structure in star-forming clouds is fundamental to this picture, and there is indeed considerable evidence for such structure, but its origin is not yet well understood. The most likely explanation is that it is generated by turbulence, but the internal motions in molecular clouds are supersonic and probably also hydromagnetic, and much further work will be required to clarify the role of these motions in structuring molecular clouds.

The validity of these ideas must, of course, ultimately be demonstrated by observations. This should provide motivation for continuing efforts to study in increasing detail the structure and dynamics of molecular clouds and the relations between the properties of these clouds and the properties of the stellar systems that form in them.

ACKNOWLEDGMENT

I thank the referee, J. M. Scalo, for comments that led to a number of clarifications in the paper.

REFERENCES

Arny, T. & Weissman, P., 1973. *Astr. J.*, **78**, 309.
Bally, J., Langer, W. D., Wilson, R. W., Stark, A. A. & Pound, M. W., 1991. In: *Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147*, p. 11, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.
Bastien, P., Arcoragi, J.-P., Benz, W., Bonnell, I. & Martel, H., 1991. *Astrophys. J.*, **378**, 255.
Beacom, J. F., Dominik, K. G., Melott, A. L., Perkins, S. P. & Shandarin, S. F., 1991. *Astrophys. J.*, **372**, 351.
Blaauw, A., 1964. *Ann. Rev. Astr. Astrophys.*, **2**, 213.
Cayrel, R., 1990. In: *Physical Processes in Fragmentation and Star Formation*, p. 343, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.
Dickman, R. L., Horvath, M. A. & Margulis, M., 1990. *Astrophys. J.*, **365**, 586.
Elmegreen, B. G., 1985. In: *Birth and Infancy of Stars*, p. 257, eds Lucas, R., Omont, A. & Stora, R., North-Holland, Amsterdam.
Elson, R. A. W., 1991. *Astrophys. J. Suppl.*, **76**, 185.
Evans, N. J., 1991. In: *Frontiers of Stellar Evolution*, p. 45, ed. Lambert, D. L., Astronomical Society of the Pacific, San Francisco.
Evans, N. J. & Lada, E. A., 1991. In: *Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147*, p. 293, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.
Falgarone, E., 1989. In: *Structure and Dynamics of the Interstellar Medium, IAU Colloq. No. 120*, p. 68, eds Tenorio-Tagle, G., Moles, M. & Melnick, J., Springer-Verlag, Berlin.
Falgarone, E. & Phillips, T. G., 1990. *Astrophys. J.*, **359**, 344.
Falgarone, E. & Phillips, T. G., 1991. In: *Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147*, p. 119, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.
Falgarone, E., Phillips, T. G. & Walker, C. K., 1991. *Astrophys. J.*, **378**, 186.
Ferrini, F., 1991. In: *Chemical and Dynamical Evolution of Galaxies*, eds Ferrini, F., Franco, J. & Matteucci, F., Giardini Editore, Pisa, in press.
Fryxell, B. A. & Taam, R. E., 1988. *Astrophys. J.*, **335**, 862.
Henriksen, R. N., 1986. *Astrophys. J.*, **310**, 189.
Kates, R. E., Kotok, E. V. & Klypin, A. A., 1991. *Astr. Astrophys.*, **243**, 295.

Lada, C. J. & Lada, E. A., 1991. In: *The Formation and Evolution of Star Clusters,* p. 3, ed. Janes, K., Astronomical Society of the Pacific, San Francisco.

Lada, E. A., Bally, J. & Stark, A. A., 1991. *Astrophys. J.,* **368,** 432.

Larson, R. B., 1978. *Mon. Not. R. astr. Soc.,* **184,** 69.

Larson, R. B., 1981. *Mon. Not. R. astr. Soc.,* **194,** 809.

Larson, R. B., 1982. *Mon. Not. R. astr. Soc.,* **200,** 159.

Larson, R. B., 1984. *Mon. Not. R. astr. Soc.,* **206,** 197.

Larson, R. B., 1985. *Mon. Not. R. astr. Soc.,* **214,** 379.

Larson, R. B., 1986. In: *Stellar Populations,* p. 101, eds Norman, C. A., Renzini, A. & Tosi, M., Cambridge University Press, Cambridge.

Larson, R. B., 1989. In: *Structure and Dynamics of the Interstellar Medium, IAU Colloq. No. 120,* p. 44, eds Tenorio-Tagle, G., Moles, M. & Melnick, J., Springer-Verlag, Berlin.

Larson, R. B., 1990. In: *Physical Processes in Fragmentation and Star Formation,* p. 389, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.

Larson, R. B., 1991. In: *Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147,* p. 261, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.

Léorat, J., Passot, T. & Pouquet, A., 1990. *Mon. Not. R. astr. Soc.,* **243,** 293.

Mandelbrot, B. B., 1977. *Fractals: Form, Chance, and Dimension,* Freeman, San Francisco.

Mandelbrot, B. B., 1982. *The Fractal Geometry of Nature,* Freeman, San Francisco.

Miller, G. E. & Scalo, J. M., 1979. *Astrophys. J. Suppl.,* **41,** 513.

Miyama, S. M., Hayashi, C. & Narita, S., 1984. *Astrophys. J.,* **279,** 621.

Miyama, S. M., Narita, S. & Hayashi, C., 1987a. *Prog. theor. Phys.,* **78,** 1051.

Miyama, S. M., Narita, S. & Hayashi, C., 1987b. *Prog. theor. Phys.,* **78,** 1273.

Monaghan, J. J. & Lattanzio, J. C., 1991. *Astrophys. J.,* **375,** 177.

Mouschovias, T. Ch., 1990. In: *Physical Processes in Fragmentation and Star Formation,* p. 117, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.

Myers, P. C., 1991. In: *Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147,* p. 221, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.

Myers, P. C., Fuller, G. A., Goodman, A. A. & Benson, P. J., 1991. *Astrophys. J.,* **376,** 561.

Nakano, T., 1966. *Prog. theor. Phys.,* **36,** 515.

Park, C. & Gott, J. R., 1991. *Mon. Not. R. astr. Soc.,* **249,** 288.

Passot, T., Pouquet, A. & Woodward, P., 1988. *Astr. Astrophys.,* **197,** 228.

Pouquet, A., Passot, T. & Léorat, J., 1991. In: *Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147,* p. 101, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.

Pumphrey, W. A. & Scalo, J. M., 1983. *Astrophys. J.,* **269,** 531.

Scalo, J. M., 1985. In: *Protostars & Planets II,* p. 201, eds Black, D. C. & Matthews, M. S., University of Arizona Press, Tucson.

Scalo, J. M., 1986. *Fundam. Cosmic Phys.,* **11,** 1.

Scalo, J. M., 1988. In: *Molecular Clouds in the Milky Way and External Galaxies,* p. 201, eds Dickman, R. L., Snell, R. L. & Young, J. S., Springer-Verlag, Berlin.

Scalo, J. M., 1990. In: *Physical Processes in Fragmentation and Star Formation,* p. 151, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.

Schneider, S. & Elmegreen, B. G., 1979. *Astrophys. J. Suppl.,* **41,** 87.

Shu, F. H., Lizano, S., Adams, F. C. & Ruden, S. P., 1988. In: *Formation and Evolution of Low Mass Stars,* p. 123, eds Dupree, A. K. & Lago, M. T. V. T., Kluwer, Dordrecht.

Silk, J., 1978. In: *Protostars & Planets, IAU Colloq. No. 52,* p. 172, eds Gehrels, T. & Matthews, M. S., University of Arizona Press, Tucson.

Silk, J. & Takahashi, T., 1979. *Astrophys. J.,* **229,** 242.

Sreenivasan, K. R., 1991. *Ann. Rev. Fluid Mech.,* **23,** 539.

Sreenivasan, K. R. & Méneveau, C., 1986. *J. Fluid Mech.,* **173,** 357.

Stacy, J. G., Benson, P. J., Myers, P. C. & Goodman, A. A., 1988. In: *Interstellar Matter: Proceedings of the Second Haystack Observatory Meeting,* p. 179, eds Moran, J. M. & Ho, P. T. P., Gordon and Breach, New York.

Stutzki, J., Genzel, R., Graf, U., Harris, A. I., Sternberg, A. & Güsten, R., 1991. In: *Fragmentation of Molecular Clouds and Star Formation,IAU Symp. No. 147,* p. 235, eds Falgarone, E., Boulanger, F. & Duvert, G., Kluwer, Dordrecht.

Tajima, T. & Leboeuf, J. N., 1980. *Phys. Fluids,* **23,** 884.

Zinnecker, H., 1982. In: *Symposium on the Orion Nebula to Honor Henry Draper,* eds Glassgold, A. E., Huggins, P. J. & Schucking, E. L., *Ann. New York Acad. Sci.,* **395,** 226.

Zinnecker, H., 1987. In: *Evolution of Galaxies, 10th European Regional Meeting of the IAU, Vol. 4,* p. 77, ed. Palous, J., Czechoslovak Academy of Sciences, Prague.

Zinnecker, H., 1989. In: *Evolutionary Phenomena in Galaxies,* p. 113, eds Beckman, J. E. & Pagel, B. E. J., Cambridge University Press, Cambridge.