EVOLUTION OF GALAXIES GOVERNED BY DISK DYNAMICS AND SPIRAL STRUCTURE

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INTRODUCTION

My major topic will be the evolutionary changes in disk galaxies caused by the continuing process of star formation. The task of interpreting observations to derive the past rate of star formation is treacherous, as I am sure will be evident in the various observational papers presented at this colloquium. Therefore, I will mention only briefly some of the basic aspects of models which have been used to discuss that past evolution.

The star formation rate and the initial mass function (IMF) are the two physical processes which are central to the construction of evolutionary models. However, still they remain terribly uncertain, both in terms of their determination by observational and empirical means and in the state of understanding them by physical theoretical models. Consequently, in my view, the most crucial task to undertake is the study of the <u>current</u> star formation in disk galaxies -- observationally and theoretically. Once that process is understood physically, it will be possible to construct models of the past history without resorting to arbitrary assumptions other than initial conditions.

I will first briefly review the status of past models for the history of the rate of star formation and nucleosynthesis in the Galaxy. They are all descriptive rather than physical, that is, they were constructed to fit observations rather than through use of physical principles. This is not meant as a criticism, for descriptive models are all that one can do prior to the knowledge of physical principles.

My second topic will be the discussion of some observational work which is directed towards testing certain specific physical principles

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which have been proposed for star formation. Lastly, I will describe some simple theoretical considerations which I believe are important for understanding the early development of spirals and the current star formation in the patchy outer parts of spirals and in Magellanic irregular galaxies.

STELLAR BIRTHRATE AND NUCLEOSYNTHESIS HISTORY OF THE GALACTIC DISK

The evidence for a long history of star formation in the galactic disk comes from the direct calibrations of ages of stars and the discovery that there appear to be stars of almost all ages, extending back about 14 Gyr (Gyr = 10^9 yr) ago. Mayor and Martinet (1977) conclude that the decrease is consistent with a smooth curve (they assume an exponential with time), and that this curve lies somewhere between a uniform rate and one which decreases by a factor of 7. This and other related observational work will be discussed at length by later speakers. I only wish to point out that the shape of the curve is almost undetermined; in particular, there may have been episodes of star formation interspersed with none. In fact, Demarque and McClure (1977) point out that there is little evidence that any disk stars formed prior to the formation of NGC 188 about 5 to 6 Gyr ago. The galactic disk may be a late acquisition.

Another way that the stellar birthrate history has been probed is through the study of the heavy element abundance Z. In brief, the observations consist of a variation of the mean Z with time, a dispersion in Z(t) at each t, and counts of the number of old stars within various Z intervals (c.f. Figures 1 and 2). The so-called G-dwarf problem is one created by model builders themselves because the simplest model does not fit the observations. To fit the observed data several non-simple models have been constructed, each of which solves the metallicity problem but which have not been thoroughly proven on the basis of independent arguments nor have they been shown to be inevitable consequences of well understood basic physical laws.

The most simple model makes the following set of assumptions:

(1) Constant initial mass function (IMF),
(2) heavy elements created and ejected by stars, with heavy element yields a function of the IMF only (and hence constant by 1),
(3) closed box of material, allowing no flows,
(4) complete and instantaneous mixing of the stellar ejecta throughout the box, and
(5) initial value of Z_0=0.

For mathematical convenience the Instantaneous Recycling Approximation (Talbot and Arnett 1971) is useful. This is a valid approximation for heavy elements produced by shortlived stars, so the conflict with

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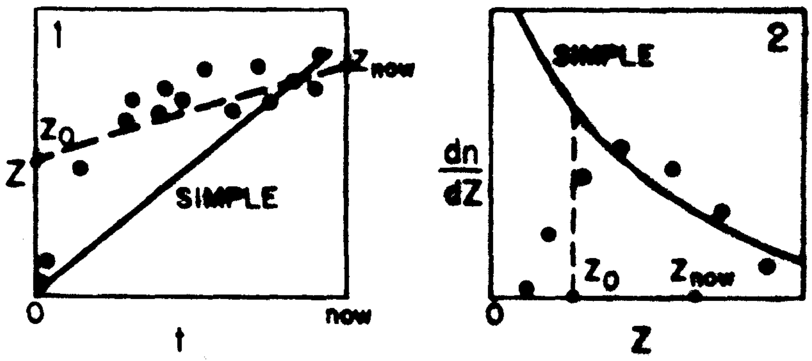

Figure 1. A schematic plot of observed stellar metallicity Z against time and of two models.

Figure 2. A schematic plot of the differential number distribution of old stars against their metallicity Z.

observations cannot be attributed to its use. It is straightforward to derive that in general, for the above assumptions,

$$Z(t) = Z_0 + p_Z \quad \ell n[M_I(0)/M_I(t)] \tag{1}$$

and

$$dn_s/dZ = N_s(Z) = (\phi_s/p_Z)\exp[-(Z-Z_0)/p_Z] \tag{2}$$

(where I have relaxed assumption 5 by explicitly including the initial value $Z(0)=Z_0$). $M_I(t)$ is the amount of interstellar matter in the box at time t, ϕ_s is the value of the IMF for those stars selected for counting, dn_s is the number of selected stars with metallicity in the interval Z to Z + dZ, and p_Z is the yield which is proportional to the IMF value for the stars which produce Z.

Both of these equations are independent of the time dependence of the stellar birthrate function B(t). This independence is significant in that the observations prove that the simple model with $Z_0 = 0$ is inadequate for all possible forms of the function B(t).

A mathematically convenient form for B(t) is the exponential $\nu_0 \exp(-t/T)$; in this case $Z(t) \propto t$. It is clear that that does not fit the available data (Figure 1) and no other reasonable form for

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B(t) will fit the data either. The same is true for $N_S(Z)$ (Figure 2). It is clear that both sets of data are in much better agreement with $Z_0 \simeq Z(\text{now})/2$. This is an example of a descriptive model which works, but contains no physical basis. It can be put upon somewhat more solid ground by the Prompt Initial Enrichment assumption wherein there is assumed to be an early phase in which low mass stars (such as those counted in N_s) do not form until after Z rises to Z_0 (Truran and Cameron 1971). This is one special form of the general class of solution involving a variable initial mass function (VIMF).

Methods for achieving other descriptive solutions to this problem may be obtained by inspection of equation (2). The fundamental features of the observations may be fit by making the ratio (ϕ_S/p_Z) very small for small Z. VIMF solutions may be invented which achieve this (note that Schmidt's 1963 particular VIMF prescription does not fit, c.f. Talbot 1973). For example, the assumption that $p_Z = p_0(Z_0/Z)^\alpha$ can be made to fit the $N_s(Z)$ distribution quite well by suitably choosing p_0, Z_0, and α.

Another type of solution which has (ϕ_S/p_Z) vary in the appropriate fashion is to have metal production ($\propto p_Z$) occur in one region of space and the formation of the selected stars ($\propto \phi_S$) in another region of space. In these models there must be metal-poor dwarfs formed (assuming constant IMF) but they don't exist in the local neighborhood to be counted. This model was discussed by Ostriker and Thuan (1975). This is one type of model which invokes spatial inhomogeneities to solve the G-dwarf problem. The most basic discussion of the inhomogeneity solution was given by Searle (1972); he has more recently rediscussed this idea for the particular case of halo star metal abundances (Searle 1977).

Larson's (1976) collapse models are another method which relies upon spatial inhomogeneity, in this case it is the dilution by metal-poor gas which maintains $Z \simeq$ constant. This solution fits the data only if one additionally invokes small-scale inhomogeneities in Z and/or observational scatter.

The metal-enhanced star formation (MESF) model (Talbot and Arnett 1973; Talbot 1974) also invokes small-scale chemical inhomogeneities, but it further utilizes the fact that the most metal-rich parcels of gas will be the coolest and therefore the most prone to form stars.

The relative merits and uncertainties for these methods are discussed by Talbot (1973) and Audouze and Tinsley (1976). Each method achieves what it sets out to do. It seems likely that all proposed processes contribute to some extent. Resolution of their relative importance must await independent tests.

It seems probable that material flows occur in ways such as those described in Larson's collapse model and Ostriker and Thuan's model for enrichment by the halo. Even with those models some chemical inhomogeneities are required. There are strong theoretical arguments (e.g. Silk 1977) that fragmentation of clouds into stars will depend upon Z, hence both MESF and VIMF may occur.

With these uncertainties haunting the interpretation of past star formation processes, it is clear that it is very important to study star formation which is occuring now. For example, observations may show directly that the IMF does vary (Burki 1977; Freeman 1977). Once these physical principles of current processes are understood it may be possible to apply them to problems of ancient history.

THE CORRELATION BETWEEN STAR FORMATION RATE AND GAS DENSITY

Strom, Strom, and Grasdalen (1975) review the rather convincing observational evidence that most stars form from the cold dense clouds seen as dark nebulae or molecular clouds. The very clear correlation between the radial distribution of the indicators of young stars and that of CO (e.g., fig. 10 of Burton 1976) suggests that to a fairly good approximation the surface density of star formation B (in M☉ pc^{-2} Gyr^{-1}) is approximately proportional to the surface density of the high density molecular cloud material Σ_m (in M☉ pc^{-2}). These two sets of observational data suggest that the following expression is the one which should be used to relate star formation to the interstellar medium (ISM):

$$B = \nu_* \Sigma_m \tag{3}$$

where ν_*^{-1} is the present value for the characteristic time for converting molecular cloud material into stars. A priori one does not know how ν_* may itself depend upon physical quantities such as gas density, temperature, etc., but the data from Burton (1976) shows that ν_* varies slowly with galactocentric radius in our Galaxy.

The classical correlation studies between B and ISM density are of two types: (1) looking for relationships of the form $B \propto \Sigma_{HI}^n$ by studying the way B and Σ_{HI} vary over the faces of galaxies (e.g., Madore, van den Bergh, and Rogstad 1974), and (2) comparing scale heights H in the z-direction for B and HI gas. The latter was the basic way by which Schmidt (1959) concluded that the rate of star formation is proportional to the gas volume density squared.

The surface density studies give $n \simeq 1.5$ to 3, with a general tendency to be close enough to Schmidt's $n = 2$ that that value is often taken to have some fundamental significance. However, n not only varies from galaxy to galaxy, but also within single galaxies. Those types of surface density correlations are difficult to interpret physically because they have no direct means of allowing for positional variations in the equivalent widths W of B and the HI gas

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(Talbot 1971). Lequeux will discuss the variation of these widths with position in our Galaxy later in this colloquium.

One must be careful about the physical interpretation of any of these analyses. For example, the method of deducing n from the equivalent widths of B and HI uses (for gaussian distributions) $W_B = W_{HI}/\sqrt{n}$ to deduce $n \simeq 2$ to 3 (see Schmidt 1959). However, this does not show that the rate of star formation is actually physically governed by the square of the HI gas density. All that it shows is that star formation occurs from material which has a smaller scale height than the average HI; i.e. it occurs from material with z-velocity dispersion lower than that of the HI gas. I believe that it is due to the fact that the H_2 molecular clouds have a lower velocity dispersion than do the lower density HI clouds, and stars form from molecular clouds rather than low density clouds.

If this interpretation is true, the physically relevant question is, why is the molecular cloud velocity dispersion consistenly about $\sqrt{2}$ to $\sqrt{3}$ smaller than that of the HI gas? From the point of view of a theoritician interested in the formation of stars, that is a completely different type of question than the more classical question of why the star formation rate should be proportional to the square of the gas density.

At most what the $n \simeq 2$ empirical value reveals is something about how dense molecular clouds are formed, not necessarily how stars form. The physical processes involved in the conversion of moderate density HI clouds into molecular clouds may have no connection with the physical processes which cause the molecular clouds to form stars.

For the sake of making a simple illustration let me make a simple approximate description of the interstellar medium (ISM) by assuming that it is a mixture of two types of clouds embedded in a low density intercloud medium (ICM) which is mostly ionized. The two cloud types will be dense molecular clouds (n_m per pc^3) and moderate density neutral atomic hydrogen clouds (n_{HI} per pc^3). I will assume that equilibirum between the HI clouds and the ICM is established by balance between (1) cloud evaporation and the compression of these clouds into dense molecular clouds and (2) the formation of clouds by condensation of the ICM or by sweeping-up of material by supernovae shells. Furthermore, I will assume that the equilibrium population of molecular clouds is determined by a balance between (1) cloud evaporation and cloud dissolution by young stars and (2) compression of HI clouds into dense clouds.

Many processes might be responsible for the compression of HI clouds to H_2 cloud densities. For simplicity I will discuss just one: cloud-cloud collisions. It has been shown (Stone 1970) that a collision of two moderate density clouds produces rebound and no significant subsequent compression to much higher density. However, that rebound can occur only if there is ample time before another collision occurs. If the mean time between collisions τ_c is greater than the time required for the clouds to readjust, the internal sound travel time $\tau_s = R/c$ where c is the internal sound speed, then the cloud readjusts. However, if $\tau_c << \tau_s$ the rapidity of the collisions acts very similar to an additional external pressure, so the cloud will contract to a new configuration. If the contraction continues to a sufficiently high density, free-fall collapse commences.

In this cloud-cloud collision model, the equilibrium number density of dense clouds n_m is proportional to the square of the density of the lower density clouds, n_{HI}. The rate of star formation is proportional to n and therefore it is proportional to n_{HI}^2. In many respects this model is similar to that discussed by Field and Saslaw (1965).

The star formation rate B is proportional to the efficiency of star formation, E_*, and inversely proportional to the timescale for depopulating the high density end of the cloud spectrum, τ_*^{-1}. If W_m is the equivalent width of the cloud material, and M is their average mass, then $\Sigma_m = W_m M_m n_m$ and

$$B = E_* \tau_*^{-1} W_m M_m n_m \tag{4}$$

The important point is that τ_*^{-1} may in general depend upon many separate physical processes, e.g., the rate of passage of spiral density wave shocks, the rate of exposure to supernova remnants, or simply internal self-gravitational collapse. These processes may include cloud-cloud collisions ($\propto \tau_c^{-1}$) but in general there also will be other contributions. In a general non-equilibrium situation are must compute all of the major contributors.

In an equilibrium situation, the spectrum of dense cloud properties is maintained by a balance between depletion by star formation ($\propto \tau_*^{-1}$) and repopulation by cloud-cloud collisions ($\propto \tau_c^{-1}$). Furthermore, the cloud population is maintained by a balance between this drain ($\propto \tau_*^{-1}$) and formation of clouds from the ICM. If the latter is dominated by sweeping-up by supernova remnants, then the rate of cloud creation is proportional to rate of supernova which is proportional to τ_*^{-1}. We thus see the closed-loop feedback situation which can maintain the approximate steady-state.

For this steady-state equilibrium it is necessarily true that $\tau_*^{-1} n_m = \tau_c^{-1} n_{HI_2} \propto n_{HI}^2$. To the extent that W_m and W_{HI} are constant, $B \propto \Sigma_{HI}^2$. The coefficient in front of Σ_{HI}^2 depends upon equivalent widths, cloud masses, etc., and in general it will vary with position. If there are non-equilibrium conditions (e.g. transients behind a shock wave), then the proportionality of B to Σ_{HI}^n no longer is physically relevant, although some empirical value for n can always be obtained.

The non-equilibrium transient episodes of star formation provide the laboratories for testing this and other models. Each model will have certain specific length and time scales which provide clues to the physical processes. In the simple cloud model presented, the characteristic length scales which can be observed by looking at face-on galaxies are (1) the sizes of individual clouds R (it is understood that such quanties actually have subscripts to denote cloud type), (2) mean separation of clouds as seen projected on the plane $L = (nW)^{-\frac{1}{2}}$, and (3) characteristic scales for cloud clumping λ, if mechanisms exist which produce clumping. The observable time scales will be (1) the time required for an increased density to become evident by an increased star formation activity (this will be of order $\tau_C + \tau_D$ where τ_D is the cloud collapse time once it becomes gravitationally bound) and (2) time scales attributable to the evolution of clusters of stars (evident by the colors of clusters becoming less blue).

THE SPIRAL MODE OF STAR FORMATION

The most well developed theory for star formation in spiral galaxies is that of initiation by spiral density wave shocks in the gas (Roberts 1969; Shu, et al. 1972).

Figure 3 is a sketch of the predictions of that theory. The observed dust lanes are interpreted as being due to great lateral compression by shocks. Individual clouds which pass through the shock

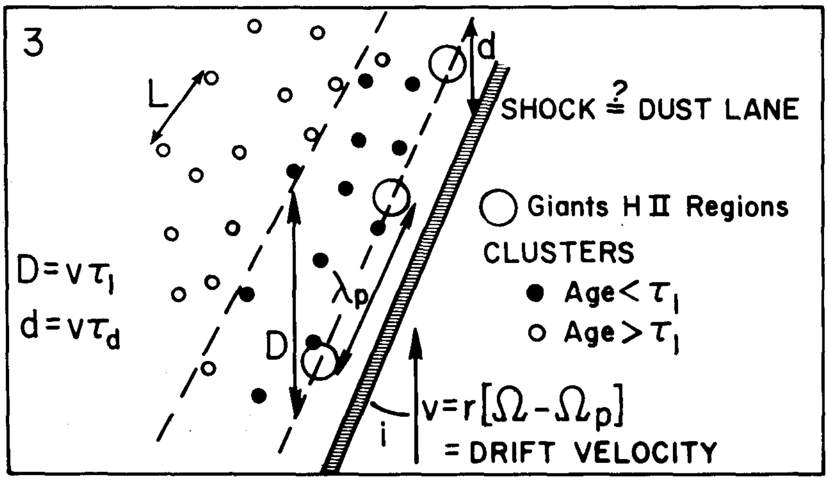

Figure 3. Distribution of objects expected behind a spiral density wave shock with some characteristic length scales noted.

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are then compressed and this initiates collapse and stars form (Woodward 1976). Clusters of sequentially older ages should be found downstream from the dust lane. A line of HII regions will mark the locus of the youngest clusters.

The pattern moves with respect to the material with a "drift velocity" $v = r[\Omega(r)-\Omega_p]$ where $\Omega(r)$ is the material angular rotation speed and Ω_p is the angular rotation speed of the pattern. (Note: the shock strength is governed by the perpendicular component $w_{\perp 0} = v \sin i$.) The width of the spatial distribution of clusters of varying age τ will be proportional to v. E.g., if O stars form with a time delay of τ_d after the shock passes, then the HII region locus will be located down stream by $d=v\tau_d$. If one can measure the ages of clusters, then v may be determined empirically by $v = D/\tau$ (c.f. Figure 3). The HII region spacing λ_p should be related to the mean spacing between clouds succeptable to formation of OB star clusters. This spacing may be simply proportional to the mean cloud spacing L if the formation of stars from clouds is random. However, if there are clumping mechanisms λ_p will be its wavelength; one such mechanism which has been proposed is Parker's magnetic Rayleigh-Taylor instability (c.f. Mouschovias, et al. 1974).

To quantitatively address these problems, my colleagues R. Dufour and E. Jensen and I are studying NGC 5236 (M83), a bright, nearly face-on southern spiral of Revised Hubble Class SAB(s)c. Figure 4 shows a blue photo, and Hα photo, and two preliminary color maps showing B-V and $Q_{UBV}=(U-B)-0.71(B-V)$.

As an example of the investigation in progress, consider the area near the organized dark lane on the east side. From studies of the colors and intensities we can show that the increased surface brightness prior to the dust lane consists of an increased surface density of old stars, i.e., there is a stellar density wave. The brightening apparent in an intensity photograph is not due to the formation of young stars alone.

Just outside of the dust lane there is a string of HII regions. They are displaced by only a few hundred pc, but if you assume circular orbits they are about 3 kpc from the dust lanes as measured along the material flow lines. Right behind the locus of HII regions begins light which is blue. Down stream the light gradually becomes less blue. By looking at the age of a standard galactic cluster versus its color, we can estimate the time since zero age for these clusters. From this age versus distance down stream, we compute the "drift velocity" $v \simeq 30$ to 60 km/s.

If the density wave theory is valid, this observed drift velocity should correspond to the predicted v. From the rotation curve of Rogstad, Lockhart, and Wright (1974), and by placing corotation out at the farthest HII regions, we compute $v \simeq 30$ to 60 km/s, where most of the uncertainty is in the inclination angle.

Consequently, we believe that the empirical v and predicted v are in excellent agreement; both are still somewhat uncertain and better results will be achieved after further analysis of the data.

The HII regions are distributed along a line with irregular spacing of about 0.3 to 3 kpc. This is perhaps a measure of λ_p, the Parker instability length. The displacement of the HII regions downstream corresponds to a delay time of about 25 to 50 Myr.

This delay time is presumed to be due to a combination of the collapse time (e.g. Woodward's 1976 cloud required 6 Myr to collapse), possibly the time for the Parker instability to develop ($W/v \simeq 10$ Myr), and the time required for a giant HII region to develop (sizes are $\sim$100 pc, so internal velocities of $\sim$10 km/s require $\sim$10 Myr to achieve coherent structures of this size). These explanations approximately give the observed 25-50 Myr delay, but it is too soon to decide whether this is a significant agreement or a coincidence. It is presented as an example of the type of test which is becomming available.

The spatial distribution of the young stars is very patchy. The characteristic sizes and separation of the components of the patches are about one hundred pc. These are interpreted as being representative of typical cloud spacing as seen from above the disk, so it is approximately equal to $L_m \simeq (n_m W_m)^{-\frac{1}{2}}$. The patches occur in coherent groups with characteristic size λ_p.

Another aspect of this cloud model is that it solves a troublesome problem with the standard view of spiral density wave shocks. Recent observations of the ISM indicate that a large fraction of the volume consists of a very low density $\sim 10^6$ °K component. The sound speed in this component is so large ($\sim 10^2$ km/s) that there should never be a shock wave of the type normally discussed (with velocity jumps of order 10-20 km/s). This problem was discussed by Scott, Jensen, and Roberts (1977).

In the simple cloud picture previously described, there are HI cloud collisions with mean free paths of $\lambda_{HI} = (n_{HI}\ \sigma_{HI})^{-1}$; in the solar vicinity the value of λ_{HI} is deduced from line-of-sight studies with 21-cm, and the result is $\simeq$ 333 pc (Baker and Burton 1975). The dense molecular clouds have a λ_m given by an analogous formula; in the solar vicinity λ_m is very much larger than λ_{HI}.

The clouds travel through the intercloud medium as free ballistic particles except for the collisions; i.e., they behave much as atoms in a gas. In particular, even though a shock can not propagate in the hot intercloud gaseous medium, the "gas" which is comprised of the clouds themselves can maintain a "shock" with thickness $L_s \simeq \lambda_{HI}$ provided there are velocity jumps $\Delta u \gtrsim c_{HI}$ where c_{HI} is the velocity dispersion of the clouds (in solar vicinity $c_{HI} \simeq 8$ km/s).

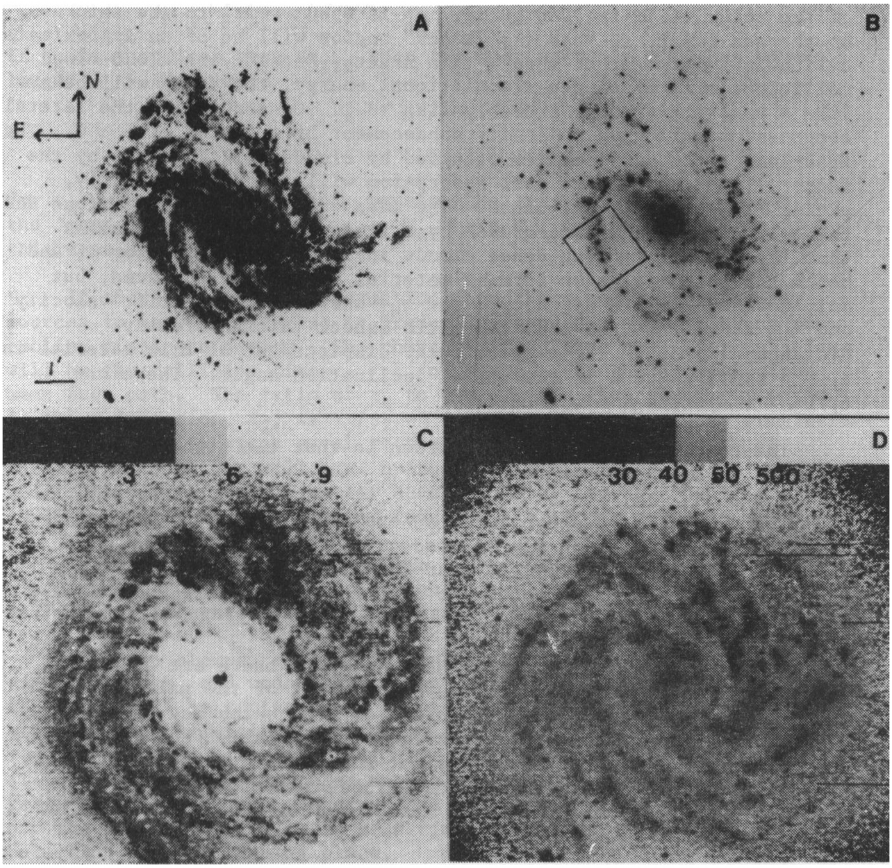

Figure 4. (a) A blue photo of NGC 5236. (b) Hα. (c) Video display of a map of B-V colors. (d) Q_{UBV} = (U-B)-0.71(B-V) calibrated with approximate ages of bright stars in each pixel (in Myr).

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The observational characteristics of such a "shock" would be (1) thickness of order λ_{HI}, and (2) irregularities on scale of order λ_{HI}. If the solar vicinity is a guide, λ_{HI} is about equal to the thickness of the gas layer, so that the "shock" region will be of an approximate cylindrical form rather than a thin sheet. Because the cloud-cloud collisions will dissipate translational energy, the "gas" will behave like a gas with $\gamma < 5/3$, probably like $\gamma \lesssim 1$. Consequently, the lateral compression will give a density enhancement by a factor of $\beta > 4$. The fraction of the surface area occupied by clouds will increase by the factor β, so the average dust absorption will increase similarly, giving rise to dark dust lanes. The mean free path for collisions and the collision time will decrease by a similar factor. This means that the rate of forming dense clouds increases by the factor β, and hence the potential star forming material n_m will be enhanced, but only downstream at a distance $d = v\ \tau_{HI}$ where v is the drift velocity and $\tau_{HI} \simeq \tau_{HI}/c_{HI}$, so that the ratio (shock thickness/delay distance) $\simeq v/c_{HI}$. The perpendicular displacement of this material is $d_\perp = d \sin i$ where i is the spiral inclination angle. Therefore $d_\perp/L_S \simeq v \sin i/c_{HI} = w_{\perp 0}/c_{HI}$.

The conclusion which may be drawn is that the stronger the shock the more separation there will be.

The proceeding discussion is an example of the type of detailed observational data which may be used to test and refine the specific theory of spiral shock induced star formation. It is very significant, however, to note that that is not the only mode of star formation, even for spirals.

The map of stellar ages in M83 shows that there are extensive patches of very young stars in the outer parts of the galaxy. These patches form short, irregular portions of arcs which may be fragments of spirals. Except for the very slight organizing effect produced by the shearing motions, it is consistant to describe those outer parts as being composed of random patches. These random fragments are similar to the random episodes of star formation seen in irregualar galaxies.

IRREGULAR MODE OF STAR FORMATION

The cloud collision model has the advantage that it does not require spiral density wave shock to form stars; it only requires density enhancements. Consider a disk composed of cloudy gas (say low density HI clouds) but with no systematic variations in the number density of these clouds. Stability analysis shows that there are certain conditions under which that disk will be unstable. For example, the Toomre (1964) and the Goldreich and Lynden-Bell (1965) analyses show that the disk will be unstable if the gas velocity dispersion

$$c_g < c_{crit} = \pi G \Sigma_g / \kappa \tag{5}$$

If c_g is just less than c_{crit} then the most unstable mode has wavelength $\lambda_u = \lambda_T/2$ where

$$\lambda_T = 4\pi^2 \Sigma_g / \kappa^2 \tag{6}$$

For $c_g << c_{crit}$, the unstable wavelengths extend from $\lambda = \lambda_T$ down to the Jeans length $\lambda_J = c_g^2/G\Sigma_g \simeq W_g$ where W_g is the equivalent thickness of the gas layer.

If there were no star formation then there would be no energy sources to keep c_g high, so it gradually decreases as collisions and cooling dissipate energy. The characteristic time scale for this loss will be the collision time $\tau_c \simeq \lambda_g/c_g$ where λ_g is the typical cloud mean free path. The ratio of τ_c to the dynamic time scale for motions in the z-direction, τ_Z, is $\tau_c/\tau_Z \simeq \lambda_g/W_g \gtrsim 1$ if the clouds originate as fragments with sizes equal to the unstable wavelengths. Under these conditions one will have hydrostatic equilibrium in the z-direction with a slow secular decrease in c_g and W_g. Because c_g decreases, a wider and wider range of λ's become unstable.

The most unstable mode will be $\lambda_u >> W_g$, so one expects clumping to occur on this scale, the clumps being composed of individual fragments down to the size $\lambda_J \simeq W_g$.

In these clumps, the number density of clouds goes up, collision times decrease, and under fairly general conditions these cloud collision will be rapid enough to produce star formation via the cloud-cloud collision picture discussed above.

The situation is altered once stars do form. They will heat and generate turbulence in the gas, thus driving c_g up and thereby turning off the instability. In the mean time, patchy irregular star formation has been taking place.

With respect to current-day star formation, this irregular mode may be the explanation for the patchy patterns observed in Magellanic irregular galaxies and the outer parts of spirals. To date no quantitative test has been tried.

This mode of star formation would be the only mode which could occur during the early phase of a spiral galaxy such as ours (if there are no stars one can not have a stellar density wave driving sprial shocks). The theory may be tested by considering the solar neighborhood of the disk of our Galaxy. Suppose it were initially all gas (Σ_g = 100 M$_\odot$ pc^{-2}) and differential rotation is the same as now (κ = 32 km s^{-1} kpc^{-1}). The gas would become unstable as soon as $c_g < c_{crit}$ = 42 km/s. The thickness would be $W_g \simeq$ 3.2 kpc, or

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$\langle|Z|\rangle \simeq$ 1 kpc. Such an unstable configuration will break up into clouds and the resulting heriachy of instability scales will cause cloud-cloud collisions. The result will be continued star formation until the instability is turned off by c_g raising above c_{crit}. The stars formed first will have $c_z \lesssim$ 42 km/s and $\langle|z|\rangle \lesssim$ 1 kpc. Compare these figures with those of the Intermediate Pop II: $c_z \simeq$ 25-70 km/s, $\langle|z|\rangle \simeq$ 700 pc.

Young OB stars and supernovae are the only mechanisms which can keep c_g up. By taking reasonable estimates for the heating produced per generation of stars, one can show that the gas disk will settle down to $c_g \simeq$ 18 km/s and $\langle|z|\rangle \simeq$ 200 pc where it will be in a state of incipient instability. Compare those figures with the Old Disk Population: $c_g \simeq$ 17-20 km/s, $\langle|z|\rangle \simeq$ 180-270 pc.

As the gas is consumed into stars, the stability criterion changes. Under present day circumstances the disk is locally stable _here_, but one can show that the instability continues far out in the disk where the surface mass is lower and hence gravity weaker.

It is evident that this irregular mode of star formation explains certain features of the early evolution of the Galactic disk. The results are obtained with no _ad hoc_ assumptions, the mechanisms are all based upon physical processes such as instabilities, fragmentation, and heating by stars.

This discussion is far from being a complete model for the evolution of disk galaxies. The primary missing element is a physical theory for the processes which govern the spiral mode of star formation, i.e., those which govern the amplitude of the stellar density wave and the pattern speed. With such a theory it should be possible to construct a physical theory for the star formation rate which will extend from the formation of the disk to the present day.

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