# STAR FORMATION, SUPERNOVAE AND THE STRUCTURE OF DISK GALAXIES

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**Abstract:** A physical model for bi-modal star formation and the structure of the interstellar medium and the self-regulating evolution of disk galaxies is presented. Stars heavier than about one solar mass are produced as a result of collisions of molecular clouds or in cloud crushing events whereas low-mass stars are produced at a steady rate in dense molecular clouds and the T-Tauri winds resulting maintain the support of these clouds against rapid collapse and fragmentation. Supernova explosions and stellar winds associated with the massive stars maintain the phase structure, and the scale height of the gas. The collective effects of these energetic processes may create a hole in the disk gas, and allow a galactic wind of metal-enriched gas to develop.

## 1. Phase Structure of the ISM and the Collective Effects of Supernovae.

The energetic processes (winds, ionising radiation and supernova explosions) associated with the young, massive stars exercise the fundamental control of the phase properties, pressure and distribution of the interstellar medium (ISM) in the plane of disk galaxies. This is the basis of the multi-phase models ( Field,Goldsmith and Habing 1969; Cox and Smith 1974; McKee and Ostriker 1977; Cox 1979,1980), although these differ in the details of how such a multi-phase medium is set up and maintained.

The local interstellar medium is perhaps not the best place to start to try to understand the phase structure of the ISM. We lie within a region of extensive recent star formation defined by the stars of the Gould's Belt, which extends over some 700pc, and encompasses the Sco-Cen, Taurus and Orion associations (Lindblad and Westin, 1985). Thus, the phase structure derived locally may not be generally applicable.

The Magellanic Clouds, on the other hand, offer a convenient laboratory in which to study the phase structure of the ISM, and evidence for cloud, inter-cloud and coronal components may be found. It has become increasingly clear that Type II supernovae interact with a highly modified ISM. However, Type I supernovae will tend to occur well separated in time and space from their star formation region, and are therefore much more useful in probing "normal" samples of the ISM. From a variety of lines of evidence, Tuohy *et al.* (1982) have shown that the Balmer dominated SNR are most likely to be the remnants of Type I SNR. For these, the $H\alpha$ data suggest that the SNR is interacting with a phase of the ISM which has a density of about $0.1$ $cm^{-3}$, whereas the X-ray data gives $0.3$ $cm^{-3}$ for the same LMC remnants. This phase can be identified with an intercloud medium. The cloud medium, on the other hand has a density of about $10\text{-}30$ $cm^{-3}$ (Dopita, 1979; Wilson 1983), and is probably in stochastic pressure balance with the intercloud.

The supernova rate in the LMC is about 1 per 200 years. This is insufficient to maintain a coronal medium with a large filling factor globally. However, in regions of

local enhancement of the star formation rate, the collective effects of supernova explosions can be sufficient to strip out the disk HI, creating a bubble of coronal gas which eventually finds its way into an extended hot halo. This is graphically illustrated by the case of Shapley Constellation III (Dopita, Mathewson and Ford, 1985). This region of very extensive star formation over the past $2x10^7$ year has produced a hole in the disk HI almost 2kpc across, and energetic processes such as stellar winds and SN explosions have pushed out a shell of HI at a velocity of 36 km.s$^{-1}$. Such HI will take about $2x10^8$ years to return to the plane. Furthermore, once the disk HI is swept out, coronal gas produced by subsequent SN events is free to escape into a hot coronal medium which can pressurise the disk gas. Such coronal gas is undoubtedly present and has been observed directly in soft X-rays in Constellation III (see Helfand, Wu and Wang 1987, this conference, not published).

For the Galaxy, it has become clear that a hot corona of shock-heated gas first suggested by Spitzer (1956) does indeed exist. The presence of this gas is evident locally in the soft X-ray observations (Tanaka and Bleeker 1977; McCammon *et al.* 1983; Jakobsen and Kahn 1986), and in observations of OVI absorption (Jenkins 1978). As it cools, it gives rise to absorption in highly ionised species such as N V, C IV and Si IV which can be observed with the IUE Satellite (Savage and de Boer 1978,82; York *et al.* 1982; Pettini *et al.* 1982; de Boer and Savage 1983). From this work, it is evident that this gas has a (local) scale height for cooling of about 3-4 kpc, and is denser and more confined to the disk towards the inner parts of the Galaxy.

If the gravitational binding energy of this hot gas is less than its thermal energy minus the radiative losses as it streams out into the halo, then a galactic wind, rather than a steady state "galactic fountain" will result. The conditions under which this will occur were discussed in an elegant paper by Chevalier and Oegerle (1979). In our local solar neighbourhood, and in the inner regions of the Galaxy, this condition does not appear to be met. However, the cooling timescale of this material at LMC and SMC abundances is very long, of order $(0.3 - 3)x10^9$ years. Even if it cools, the height to which the hot gas rises is sufficiently distant above the plane to be very weakly bound to the system. It is likely that a galactic wind can be driven in this case.

The pattern of elemental abundances (Dopita 1987) strongly suggests that this does indeed occur. The chemical yield of oxygen in the Magellanic Clouds is lower than that of the galaxy by a factor of two to three (e.g. Dufour, 1984). However, data from stellar atmospheres of young disk stars shows that **both** of [Fe/H] and [O/Fe] are lower in the Magellanic Clouds. This is in contradistinction with the Galaxy, for which old disk stars show a **lower** [Fe/H] is coupled with a **higher** [O/Fe] (Tomkin and Lambert, 1984; Tomkin, Sneden and Lambert, 1986; Sneden 1985; Nissen Edvardsson and Gustafsson 1985). Since O is made in massive stars, and Fe in lower mass stars, this difference could be taken to mean that the slopes of the IMFs are different. However, such observational evidence as we have does not support such a conclusion. The alternative hypothesis is that oxygen has been preferentially lost to the system. This could occur through the funnels opened out into the galactic halo by bursts of star formation. These will have filled by the time the Fe-producing Type I events occur, allowing the retention of this element.

## 2. Star-Formation - Bimodal or Not?

As Silk (1985), pointed out, the essential ingredients of a star formation theory are

the initial mass function (IMF), the star formation efficiency and the rate of star formation. Most models of galactic evolution (Audouze and Tinsley 1977; Vader and de Jong 1981) have tended to assume a constant IMF and to reduce the star formation problem to a simple "prescription" of the rate in terms of the local HI gas density (Schmidt 1959), or of HI surface density (Sanduleak 1969; Hamajima and Tosa 1975).

The rôle of the IMF has been receiving increasing attention in recent papers. In our own Galaxy, star formation may well have a bimodal character, with high mass stars being preferentially formed in the vicinity of the spiral arms but low-mass stars being formed throughout the disk (Güsten and Mezger 1983). If the CO-emitting molecular clouds map star-formation regions, then their distribution in the Galaxy appears to offer convincing support of the bimodal hypothesis (Scoville and Good 1987). The CO clouds are clearly divided into two populations which reflect their kinetic temperatures. The warm molecular clouds are clustered, are associated with HII regions and form a spiral arm population. The cold core clouds are distributed throughout the disk. Scoville Sanders and Clemens (1986) argue that, since the star formation efficiency for massive stars appears to decrease as the mass of the parent cloud increases, the formation of these stars must be triggered by an external cause, such as cloud-cloud collisions, rather than internally as in the sequential star formation models.

The apparent segregation of the high-mass and low-mass modes of star formation becomes even more pronounced in starburst regions. Here, several analyses suggest that, in these regions, only the high mass stars are being formed and that the low mass cutoff in the IMF is of order 3 solar masses ( Rieke *et al*. 1980,1985; Olaffsson, Bergrall and Ekman 1984; Augarde and Lequeux 1985).

In an inspiring recent paper, Larson (1986) has presented convincing arguments that, provided that the global rate of star formation decreases with time, the IMF is a double peaked function. The division between the "high" and "low" mass sections of the IMF occurs at about one solar mass, so that, from the point of view of galactic chemical evolution, only the high mass mode of star formation is important.

Although, in our own Galaxy, the two modes of star formation appear to be spatially distinct, with the high-mass stars preferentially formed near spiral arms, it is not necessary, or even desirable, to associate this with a density wave trigger. Elmegreen (1985,86) has shown that galaxies of the same Hubble types with and without a density wave have effectively identical star formation rates. The rôle of the density wave is therefore one of spatial ordering of the star formation regions rather than one of enhancement of star formation rate.

## 3. The High-Mass Mode of Star Formation.

Cloud-cloud collisions, or cloud crushing events generate a dense sheet of shock-compressed material. Let us assume that high-mass star formation results from the development of gravitational instabilities in such a shocked layer (Mouschovias, Shu and Woodward 1974; Elmegreen, 1979,1982; Cowie, 1981; Balbus and Cowie, 1985). Why should this preferentially produce high-mass stars? For an infinite isothermal sheet of surface density $\sigma$ $M_{\odot}$ $pc^{-2}$, the fastest growing mode of instability (Larson 1985; Field 1985) has a characteristic mass $M_C$ given by

$$M_C = 2.4 \, T^2 / \sigma \quad M_{\odot}$$

The typical cloud surface density is of order 100-200 $M_\odot$ $pc^{-2}$. For low-mass star formation, cloud temperatures are 5-15 K so that $M_C$ lies in the range 0.3-5 solar masses. However, in a shocked sheet, the surface density increases as the mean temperature of the post-shock gas falls towards its equilibrium level. Thus, the most massive modes of instability are triggered first, and fragmentation proceeds to smaller and smaller characteristic Jeans mass. However, this process is terminated when the massive stars reach the main sequence and ionise and break up the shocked layer. The characteristic Jeans mass of fragments is therefore determined by their characteristic temperature, given by the condition that the cooling timescale at this temperature should be comparable to the collapse timescale of the largest fragment.

Cloud-cloud collisions reduce the momentum, and therefore, the velocity dispersion of the gas in the vertical (w-plane). Thus, energetic processes associated with the high-mass mode of star formation must, in the steady state, feed as much momentum into the gas of the ISM as is being lost in cloud-cloud collisions. If $d\sigma*/dt$ is the surface rate of star formation, and $\sigma_g$ is the surface density of gas, then:

$$(d\sigma*/dt) = \beta\, \sigma_g\, /\, \tau_{cc} \tag{3.1}$$

where the cloud-cloud collision timescale is $\tau_{cc}$ and where the constant of proportionality $\beta$ is composed of both a "spontaneous" term and a "stimulated" term which accounts for the fact that a burst of star formation may induce a local overpressure leading to cloud crushing and induced star formation in its vicinity. These processes represent the justification for the model of stochastic self-propagating star formation (Gerola and Seiden 1978; Seiden and Gerola 1979; Feitzinger et al. 1981) which has enjoyed considerable success in reproducing the morphological features of both spiral and irregular disk galaxies. Here we assume that the coefficient of stimulated star formation is linearly related to the spontaneous term, so that $\beta$ is not too sensitive to the galaxian environment.

Since the cloud-cloud collisions are radiative, the physical parameter which is conserved in the collision is the momentum. In the steady state disk, therefore, the modulus of the sum of the momentum vectors of the individual gas clouds is maintained at a constant value. Thus, in steady-state;

$$\gamma\, (d\sigma*/dt) = \sigma_g v_g/\tau_{cc} \tag{3.2}$$

where $v_g$ is the vertical w-velocity dispersion of the gaseous layer and $\gamma$ is a coupling constant. To the extent that the IMF and the energy yield from the high mass stellar population does not depend on metallicity, $\gamma$ will be independent of galaxian environment.

Equations (3.1) and (3.2) together imply an observational consequence;

$$v_g = \beta\gamma \tag{3.3}$$

that is to say that the vertical velocity dispersion of the gas in **all galaxies** will be the same, and independent of the radial coordinate. This is true of all disk galaxies which have so far been observed (van der Kruit and Shostak 1984, van der Kruit 1985; private communication, Meatheringham et al. 1987). The HI velocity dispersion is of order 6-10 $km.s^{-1}$, and varies little between the arm and interarm regions. However, it is seen to increase in regions of active star formation, such as the 30 Doradus region in the LMC.

If the volume filling factor of molecular clouds in the gaseous disk is f, then the cloud-cloud collision timescale is given approximately by:

$$\tau_{cc} = 2\, z_g\, /v_g\, f^{2/3} \tag{3.4}$$

Star formation pressurises the ISM in the plane, and, because the hot gas from supernova explosions can bubble up to form a hot halo to the galaxy, the scale height for pressure variation is long compared with the matter scale height. Thus, in regions where the hot coronal gas generated by supernova explosions is incapable of driving a galactic wind the pressure, P, is simply proportional to the surface rate of star formation ;

$$P = \alpha\, (\, d\sigma_*/dt\, ) \tag{3.5}$$

We assume that the molecular and atomic gas clouds are in equilibrium with the external pressure, (this is implied by the scaling relationships for individual molecular clouds; Larson, 1981; Chièze 1987), and that they move in the disk potential defined by the gas and the stars with scale height $z_*$.

This then allows a solution for the net star formation rate per unit area of disk:

$$(d\sigma_*/dt) = \text{const.}\ z_*^{-1/2} . \sigma_t^{1/2}\ \sigma_g \tag{3.6}$$

As might have been expected on purely phenomenological grounds, the star formation rate depends primarily on the local surface density of gas. However, there is also a dependence on total surface density, and on the stellar scale height. Since the scale height evolves with time due to stellar diffusion (see below), the $z_*$ term introduces an additional temporal evolution of the star formation rate.

## 4. The Low-Mass Mode of Star Formation.

It has long been recognised that the lifetime of molecular clouds is at least an order of magnitude longer than their free-fall timescales (Kwan 1979; Blitz and Shu 1980) and that the typical turbulent velocities are highly supersonic. It is clear that an energy source is required to give the required turbulent support. Norman and Silk (1980) and Franco (1983) suggested that the winds from young stellar objects might provide this energetic input. Franco and Cox (1983) were able to derive a stellar birthrate on the assumption that this turbulent input also serves to regulate the rate of low-mass star formation within molecular clouds. Essentially, the structure of a such a cloud at any instant can be regarded as a set of interlocking shells of compressed gas, orbiting each other under their mutual gravitational attraction. Amongst these, just a sufficient number are in a state of collapse under their self-gravity to provide enough new stars for the turbulent support. Thus, in the absence of any external perturbation, the cloud is converted into stars at a nearly constant rate.

Direct observational evidence for such a picture is forthcoming from two separate directions. Firstly, Fukui *et al.* (1987) have shown that in one cloud, the Orion Southern molecular cloud, the energy input from the CO outflow sources found in an unbiased survey is sufficient to balance the cloud against turbulence dissipation, provided that the timescale over which this operates is an order of magnitude greater than the free-fall timescale. More general evidence to support the Franco and Cox picture comes from the observed mass / radius or velocity dispersion / radius relations. Larson (1981) found

from observation that $M \propto R^2$ and that the velocity dispersion, $\Delta v \propto R^{1/2}$. Chièze (1987) has shown that this is exactly what would be expected if the interstellar clouds are close to gravitational instability in a constant pressure environment, and suggests that the sub-condensations may form a gravitational N-body system in a quasi-static virialised condition, which will leave the scaling relationships unchanged for the individual fragments.

Following Franco and Cox (1983), at any instant the volume of the cloud, $V_c$, should be filled with $N_s$ interacting momentum-conserving shells each of volume $V_{int}$;

$$V_c = N_s V_{int} \tag{4.1}$$

If the interaction timescale is $t_{int}$, then the rate of star formation per unit volume, $S_v$, will be given by:

$$S_v = \varepsilon (V_{int} t_{int})^{-1} \tag{4.2}$$

where $\varepsilon$ is an efficiency factor. This equation assumes that the cooling timescale in the shock-compressed layer is short compared with $t_{int}$.

By consideration of the detailed physics of this situation, we arrive at the star formation rate per unit mass, $S_m = S_v / \rho_c$;

$$S_m = const.\rho_c{}^\zeta \tag{4.3}$$

where possible values of the exponent $\zeta$ lie in the range -1/8 to +1/4, respectively. Thus the assumption that the low mass star formation rate is simply proportional to the mass of available gas is, in general, a very adequate assumption.

The rate given by eqn. (3.8) is appropriate for molecular clouds which are in the quasi-equilibrium state. However it must be recognised that clouds are destroyed by stellar winds and supernova explosions in regions of high-mass star formation, and fragments may be blown to large scale height, as has been observed in very active regions of star-formation in the Magellanic Clouds (Caulet *et al.* 1982; Dopita, Mathewson and Ford 1985) the Galaxy ( Heiles 1979, 1984), or in M31 (Brinks 1981). This is the probable origin of the so-called "cirrus" clouds. If molecular clouds reform out of this component, they must do so as a result of coalescent collisions at low relative velocity, followed by radiative shedding of internal turbulent motions. This implies that the steady-state low-mass star-formation of eqn. (3.8) is effective only for a duty factor F given by;

$$F = \tau_{cc} / [ \tau_{cc} + \tau_{diss} ] \tag{4.4}$$

where $\tau_{diss}$ is the timescale of turbulence dissipation. At densities larger than 200 cm$^{-3}$, the cooling is dominated by molecular species of which by far the most dominant is CO (Goldsmith and Langer, 1978, Hollenbach and McKee,1979), which ensures that the cooling rate declines rapidly toward low abundances. The timescale for dissipation of turbulence is;

$$\tau_{diss} = ( E_{therm} + E_{turb} + E_{shear} ) / \Lambda \tag{4.5}$$

where $\Lambda$ is the cooling rate per molecule and the terms, E, represent respectively the

energy per molecule in thermal motions, random turbulence and in turbulence due to rotational velocity shear, $(1/r).d(V_{rot}/r)/dr$, across the region over which cloud fragments are accreted i.e., on the local Oort A value. Thus, equations (4.4) and (4.5) show that, in regions of low metal abundance, or in regions of high velocity shear, the duty factor for low-mass star formation becomes low.

## 5. The Structural Evolution of the Disk.

In order to use the results of the previous two sections in a model of galactic evolution, we require to know how the gaseous and stellar disks evolve with age. Essentially, this resolves itself into three separate problems, the evolution of the gas layer, stellar diffusion and the infall / outflow problem.

The total surface density, $\sigma_T$ (r), in disk galaxies is seen to decline radially outwards according to an exponential law with scale length $R_o$;

$$\sigma_T (r) = \sigma(0).exp[ -r / R_o]$$

(Freeman 1970, van der Kruit and Searle 1981a,b). Since eqn.(3.3) implies a constant velocity dispersion in the gas layer then the vertical scale height in the gas varies as;

$$z_g = z_g(0).exp[-r / 2R_o] \tag{5.1}$$

Such a variation is in fair agreement with the observations of the thickness of the HI layer in our Galaxy, assuming a disk scale length of order 4 kpc (Downes and Güsten, 1982).

Stars born in this gas layer will diffuse out of the layer by the dynamical heating which is a result of interactions with gravitational perturbations in the disk, spiral density waves, or giant molecular clouds (Spitzer and Schwarzschild 1951,53; Wielen (1977), Twarog 1980; Vader and de Jong 1981; Lacey 1984 and Villumsen 1985). According to this theory, if stars are born at an intrinsic velocity dispersion $V_*(0)$, then at time t they will have acquired a velocity dispersion $V_*( t )$ given by:

$$V_*( t ) = V_*(0) [ 1 + t / t_{diff} ]^{1/3} \tag{5.2}$$

this equation remains valid only for so long as the scattering clouds and the stars can be considered to remain in the same layer. The breakdown of this assumption will lead to a change in the exponent. Weilen (1977) finds empirically that an exponent of 1/2 gives a

To a first approximation, we can assume that the conversion of matter into stars and remnants proceeds exponentially with time, and that the gas collapses to a thin disk on a timescale which is short in comparison to the current age of the galaxy. These equations can therefore be used to compute the time evolution of the mean stellar velocity dispersion $V_*$. From many runs with different gas depletion and infall timescales, an analytic fit to $V_*$ is found to be;

$$V_* = V_g [1 + (t / t_r)(\sigma_T / \sigma_r)^2]^m \tag{5.5}$$

where the exponent, m varies between 0.25 and 0.31, in good agreement with both Lacey (1984) and Villumsen (1985). With the particular value m=0.25, a very interesting result is found. From the above equations it follows that, at any radial position in the galaxy, where the surface density is $\sigma_T(r)$, the scale height of the stars, $z_*(r,t)$, is given by:

$$z_*(r,t) = (V_g^2 / \pi G \sigma_T(r,t)) [1 + (t / t_r)(\sigma_T(r,t) / \sigma_r)^2]^{1/2} \tag{5.6}$$

Since $t_r \ll t$ at the current time, this simplifies to:

$$z_*(r,t) = z_*(t) = (V_g^2 / \pi G \sigma_r)(t / t_r)^{1/2} \tag{5.7}$$

Thus we have the very important result that, in a galaxy in which the disk formed at a particular epoch, the **current scale height** of the stars **depends only on the age of the disk**, and is independent of the radial coordinate in the galaxy. The variation in the exponent m from the value of 1/4 is so weak that this result is essentially independent of the actual value of m (see also Lacey and Fall 1983). This result is exactly what is required to explain the results of van der Kruit and Searle 1981a,b;1982, who found that the observed light distribution in edge-on galaxies could be best fitted by a model in which the stellar scale height is constant with radius.

Eqn. (5.7) allows the functional dependence on the rate of high-mass star formation in equation (3.6) to be fully determined. This shows that stellar diffusion, by allowing the gas layer to swell up at late times, has the effect of reducing cloud/cloud collisions and, therefore, the star formation rate.

## 6. Evolution of the Solar Neighbourhood

The observational material that has been accumulated in our solar neighbourhood over the years is sufficient to place very severe restraints on any model of galactic evolution. The end point of the models is determined by the measured age, metallicity, present-day local gas and stellar content and scale height, estimates of the mass fraction in stellar remnants, the rate of star formation and the gas depletion timescale. The history of the local disk can be inferred by age / metallicity , metallicity / height , stellar dynamics / age and element abundance ratio / metallicity relationships, or by the metallicity distributions of long - lived stars.

There is absolutely no reason to suppose that our solar neighbourhood is in any way peculiar in its properties. It is therefore reasonable to hope that a galactic evolution model which can successfully account for all the locally observed relationships, should also be capable of describing the radial variation of observable parameters in our Galaxy. These include gas content and star formation rates,the gas and stellar scale height, the metallicity distributions of stars and the abundance gradient in the gas.

The local surface density  of  matter in the region of the sun is about 75 $M_\odot pc^{-2}$ and has a scale height of about 300 pc (Güsten and Mezger 1982; Bahcall 1984a,b). An appreciable fraction of this is in an unseen form, with a surface density of about 30 $M_\odot pc^{-2}$ and a scale height not exceeding 700 pc.The local gas content has been estimated by Güsten and Mezger (1982), using the observations of Burton and Gordon (1978) and, more recently, Lacey and Fall (1985) and Rana and Wilkinson (1986) have extensively reviewed the question, which depends critically on the assumed molecular fraction. Derived values range from 3.0 to 6.5 $M_\odot pc^{-2}$ with a mean of about 5 $M_\odot pc^{-2}$. Thus the gas fraction ranges from 0.04-0.085, with a best guess value of about 0.06.

The local star formation rates are variously computed at between 3 and 8 $M_\odot$ $pc^{-2}Gyr^{-1}$ (Miller and Scalo,1978; Smith,Biermann and Mezger, 1978; Güsten and Mezger ,1982). Thus gas passes through a stellar generation in a timescale of order 1-2 Gyr in the solar neighbourhood. This timescale is oppressively short, a fact that had been noted by Larson, Tinsley and Caldwell (1980), by Rocca-Volmerange, Lequeux and Maucherat-Joubert (1981) in  the context of the Magellanic Clouds and, for a sample of other galaxies, by  Kennicutt (1983). The problem is therefore not confined to the solar neighbourhood. Even when the return of gas by intermediate mass stars is taken into account, the gas depletion timescale is only 2-8 Gyr, still very short when compared with the disk age of 15 Gyr.

The collapse timescale to the thin disk configuration is taken as a free parameter, but should not be very different from the free-fall timescale in any particular model galaxy. This timescale,$\tau_{ff}$, is given by $\tau_{ff} = 1.65(R_{100} / M_{11})^{1/2}$ Gyr ; where $R_{100}$ is the proto-galactic radius in units of 100 kpc, and $M_{11}$ is the galaxian mass in units of $10^{11}$ solar masses. For our Galaxy, the mass is of order $M_{11} = 5$ (White and Frenk, 1983; Meatheringham *et al.* 1987). The radius cannot initially have been very much larger than 100 kpc, therefore the free-fall timescale was of order 1 Gyr.

In our model of star-formation, the current gas content of our local region of the Galaxy is determined principally by three efficiency factors; the efficiencies of the high and low mass modes of star formation, and the duty factor for low mass star formation. We express the first of these as an initial gas depletion timescale, $\tau_{gas}$, which is inversely proportional to the initial rate of high mass star formation in a wholly gaseous disk with the reference surface density of 100 $M_\odot .pc^{-2}$. The relative efficiency of low mass star formation, R,  is the rate relative to the high mass mode at time t = 0 in these reference conditions, with a duty factor of 1.0. Both these factors are constrained by the observed gas fraction and the current age of the disk. The duty factor depends critically on metallicity and the local turbulent energy content of the coalescing cloudlets. Since the duty factor determines the low-metallicity cut-off of the low mass mode of star formation in the disk, it is very tightly constrained by the observations of the metallicity distribution in the lower main sequence  (Pagel and Patchett 1975) .

It turns out that these observational restraints are fairly severe. The power law slope of the IMF, p, is restricted to a very narrow range p = 2.2±0.15 and the sensitivity to changes in $\tau_{gas}$ and R is shown in figure 1, from which it can be inferred that the "best guess" parameters are; $\tau_{gas} = 2.2±0.4$ Gyr; R = 2.0±1.0 and $\tau_{diss}/\tau_{cc} = 0.2±0.1$.

With the parameters set by the above procedure, the model may now be used in a predictive fashion. To give age / metallicity relationships, the variation of metallicity ratios with age, and to predict metallicity / velocity dispersion / scale height relaionships for the local disk stars.

The evolution of the scale height or the velocity dispersion depends, in this model, on both the metallicity / age relationship and the orbital diffusion process. The value of the initial diffusion timescale is determined by the requirement that the initial gas velocity dispersion is 8 km s$^{-1}$(Stark, 1979); which remains independent of time in our models, and that the current scale height for the disk dwarf stars in the solar neighbourhood is 300 pc (Gilmore and Reid, 1983). This gives an initial diffusion timescale for the reference surface density (100M$_\odot$ pc$^{-2}$) of 1.0±0.3 10$^7$ years. With this parameter, the theoretical age / metallicity / velocity dispersion relationships are solved, and is given in table 1 with observational determinations by Janes (1979) and Norris (1987). The velocity dispersion of the oldest disk stars is predicted to be 42 km s$^{-1}$ in this model, using an initial gas velocity dispersion taken from Stark (1979) and references therein.

From the discussion in this section, it is clear that the solar neighbourhood presents an adequate number of observational relationships to overdetermine the free parameters in our galactic enrichment model. Although the derived parameters are unique in the sense that they are closely constrained by the observations, it is possible to fit this observational data set almost as well on the basis of a completely different set of assumptions. See, for example, Vader and de Jong (1981). The true test of the model lies in its ability to predict the gross structural properties of disk galaxies, see above, and in its ability to account for the radial dependence of observable physical and chemical parameters of galaxies in the context of a single set of star formation efficiency parameters. This will now be tested in the case of our Galaxy.

TABLE 1: METALLICITY / AGE / DYNAMIC RELATIONSHIPS FOR DISK RED GIANTS

| Twarog (1980) | | Janes | Norris | Model Results | | |
|---|---|---|---|---|---|---|
| Age (Gyr) | [Fe/H] | $V_z$ (km.s$^{-1}$) | $V_z$ (km.s$^{-1}$) | Age (Gyr) | [Fe/H] | $V_z$(km.s$^{-1}$) |
| 0.0 | ...... | 8.0 | | 0.0 | ...... | 8.0 |
| 0.5 | 0.18 | 16.7 | 15.5 | 0.5 | 0.10 | 8.5 |
| 2.0 | 0.10 | 13.0 | 16.2 | 2.0 | 0.05 | 10.3 |
| 3.4 | 0.00 | 13.9 | 12.0 | 3.4 | 0.00 | 12.3 |
| 5.3 | -0.08 | 16.3 | 14.1 | 5.3 | -0.09 | 15.0 |
| 7.2 | -0.17 | 18.5 | 14.4 | 7.2 | -0.21 | 17.8 |
| 8.6 | -0.26 | 21.6 | 17.2 | 8.6 | -0.30 | 21.2 |
| 9.7 | -0.35 | 23.1 | 18.2 | 9.7 | -0.41 | 24.7 |
| 10.8 | -0.46 | 26.0 | 21.3 | 10.8 | -0.58 | 29.2 |
| 11.6 | -0.57 | 35.4 | 33.0 | 11.6 | -0.68 | 32.1 |

## 7. Global Evolution of the Galaxy.

The hypothesis of bimodal star formation has already been the subject of evolutionary models (Güsten and Mezger, 1983; Larson 1986; Wyse and Silk 1987). The major problem here is to avoid ad-hoc assumptions about the relative star formation efficiencies in the high and low mass modes. In the context of the bimodal star-formation model presented here, there remains one obstacle to the application of the solar neighbourhood model to the Galaxy at large. The duty factor for low mass star formation, and by implication the timescale for the dissipation of turbulence, has only been determined locally. The local Oort A value is 15 km.s$^{-1}$.kpc$^{-1}$. In the region over which molecular clouds reform, roughly equal to the thickness of the molecular cloud region of the disk, about 140 pc, the shear heating term is of order 2-5 times as large as the thermal term. In fact, there is little difference between models provided that the shear term exceeds the thermal and random terms, so we adopt a value of 4 for the ratio of these terms locally, with a probable error of a factor of two.

The observational material on gas content, star formation rates and oxygen abundance, have been adequately reviewed recently by Lacey and Fall (1985), and to facilitate comparison with their results, these observations as summarized in their figures 2, 3c and 3d are used here. We have supplemented the abundance data they used by the Mezger *et al.* (1979) observations of HII regions near the galactic center.

The results of the closed box model (with a 1.0 Gyr collapse timescale) are shown as a solid line in figure 1. It is clear that the model gives an excellent fit to the run of gas content and to
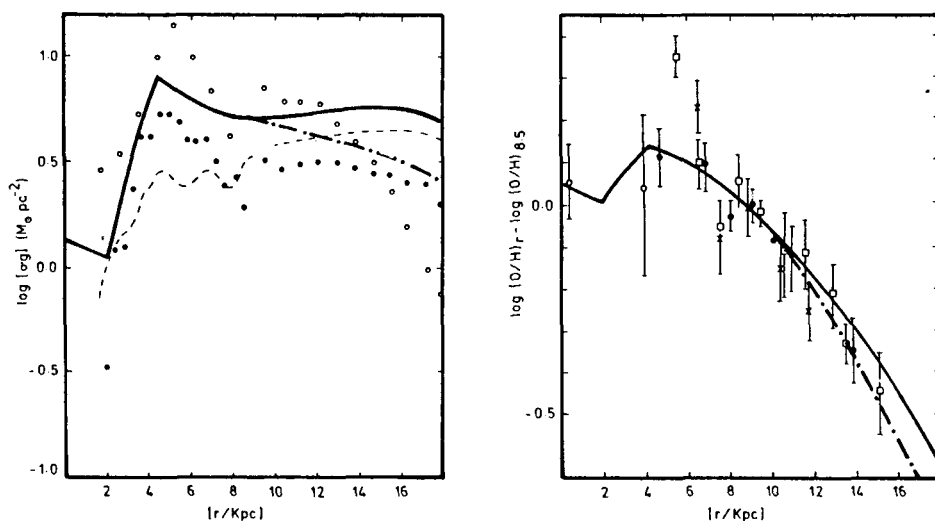


Figure 1: *The run of gas content, left, and oxygen abundance, right, with radius in the Galaxy, adapted from Lacey and Fall (1985). The solid curve is for the model without outflow, and the dot dash curve is for the model in which the gas loss increases linearly with radius outside 9 kpc.*

the oxygen abundance variation between 0 and 10 kpc in the disk. Note that, by contrast with the simple model, the abundance gradient in the gas is quite steep. This is the result of the change in effective yield with radius associated with the partial suppression of the low mass mode of star formation in the inner regions of the galaxy.

The model predicts the presence of a central hole in the gas distribution which corresponds to the changeover from a flat rotation curve to a solid-body rotation curve near the center. The disappearance of the shear term leads to a rapid re-formation timescale for molecular clouds close to the galactic center, and a correspondingly more efficient low mass mode of star formation. As a result, the gas is depleted in a shorter timescale, and a lower gas content and oxygen abundance result. Other galaxies also show this central hole (Wevers 1984), and, in the cases where the resolution is adequate to draw conclusions, this also appears to be associated with the transition from flat to solid-body rotation. Perhaps the clearest example of the phenomenon is M31 (Brinks 1981,1984). Here the transition is particularly abrupt, and corresponds to high precision with the inner edge of the HI-rich disk.

Since the low-mass mode of star formation develops when a critical metallicity is reached in the gas, the abundance gradient shown by the stars will be less than that which applies to the gas. Also, since the rate of star formation passes through a peak in the models, we expect that the average metallicity of the stars will be lower than that of the gas at any radius. Lewis (1986) has determined the abundances and the radial coordinates of some 600 disk giants, and indeed, finds this to be true.

## 8. Application to External Galaxies.

Dopita (1985), showed that the Donas and Deharveng sample of galaxies gave a good observational correlation between the specific rate of star formation of massive stars, and the gas fraction. In the model presented here, the theoretical tracks represent only a first-order fit to the observed correlation. However, they also demonstrate that scatter on this correlation may be induced by secondary parameters such as disk size (in scalelengths), age, total surface density, and variations in the relative efficiencies of the two modes of star formation caused principally by the mean velocity shear, in closed box models, or by galactic winds, in open models.

Provided that the epoch of galaxy formation is well-defined, at least for the larger spirals, we expect to find a second correlation, between the metallicity of the disk and its surface brightness. This will occur because the relative number of high mass stars ever formed, and the conversion of the matter into stars is more complete in regions of higher surface densities. Such a correlation was found by Wevers (1984), in the form of a correlation between the abundance - sensitive HII region line ratio $\log([OIII] + [OII])/H\beta$, as observed by McCall (1982) and the J-band surface brightness, $\mu_J$. Provided that the mass to light ratio of the stellar population remains constant, $\mu_J$ will be proportional to the logarithm of the surface density. In figure 2 is shown the comparison between the observation and model correlations, where the HII region line ratios have been converted to absolute abundance using the calibration of Dopita and Evans (1986). The agreement is very good provided that a surface brightness $\mu_J$ of 20.0 corresponds to a surface density of about 1000 $M_\odot$. $pc^{-2}$. According to the model, scatter in this correlation results
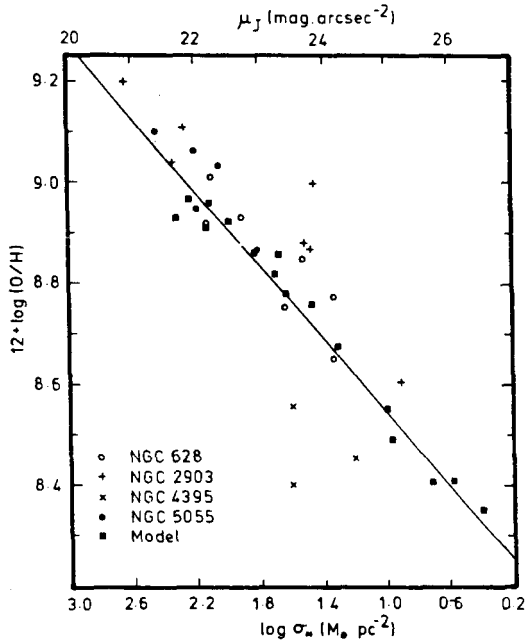
Figure 2: *The correlation between the oxygen abundance and disk surface brightness. This uses the results of McCall (1982) for HII regions, converted to abundance using the calibration of Dopita and Evans (1986), and the surface photometry of Wevers (1984). Also shown are points in the oxygen abundance / surface density plane from a variety of models (filled squares), and the best fit line to the models. The observational points and the models are in good agreement if the four galaxies plotted are approximately coaeval, and if $\mu_J = 20.0$ mag corresponds to a disk surface density of 1000 $M_\odot.pc^{-2}$.*

principally from the local shear in the rotation, and from scatter in the true ages of disk galaxies.

## 9. Conclusions

The physical model of bimodal star formation developed here has been successfully applied to observations of the solar neighbourhood and the Galaxy in general. We have shown that the observational data in our solar neighbourhood is sufficiently extensive to overdetermine the problem and to restrict all the free parameters of the theory to within very narrow ranges. With these parameters, the theory accounts for the chemical and structural evolution of the solar neighbourhood and can give a good description of the radial variation of gas content, star formation rates and metallicity and the metallicity distribution in the Galaxy.

For external galaxies, the model predicts a constant stellar scale height across the disk, a constant axial velocity dispersion in the gas, and a correlation between the gas fraction and the specific star formation rate. All of these are observed structural parameters of disk galaxies. The model also predicts the observed correlation between the surface density and the metallicity in a given galaxy, or from one galaxy to another, provided that they were born at a common epoch.

In all models, the low-mass mode of star formation, dominant below one solar mass, becomes rapidly more important as the metal abundance exceeds a critical threshold. The early disk history of these galactic models is biased towards the formation of more massive stars. This allows a greater fraction of the total matter, typically of order 30% of the total, to become trapped in dark remnants such as neutron stars, black holes and white dwarfs. This is a similar result to that obtained by Larson (1986), except that we find a rather smaller fraction of matter is trapped in dark remnants.

We predict that galaxies showing a central hole in their HI distribution, or in the rate of high-mass star formation, are galaxies in which these inner sections show solid-body rotation and in which the outer portion  of the rotation curve is flat.

Finally, it is tempting to speculate that the star formation processes discussed here in the context of disk galaxies, may be equally applicable to other galaxian environments. For example; the collision of two galaxies would be expected to produce a very intense burst of high mass star formation. The formation of globular clusters in the halos of galaxies could be the result of quiescent low-mass star formation in primordial concentrations of matter over the collapse timescale of the galaxy, when cloud-cloud collisions are unimportant. Elliptical galaxies might result from the development of a multi-phase medium in the halo phase, with star-formation running to completion before disk formation can complete.

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