RevMexAA (Serie de Conferencias), **22**, 13–17 (2004)

STAR FORMATION AT THE EDGE OF CHAOS: SELF ORGANIZED CRITICALITY AND THE IMF

Jorge Melnick[1] and Fernando Selman[1]

RESUMEN

La función inicial de masa (IMF) para estrellas más masivas que algunas masas solares, parece ser una función universal que puede ser aproximada por una ley de potencias con una pendiente sorprendentemente cercana al valor encontrado por Salpeter hace 50 años. Usamos el cúmulo central de 30 Doradus para determinar un valor exacto de la pendiente de la IMF y mostramos que los pocos valores discrepantes en la literatura, son causados por la sistemática en el tratamiento de datos. Proponemos que la formación de estrellas masivas muestra esta sorprendente regularidad en un amplio rango de parámetros físicos por estar regulada por la ley de la complejidad. Precisando, se encuentra en un estado crítico auto-organizado (SOC), un estado de transición entre el orden y el caos.

ABSTRACT

The IMF for stars more massive than a few solar masses appears to be a universal function that can be well approximated by a power-law of slope surprisingly close to the value found by Salpeter 50 years ago. We use the central cluster of 30 Doradus to determine an accurate value for the IMF slope, and we show that the few seriously discrepant IMF's reported in the literature are most likely due to systematics in the data processing. We propose that massive star formation shows this surprising regularity over a wide range of physical parameters because it is regulated by the laws of complexity. More precisely, we propose that the ISM is in a state of Self-Organized Criticality (SOC) which is a transition between order and chaos.

Key Words: **ISM: STRUCTURE — STARS: EARLY-TYPE — STARS: LUMINOSITY, MASS FUNCTION**

1. THE THEME

Above a certain threshold mass, which appears to vary from cluster to cluster, but which is close to $1M_\odot$, there is strong observational evidence that the IMF is a universal function that can be well approximated by power-law of slope very close, if not identical, to the value found by Salpeter 50 years ago: $\Gamma = -1.35$ (Salpeter, 1955; for a recent review see Kroupa, 2002). This is a very important result, but also a rather surprising one since *a priori* one would expect the physics of star formation to depend on ISM parameters such as temperature, density, pressure, or metallically. Yet, the IMF seems to be invariant over a reasonably wide range of these parameters.

There are, however, a few places where the (massive star)[2] IMF appears to depart significantly, and even dramatically, from the 'universal' power-law. The two most significant objects that apparently show discrepant IMF's are the extreme field in the LMC, and the Arches cluster near the Galactic center. Interestingly, these objects represent the extremes in the stellar (and therefore presumably also ISM) densities of objects for which reliable IMF's have been measured.

We will show in this paper that in both cases: the high density extreme (Arches), and the low density extreme (LMC field), the discrepancy can be ascribed to systematics in the data. Thus, there is no convincing case yet of a well determined IMF that is different from the universal (Salpeter) function. We propose in this Paper that this is a natural consequence of the Fractal structure of the interstellar medium.

2. THE IMF

2.1. *The IMF of 30 Doradus*

Large telescopes, modern instrumentation, and powerful software tools allow the IMF of clusters and associations to be determined rather accurately. In fact, the accuracy is often limited by stochastic effects: a very massive cluster is required to properly sample the mass range (say 1-100$M_\odot$), but there are very few such clusters that can be resolved even using state-of-the art instrumentation on the ground or

[1]European Southern Observatory, La Silla, Chile.

[2]Throughout this paper we use IMF to refer to the *massive star* IMF defined in the text.

in space. We refer the reader to the paper by Kroupa (2002) for a comprehensive review of the IMF. Here we will restrict the discussion to the best studied of these clusters: 30 Doradus, for which the most accurate (both in terms of how the data was treated and in terms of stochastic fluctuations) IMF to date has been determined (Selman et al., 1999).

30 Dor is the largest HII region in the LMC, and one of the largest HII regions in the Local Group. It is ionised by a massive ($M \simeq 3 \times 10^5 \mathrm{M}_\odot$), young (age$\leq$ 3Myrs) cluster containing about 8000 OB stars. Except for the very central regions, the 30 Dor cluster can be resolved by direct CCD imaging from the ground making it a unique laboratory to study the physics of massive star formation (see e.g. Selman, 2003, and references therein).

Technically, the most difficult problem in determining the IMF of any young cluster or association is the transformation of observables (e.g. UBV photometry) into physical parameters such as mass and age. The difficulty comes basically from two fronts: the rather low sensitivity of the UBV photometry to the effective temperatures of massive stars, and the fact that in young clusters the reddening varies significantly from star to star. Selman et al. (1999) introduced a new technique called the Colour-Magnitude Stereogram (CMS) to transform UBV photometry into mass and age. In the presence of variable reddening the theoretical evolutionary tracks become surfaces in the CMS, the *theoretical surfaces*. The job consists in transforming these surfaces from the theoretical (T_{eff}, M_{bol}, age) space into the observable [(B-V), (U-B), V] space, and to find, for each star, the most likely set of parameters. Figure 1 shows the CMS for 30 Dor together with 4.5Myr, 12Myr, and 50Myr isochrones. The theoretical surface is shown for the 12Myr isochrone and a range of $0 < A_V < 3$ mag in extinction.

Figure 2 shows the distribution of reddening obtained for the stars in the cluster divided in two mass bins. The extinction in V varies by more than 2 magnitudes from star to star. This means that, in order to be complete to any given mass, the photometry has to be complete at least two magnitudes fainter than the magnitude corresponding to a star of that mass. The figure also shows that there are no systematic differences in the reddening distributions as a function of mass. This makes it possible to statistically correct for the stars hidden by the variable reddening.

Figure 3 shows the IMF obtained by combining ground based IMF photometry for the whole cluster, excluding the central core (Selman et al. 1999),

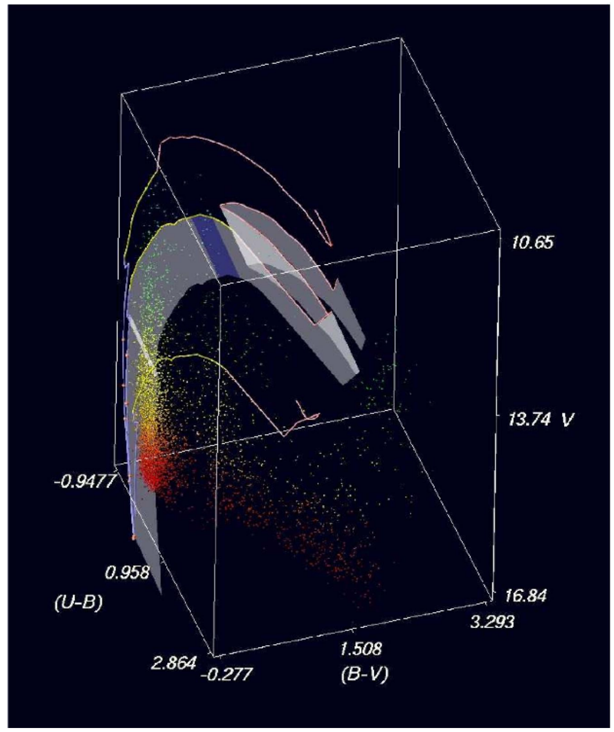

Fig. 1. The colour-magnitude stereogram for 30 Dor. The theoretical surface is shown for a 12Myr isochrone and a range of 3 magnitudes in A_V

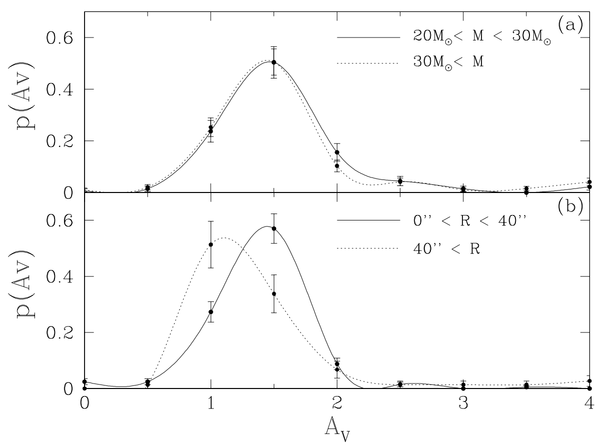

Fig. 2. Top: V-band extinction distribution as a function of mass. Bottom: As a function of distance to the center of the cluster. The average extinction is larger in the central part of the cluster.

with HST photometry of the central regions (Hunter et al. 1995, 1996). The three sets of points in the ground based data show the raw counts (triangles), the counts corrected for photometric incompleteness (squares), and the counts corrected for variable reddening using the distribution showed in Figure 2 (cir-

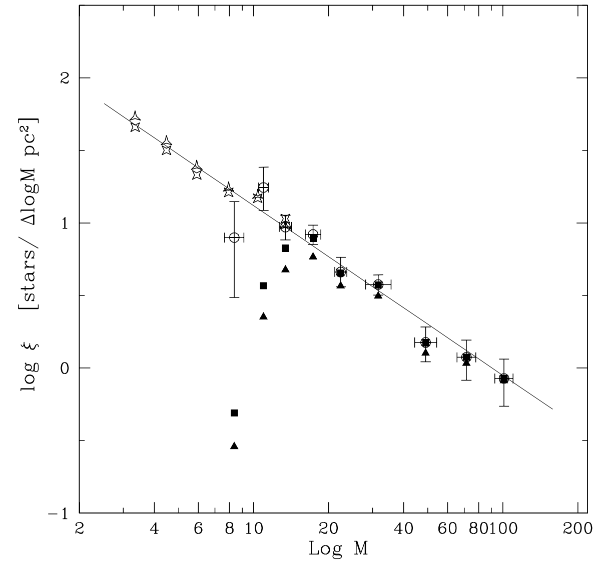

Fig. 3. The IMF of the 30 Doradus cluster. Filled triangles show the raw counts; squares the counts corrected for photometric completeness; open circles correction for variable reddening. Two sets of HST data for the central region are shown (lower magnitudes)

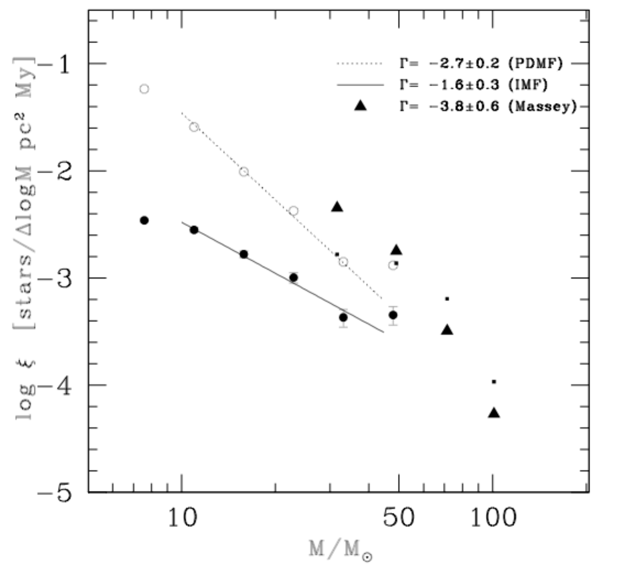

Fig. 4. The IMF of the LMC field

cles). Two sets of HST data are shown with open symbols for stars of mass lower than $10M_\odot$. The error bars show the counting statistics which are acceptable even for the most massive bins. The power-law fit to the data gives a slope of $\Gamma = -1.37 \pm 0.05$.

The main conclusions from the study of 30 Doradus are: (a) the IMF is very well represented by a power-law of slope indistinguishable from the Salpeter value, and (b) the effect of variable reddening, if not corrected, is very severe near the magnitude limit of the photometry and can seriously *flatten* the slope.

2.2. *The discrepant cases: LMC and Arches*

At the extreme ends of the range of stellar densities for which the IMF has been determined with reasonable accuracy lie two objects that show very discrepant IMF's. At the low density end, the LMC field far from even the smallest clusters and associations, is reported by Massey (2002) to have a slope $\Gamma = -3.8 \pm 0.6$, At the very high density end, the Arches cluster near the center of the Milky Way , yields a slope ranging from $\Gamma = -0.6$ in the central region, to $\Gamma = -0.9$ elsewhere (Stolte et al., 2003). If these observations are correct, they point to a very strong dependency of the IMF on density which should provide crucial clues to understand the physics of star formation.

In the course of an investigation of the properties of the 30 Doradus super-association, we obtained a new determination of the IMF for the LMC field using the same techniques described above for the central cluster (Selman, 2003; Selman and Melnick 2004). This is shown in Figure 4 where we plot our results together with those of Massey (2002). The transformation from present day mass function (PDMF) to IMF is done assuming constant star formation in both cases. Our IMF is seen to be significantly flatter than that of Massey. The discrepancy is due to saturation effects in the CCD which set-in at $V \simeq 12$ mag, or $\geq 40M_\odot$ on the main sequence. Massey has only one mass-bin below this limit (Fig. 4). so he discarded stars brighter than V=12. Instead, since our data goes deeper (but also saturates at V=12), we were able to restrict the IMF to stars between 10 and $40M_\odot$.

In order to check for systematic effects due to the different fields and difference mass ranges covered by the two data sets, we corrected Massey's data for incompleteness using the theoretical evolutionary tracks and recovered our value for the IMF slope in the field in common.

Unfortunately, in the case of the Arches cluster we do not have independent data to check the published results. However, Stolte et al. (2002) reported significant variations in the extinction from star to star in the cluster. In fact, there seems to be a strong radial gradient in reddening, in the sense that the central parts of the cluster are less reddened. A close inspection of the 2MASS images of the field reveal

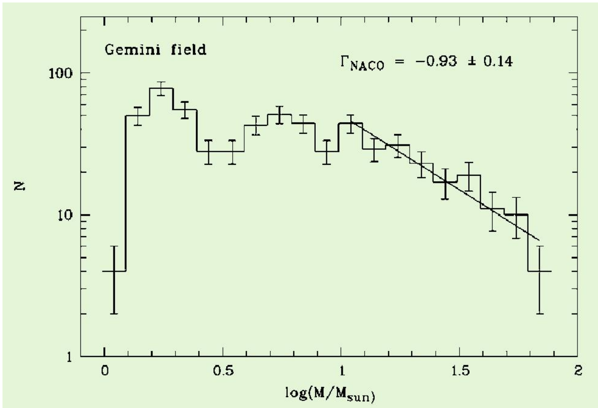

Fig. 5. The IMF of the Arches cluster taken from Stolte et al. (2003). Due to differential reddening, only the $M > 20\mathrm{M}_\odot$ bins are probably complete leading to a steeper IMF than is shown in the figure.

the presence of several dark patches in the vicinity of the cluster, suggesting that the observed gradient may be due to foreground extinction. Whatever its origin, the observed variance in extinction implies that, in order to be complete to any given mass, the photometry must go several magnitudes deeper than the K-magnitude corresponding to that mass. Contamination by Bulge stars adds a further complication that led Stolte et al. (2003) to limit their analysis to M≥10M$_\odot$ ($K \sim 15.1$). According to Stolte et al. (2002), the extinction in the cluster varies from $A_K = 1.9$ to $A_K = 4.1$. Therefore, in order to count all stars more massive than 10M$_\odot$ one has to reach K=15.1+4.1=19.2, well into the range of magnitudes where Bulge contamination is strong. If indeed the reddening variation is a function of radius, then by subtracting a radial component (as done by the authors) the variance is decreased but not avoided. Assuming the Bulge contamination to be small for stars brighter than, say, K=17.5, the corresponding completeness limit for mass would be K=17.5-4.1=13.4 or M∼ 20M$_\odot$.

Figure 5 shows the IMF of Stolte et al.(2003) for the cluster with their fit to the data. Clearly, if the fit is restricted to $M > 20\mathrm{M}_\odot$, the IMF would be significantly steeper. The flattening observed in the central region, where the variance in extinction is much lower, may be real, but still needs to be confirmed with better and deeper data, particularly in the J-band. The origin of the radial gradient in reddening also needs to be confirmed since, contrary to the Arches, in 30 Dor, the average extinction is larger in the central regions (Figure 2), while the core of 30 Dor also contains large numbers of massive WR and Of stars.

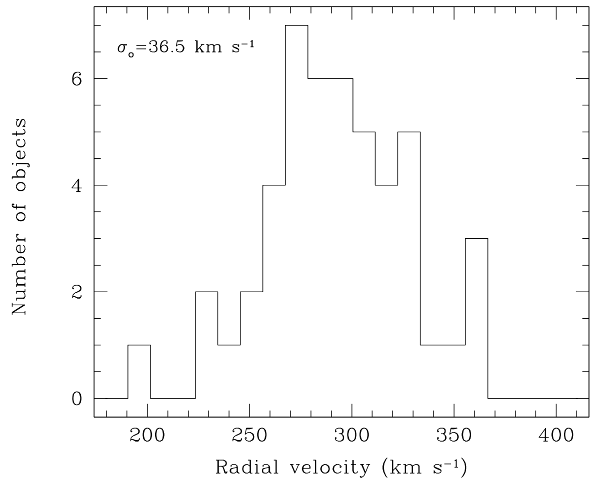

Fig. 6. The radial velocity histogram for 30 Dor. The figure shows the velocity dispersion corrected for instrumental effects.

Our strong conclusion for this section is that all the available data are consistent with the hypothesis that the (massive star) IMF is a universal function that, within the uncertainties of state of the art observations, can be well approximated by a power-law of slope $\Gamma = -1.3$.

2.3. *Caveats*

Selman (2003) has discussed some of the systematic effects that may affect photometric determinations of the IMF (binaries, stellar rotation, fraction of Be stars, star formation history, etc.) Probably the most serious potential problem comes from binaries. We have explicitly assumed that all the stars in the cluster are single stars. Figure 6 shows the distribution of radial velocities for the central cluster of 30 Doradus. The velocity dispersion, $\sigma_o = 36.5\mathrm{km}\dot{s}^{-1}$, is much larger than the Virial dispersion of a cluster of the (photometric) mass and radius of 30 Doradus (Bosch et al., 2001). Thus, either the cluster is flying apart, contains large amounts of dark matter, or a large fraction of binaries. The latter case was modelled by Bosch et al., (2001) who showed that the observed velocity dispersion is consistent with the hypothesis that all the stars in the cluster are binaries.

There are no data (yet) to confirm or deny this hypothesis which we present here only to warn the reader that the last word on the IMF has not been said yet.

3. FRACTALS

There is good observational evidence (e.g. Elmegreen, 2002 and references therein) that the

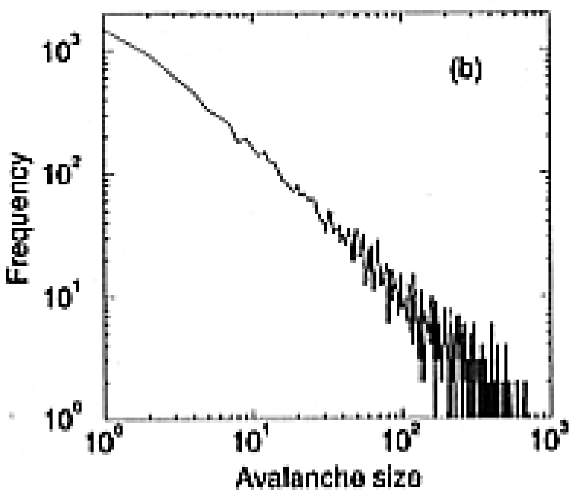

Fig. 7. The size distribution of avalanches in a sand-pile (taken from Valverde and Solé, 2000)

interstellar medium (ISM) has a fractal structure. It can be shown for arbitrary fractal geometry that the mass distribution of ISM clouds (or clumps) will be a power-law of slope very close to $\Gamma_{ISM} = -1$ (Elmegreen, 1997; Melnick and Selman, 2000). So, if we want to understand the IMF, we must first understand the origin of the fractal structure of the interstellar medium. Clearly, this is the result of the way galaxies are formed and evolve, and therefore, of a very complex process. However, we notice that power-law distributions of (log-log) slope ~ -1 occur frequently in Nature. In fact, power-law distributions are the tell-tails of a highly self-regulated process known as Self Organized Criticality, or SOC (Bak, 1996). The prototypical example of SOC is the sand-pile. A pile of sand that is formed by slowly adding grains one-by-one reaches a stage where the addition of a single grain may cause avalanches of any size. (Figure 7).

The system reaches a critical state where it self-organizes to maintain a stable configuration. In this state the distribution of avalanche sizes is a power-law of slope very close to -1. Other manifestations of this state are earthquakes (Richter law), Solar flares, traffic jams, internet traffic, etc. (see e.g. Valverde, and Sole, 2000). Since these processes are extremely complex, researchers in the field use toy models (i.e. blocks linked by springs for the earth-crust), or cellular automata to reproduce the observed behaviour, so the strongest indication of SOC in complex systems is a power-law distribution of events ('avalanches') with slope close to -1.

Therefore, we propose that due to extremely fine-tuned feed-back processes, the ISM has reached a state of Self-organized criticality. Obviously stars form as the result of gravitational collapse of gas clumps, and it requires only a few straightforward assumptions to go from the mass distribution of clumps to the IMF of stars (Elmegreen, 1997). Self-organized criticality can be seen as an intermediate state between order and chaos. So the ISM is literally at the edge of chaos. Just as a sand-pile will collapse if one adds a lot of sand at once, the ISM may become chaotic if strongly disturbed. In that case the size distribution of 'avalanches' would become unpredictable and may well be dominated by very large avalanches. We do not have a toy model for the ISM, so it is hard to quantify what is meant by 'strong disturbance'. However, it is difficult to imagine a disturbance larger than a merger event. Therefore, the mass distribution of star clusters (super-clusters) formed in extreme mergers, ULIRGS, for example, could indeed provide a challenging test.

We conclude with another caveat. If the IMF is mostly determined by complexity, then the IMF slope will be a test of the complexity, but not necessarily of the physics, of numerical models.

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