STAR FORMATION IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT. Methods used in pattern recognition and cluster analysis are applied to investigate the spatial distribution of the star forming regions. The fractal dimension of these structures is deduced. The new 21 cm, radio continuum (1.4 GHz) and IRAS surveys reveal scale structures of 700 pc to 1500 pc being identical with the optically identified star forming sites. The morphological structures delineated by young stars reflect physical parameters which determine the star formation in this galaxy. The formation of spiral arm filaments is understandable by stochastic selfpropagating star formation processes.

1. INTRODUCTION

One observational fact looking at galaxies is surprising: Out of the turbulent interstellar medium large scale features of dust and young stars emerge, ordered structures in space and time. We call these structures spiral arms, their subunits are the star forming regions. What can we learn about this structuring mechanism from the spatial distribution of the star forming sites in the Large Magellanic Cloud (LMC)? What is the typical scale length and the sphere of influence of the star forming process and what are the time scales? I will discuss these questions for the LMC, a late type stellar system, with no spiral density wave.

2. THE DISTRIBUTION OF THE STAR FORMING SITES

Considering in more detail the population distribution of the LMC reveals the following (Feitzinger 1980): The older and possibly relaxed system (with ages $>10^9$ years) shows a structure which differs from the distribution of the young star forming regions (with ages 10^7 - 10^8 years).

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The older structures are used by de Vaucouleurs and Freeman (1973) for classifying the system as SB(s)m. The young structures (Isserstedt 1984 and Isserstedt and Kohl 1984) are not uniformly distributed, but they are also not distributed chaotically. There are obviously greater strips of filaments of star forming activity loosely connected and running across the older features (Schmidt-Kaler 1977). The distribution of the HII regions (Davies et al. 1976) shows that star formation in the LMC is clumped and asymmetrically located with respect to the bar center. Extreme young objects, for example the Wolf-Rayet stars with ages of some 10^7 years follow this distribution (Fig. 1). For data and discussion of the Wolf-Rayet star population of the LMC see Breysacher (1981), Feitzinger and Isserstedt (1983) and Pitault (1983).

The asymmetry and clumpiness on the one hand and the connectedness on the other hand is revealed if we sample all objects with ages less than $2\cdot10^8$ years and outline the major regions of the UV 1200 Å - 2100 Å emission (Martin et al. 1976). In Fig. 2 we present the distribution of young stars and cepheids for different age groups according to Isserstedt (1984) and Isserstedt and Kohl (1984), and in Fig. 3b the distribution of the UV flux according to Page and Carruthers (1981). The UV brightness distribution follows clearly the spatial distribution of early type stars and HII regions; it demonstrates again the difference between the distribution of the older stellar populations revealed by visual imagery and the young star forming regions. The UV or blue luminosity gives indication on star formation in the more or less recent

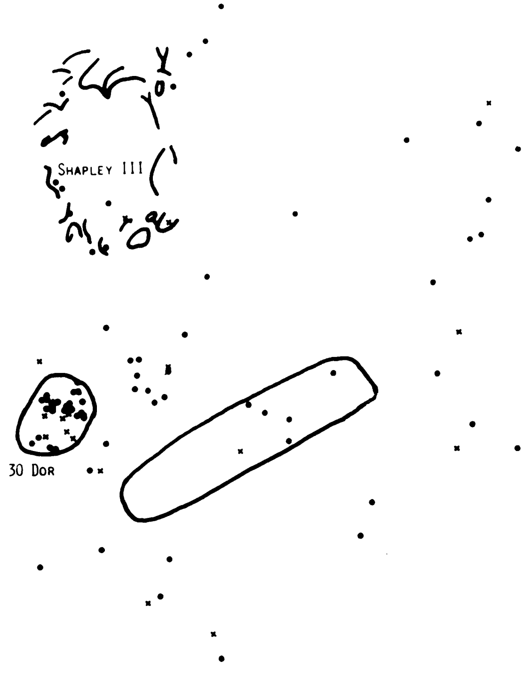

Fig. 1 The distribution of Wolf-Rayet stars/points: WN, crosses: WC

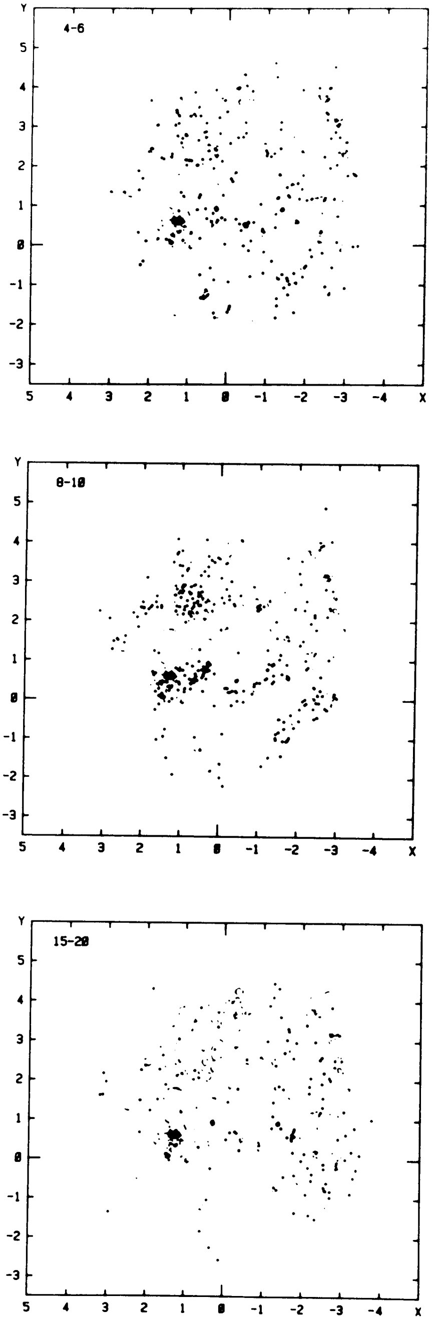

Fig. 2 The distribution of cepheids and supergiants divided in three age groups ($X \cdot 10^7$ yr) according to Isserstedt (loc. cit.)

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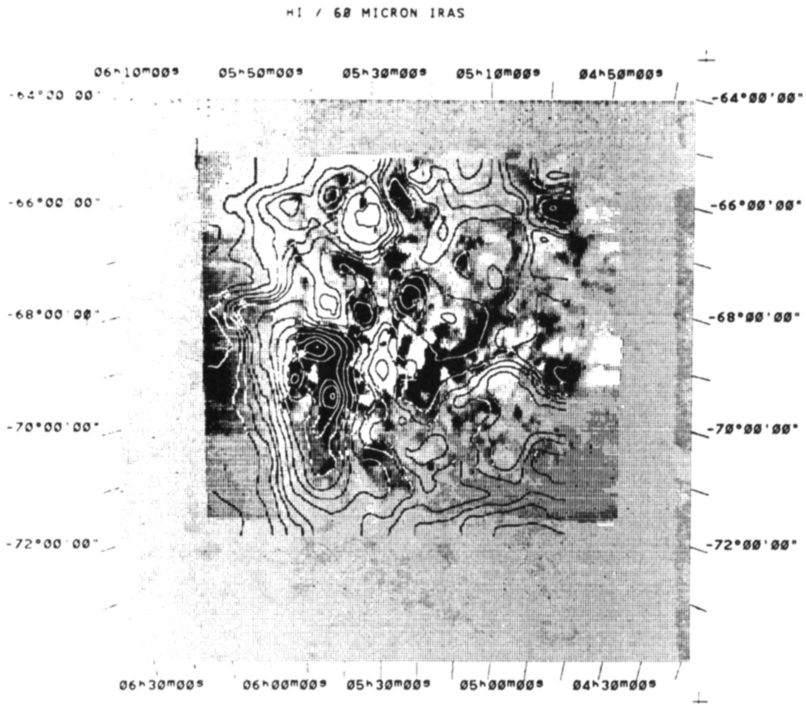

Fig. 3a The HI column density (isophotes) and the 60 μ IRAS emissivity (Israel 1985)

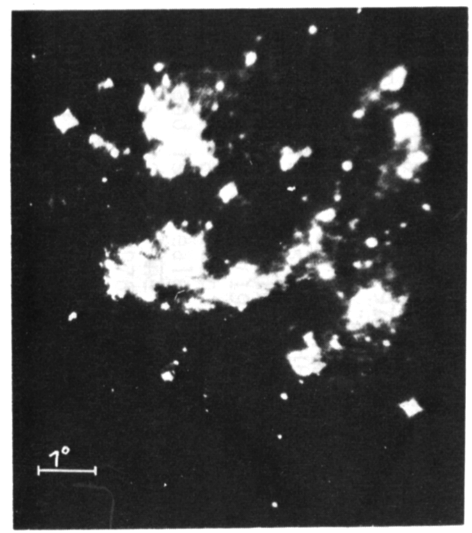

Fig. 3b The LMC in the UV (λ 1600 Å) according Page and Carruthers (1981)

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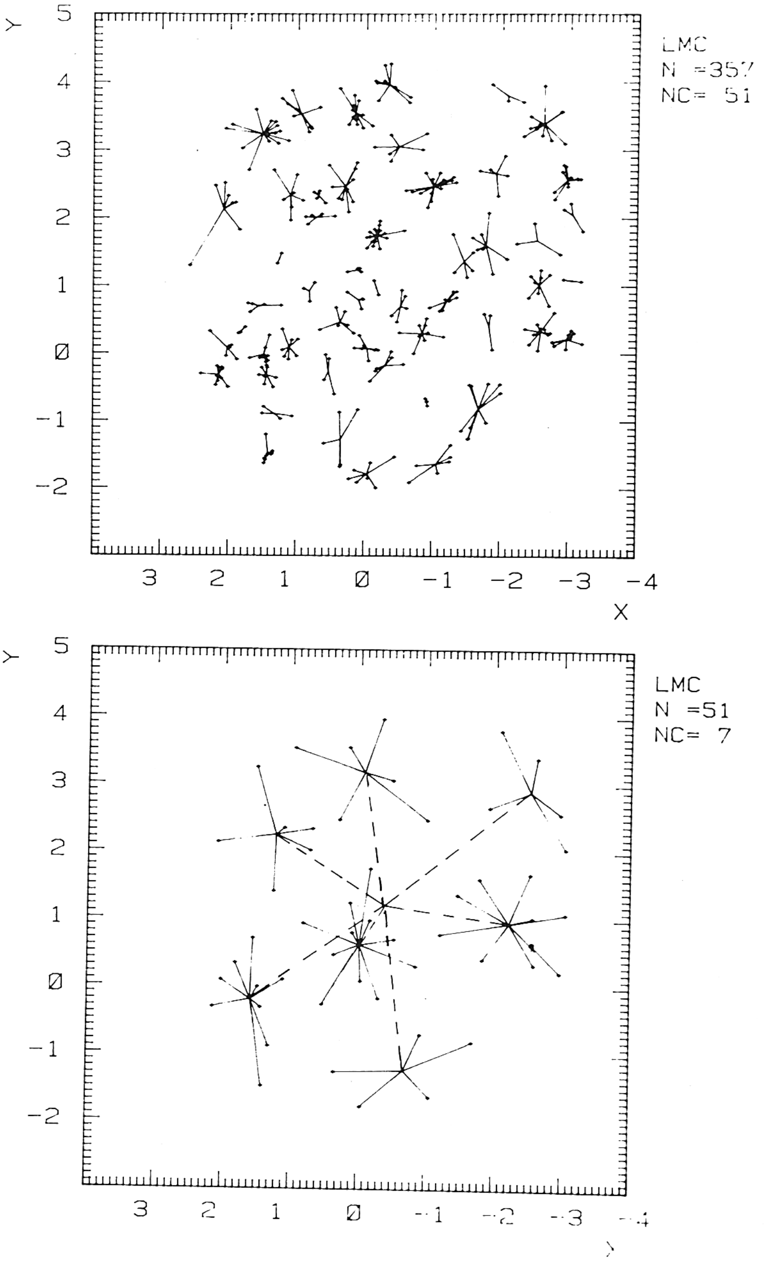

Fig. 4 The hierarchical clustering of the star forming sites. Note that the center of the last hierarchical step coincides with the LMC rotation center.

past. The distribution of the X-ray sources (Cowley et al. 1984), as another constituent of the young stellar population, follows also the active star forming regions.

Methods used in pattern recognition and cluster analysis are applied to investigate these spatial distributions of OB associations and emission regions. Methods of cluster analytic partitions reveal intermediate scale structures of 700 - 1500 pc (Feitzinger and Braunsfurth 1984). These mathematically objective methods show that a certain order is present. The young population objects are not distributed at random. The χ^2-test shows at a confidence level $>95\%$ that the objects are not distributed according to Poisson statistics. The distribution function of the linear separations of HII regions follows an exponential law. Typical values of the separations are of the order of 300 pc; this is the important scale length of the sphere of influence in the process of star formation. The appearance of a well behaving standard distribution function and regular structures may be a hint for the concept that star formation needs a distinct environment of physical parameters (Elmegreen and Elmegreen 1983, Braunsfurth and Feitzinger 1985). An astrophysical mechanism must govern the distribution. Giant molecular clouds as the original birthplaces of associations will probably determine the distribution of the star forming sites. Sequential star formation is the second step leading to structured features. Such structures, as described by the objective mathematically hierarchical linkage method are similar to the local Orion Arm, a spur or spiral arm filament in our own Galaxy (Feitzinger and Schwerdtfeger 1982, Blaauw 1985).

3. THE FRACTAL DIMENSION OF THE STAR FORMING SITES

Hesitation in dealing with the irregularity arises from the absence of tools to describe it mathematically. Mandelbrot's fractal dimension (1983) is an appropriate method to increase one's understanding of randomness or pseudo-randomness. Our method (Galinski and Feitzinger 1986) to determine the fractal dimension uses Mac Queen's technique (Anderberg 1973). For every hierarchical step i the mean distance $\langle s_i \rangle$ of the cluster components (cluster means not star cluster but star forming sites) and the number of cluster members $\langle N_i \rangle$ is determined by a χ^2-minimizing routine. The mean value of $\langle N_i \rangle$ and the magnification $\langle r \rangle$, $r = s_i/s_{i+1}$, taken over all hierarchical steps determine the fractal dimension $D = \log N/\log(1/r)$. The fractal dimension, D = 1.5 in the case of the LMC, represents in a non-topological sense the morphological structure of the distribution of the star forming sites; it describes the global distribution created by local interaction. The patchiness of the cluster distribution (Fig. 4), which is quantified by the fractal dimension, must correspond to the physical state of the interstellar medium. We expect that D depends on some sort of star forming capacity of the interstellar medium. The mechanisms controlling star formation cannot be entirely random. The mean separations of the HII regions (180 pc - 300 pc) and the maximum sphere of influence (300 pc) in late type and irregular galaxies (Hunter 1982, Gallagher and Hunter 1984) point in the same direction. The partly random distribution of the star forming regions is compatible with propagating star formation on galactic scales. The time delay between star formation in the seed cell and star formation in the surrounding generates the partly random appearance (compare section 5). This is reinforced by the slow differential rotation of the system.

The fractal dimension D, deduced from the morphological appearance of the star forming sites, may correlate with the spectrum of the turbulent velocity of the interstellar medium. Since the amount of turbulence is intimately connected with star formation, the regions of dissipation (namely the spatial set on which turbulent dissipation is concentrated) can be modeled by a fractal. For the case of a spotty or intermittent turbulence, as in the case of the interstellar medium, the classic Kolmogorov exponent 2/3 has to be modified (Mandelbrot 1983) according to

$$v \sim r^f \qquad f = 2/3 + (3-D)/3 .$$

This may be the case for galactic scales and seems to work on short scales as molecular clouds, where deviations from the Kolmogorov law are observed (Scalo 1984, Henriksen and Turner 1984).

4.THE INFRARED AND RADIO CONTINUUM MAPS

The surface distribution and the scale length (separations, connectedness, extensions) of the star forming sites can be further quantified, if we look at the distribution of the $60\mu m$ IRAS infrared (Fig. 3a) and the 1.4 GHz radio continuum emission (Fig. 5). The maximum value of the $60\mu m$ emission (Beichman et al. 1984, Schwering 1984, Israel 1985) is centered on 30 Doradus and corresponds approximately to 2.4 GJy sr^{-1}. The prominent ridge lines of the $60\mu m$ emission delineating the star forming sites correspond to an intensity level of 30% - 50% of the maximum value. The resolution is 1'. The blobs and chains of dust marked by the IR emission have a scale length of 300 pc to 1500 pc, respectively. The places of star formation in the immediate past history and the distribution of dust in the LMC show a filamentary structure. At the position of the Shapely III constellation we observe a clearly defined hole in the IR emission. The correlation of the IR with the HI column density (Rohlfs et al. 1984) is not very tight (superposed in Fig. 3a to the $60\mu m$ emission). This holds also for the surface density of the supergiants and the HI. The star forming sites are located on the edges of the great HI clumps.

The 1.4 GHz contour map (Haynes et al. 1986) gives a maximum of 32 Jy/beam area. The half power beam width is 15'. The emission detected at 1.4 GHz is dominated by radiation from ionized hydrogen complexes and supernova remnants, both recognized tracers of new star formation. The bulk of the individual sources has a flat spectrum and can be associated with bright HII regions (Klein and Wielebinski 1985). These same regions are also expected to generate relativistic particles which fur-

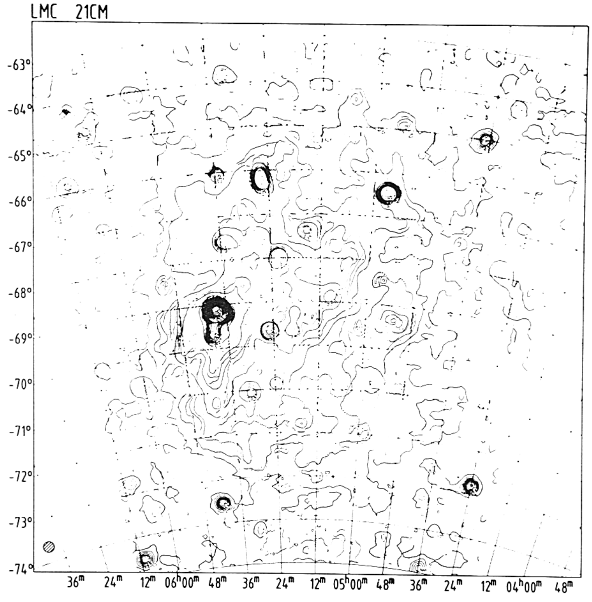

Fig. 5 The 1.4 GHz radio continuum emission (Haynes et al. 1986).

ther enhance the emission seen at 1.4 GHz (de Jong et al. 1985). We thus expect features seen in the 1.4 GHz survey to be tracers of star formation regions. The distribution of dust is also a strong tracer of regions of star formation. It is thus not surprising to find supportive evidence in the IRAS 60μm image for the star forming filaments implicit in the 1.4 GHz results. The radio continuum morphology of the LMC resembles the asymmetric pattern of the extreme population constituents. Well defined large global structures are apparent with scale lengths up to 2 kpc.

5.STOCHASTIC STAR FORMATION MODELS

It is evident from the distribution of the cepheids and supergiants, divided into defined age groups (Isserstedt 1984, Isserstedt and Kohl 1984) that star formation in the LMC occured stochastically in varying regions, with a tendency of concentrations into isolated space-time cells. Evolutionary effects are observed. A fine example is the Shapley III constellation, where star formation appeared to start approximately 15 Myr ago near the center and has propagated outwards as a stochastic and self-limiting feed back process (Dopita et al. 1985, Dopita 1985). The morphological appearance of this region in all available wavelength regions support such a picture.

The stochastic selfpropagating star formation theory is able to

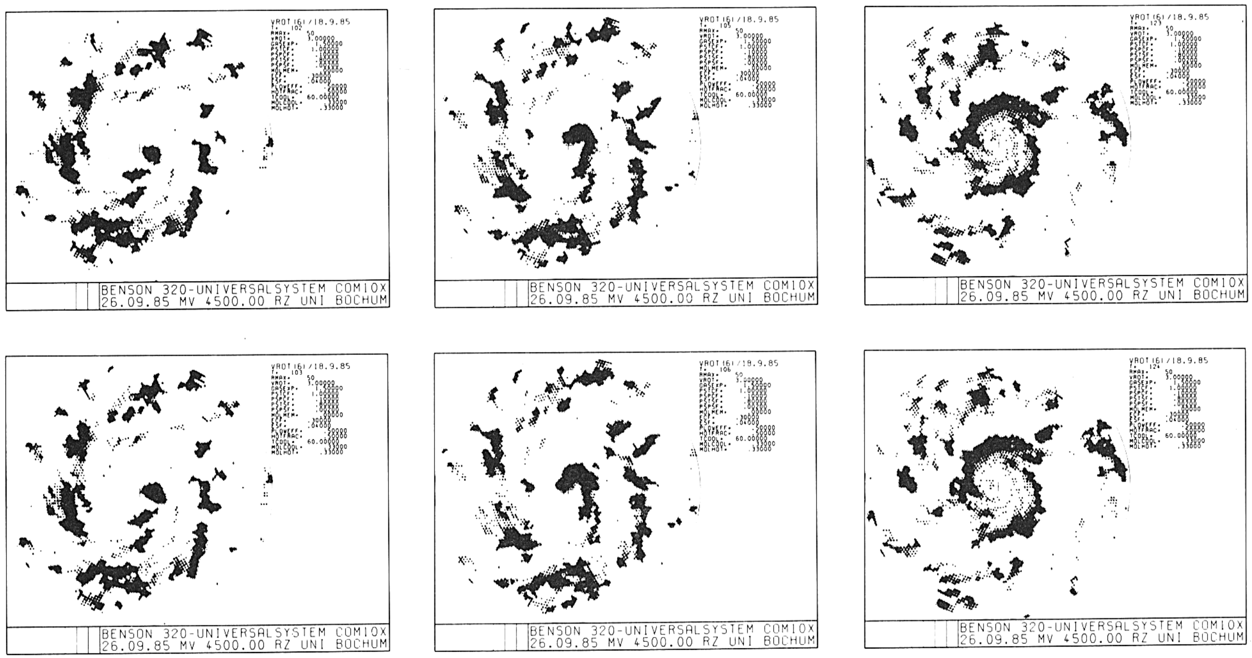

Fig. 6 Stochastic star formation model. The time steps shown are 102, 103, 105, 106, 123, 124 10^7 yr; one time step is 10^7 yr. Each frame contains 10 time steps. The size of the points is inversely proportional to the age.

simulate such structures. The models of Feitzinger et al. (1981, see also Seiden and Gerola 1983) gave patterns of too great a time regularity and steadiness in the case of the LMC. Our improved models (Feitzinger and Perschke 1986) with stochastic molecular cloud formation, three gas phases and detailed gas distributions in neighboring cells and perpendicular to the disk around star forming sites, simulate much better the percolating star formation in the LMC. The time scales regulating the star formation processes are the cooling time scales of the gas phases and the formation time scales of the molecular clouds. We produce asymmetrically located filaments of loosely connected star forming regions (Fig. 6). The distribution of the young structures changes on time scales of 10^8 yr drastically. Such a behavior is typical for late type irregular stellar systems and becomes extremely pronounced in dwarf galaxies (Hunter and Gallagher 1985 b). The new calculations show very rapid variations in the distribution of the young stars, i.e. in the morphological appearance of the system. Pattern changes as the result of jumping star formation is compatible with the finding of Isserstedt (loc. cit) on the migration of the star forming sites and invalidate the arguments against the stochasticity and confirms the stochastic ansatz as usable for the LMC and late type galaxies.

The dust distribution (Fig. 3a) is strongly correlated with the star forming sites. The no-correlation result of Isserstedt and Kohl (1984) between interstellar dust and supergiants has to be modified; possibly the E(B-V) method locates the globally distributed cold dust component. The cold dust may somewhat decrease (10% - 20%) the contrast between the high emissivity and low emissivity IR regions (Israel 1985), but not so much that the correlation is lost. The hot dust distribution is compatible with the stochastic star formation theory. In Fig. 7 we present an example for the intimate time correlation between the star formation rate and the mass fraction of molecular clouds. The time evolution of the star and molecular cloud formation oscillates; the time scales for the low and high states are $5 \cdot 10^8$ yr, this is also the time scale for changes in the appearance of the distribution of the youngest population of this stellar system, i.e. the complete reorganisation of the morphological structure.

The model calculations produce also knots of short star formation bursts, like 30 Doradus. Such bursts are not frequent, but they are also not the great exception. They seem to dominate the pattern occasionally for 10^7 yr. There is no genetic relation of these bursting space cells with the global distribution of the star forming sites. Such star formation events are a local process and small systems can also make great activity (Hunter and Gallagher 1985 a, b). The local star forming activity, as in the case of 30 Doradus, can produce large amounts of hot gas leading to the impression of a hot gaseous halo around the LMC (Feitzinger and Schmidt-Kaler 1982). In any case, the velocity field of the gas in the immediate neighborhood of such bursts will be influenced by the huge amount of energy deposited at such sites (Feitzinger et al. 1984).

The energetics of the stochastic percolating star formation processes comes from the differential rotation and the energy input of supernova, WR, O and B stars. This energy is responsible for the driving and structuring mechanisms of the manifold of gas phases and morphological forms. The average rate of wind and radiative energy input to the interstellar medium in the LMC is $E_{tot} = 2\cdot10^{41}$ erg/sec/kpc^2 ($1.2\cdot10^{39}$ erg/sec/kpc^2 solar neighborhood). This gives a ratio E_{tot} to unit hydrogen mass, normalized to the solar neighborhood, of 1 (Tarrab 1983). In the frame of the selfregulating stochastic star formation processes this high energy input is the reason for the ongoing large star forming activity of the LMC. The star forming process in individual cells, i.e. morphology, excitation, dust, stellar content (Lortet and Testor 1984) give the key information on the star forming scenario.

In spite of the apparent chaos, star forming regions are distributed over the disk of the LMC with definite clumping scales and star formation migrates in a systematic manner.

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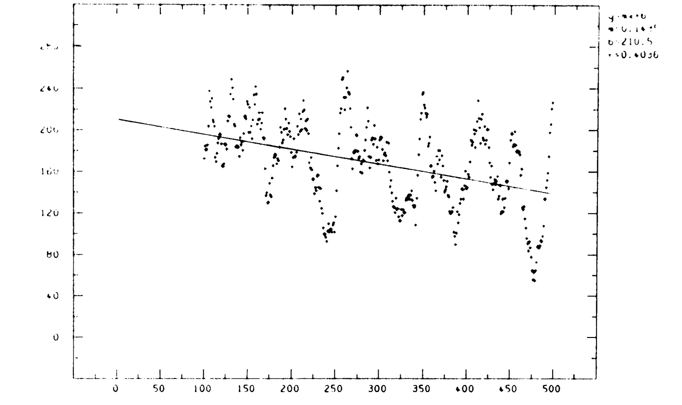

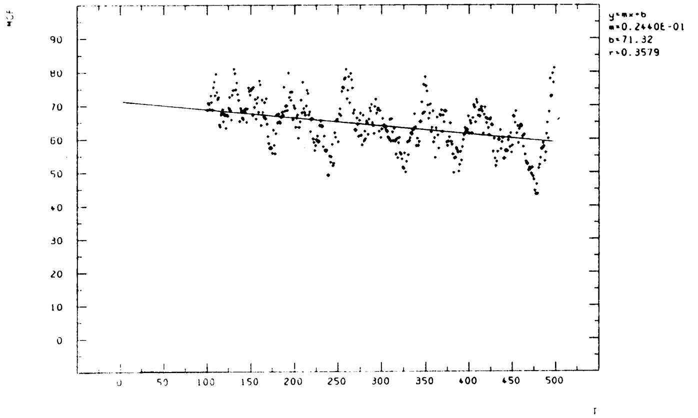

Fig. 7 Time evolution of the star forming rate (NSF = number of cells, total cell number = 7250) and molecular cloud formation (MCF = mass of molecular clouds; mass unit = 10^7 M_0) in the LMC. The time step is 10^7yr.

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