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CHEMICAL EVOLUTION AND THE FORMATION OF GALACTIC DISKS*

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ABSTRACT

The chemical evolution of two collapse models for the formation of disk galaxies is calculated in detail, and the results are compared with properties of our own and other spiral galaxies. The models show at least qualitative agreement with empirical stellar and interstellar abundance gradients and with color gradients in spiral galaxies. The outer parts of the model disks are also in general agreement with the metallicity and age distributions of stars in the solar neighborhood, and with correlations between metallicity and kinematics for nearby stars. It is concluded that the process of disk formation by gradual accumulation of gas into a plane may account in a natural way for many properties of disk galaxies. In general, gas flows within or from outside galaxies are expected to have very important effects on chemical evolution.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: stellar content — interstellar: abundances — stars: abundances — stars: stellar statistics

I. INTRODUCTION

Many attempts to model the chemical evolution of disk galaxies have been inspired by observations of gradients of color and composition in spiral galaxies, and by observations showing a metallicity distribution for solar neighborhood stars that is discordant with simple predictions (Audouze and Tinsley 1976). Gradients in color and composition can be understood if the time scale for converting gas into stars increases outward, as in models assuming density-wave–driven star formation (Oort 1974; Jensen, Strom, and Strom 1976) or in models where the star formation rate depends on the disk surface density (Talbot and Arnett 1975; Chiosi 1977). The metallicity distribution of nearby stars can be explained by an early excess of massive stars (Schmidt 1963), by star formation preferentially in metal-rich regions (Searle 1972; Talbot and Arnett 1973), or by infall of gas at a significant fraction of the star formation rate (Larson 1972; Lynden-Bell 1975; Ostriker and Thuan 1975). The detailed assumptions of all of these models are rather ad hoc, and it has not yet been possible to choose among them. Of the various processes mentioned, both a radial variation of the star formation rate and continuing infall of gas are naturally predicted by dynamical collapse models for the formation of disk galaxies (Larson 1976, hereafter Paper I). It is therefore of interest to see to what extent the collapse models can account for the observed chemical abundances in spiral galaxies and in solar neighborhood stars.

In this paper we present detailed calculations of the chemical evolution of two of the disk models of Paper I, models 6 and 9, which successfully reproduced the general morphological properties of disk galaxies. The calculations use the chemical evolution code described by Tinsley (1977), which follows separately elements from different sources and allows for finite stellar lifetimes, thus providing greater accuracy than the instantaneous recycling approximation used in Paper I. We consider here only the disk component of each dynamical model, i.e., an equatorial zone of height $z = 0.05r$, assuming it to remain vertically well mixed at each radius. As input from the full dynamical calculations, we take the rate of vertical gas inflow into the disk, the metallicity of the gas entering the disk, and the star formation rate in the disk as functions of time and radius. This procedure allows us to avoid the numerical errors produced by the coarse grid used in Paper I, which had a serious effect on the metallicity of the gas during the later stages of disk formation.

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II. ANALYTICAL APPROXIMATIONS

Since many of the numerical results can be understood in terms of simple analytical models for chemical evolution, we give first a few useful analytical approximations. We assume throughout that the initial mass function is constant and that stars form with the metallicity distribution of the ambient gas.

For a closed system that is initially all gas, the mean metallicity Z_g of the gas increases as the fractional gas content μ declines, and is given approximately by

$$Z_g = y \ln \mu^{-1} \tag{1}$$

(Searle and Sargent 1972), where y, the "yield," is the mass of metals ejected per unit mass of new stars formed. A more exact expression, with the correct limit of 1 as $\mu \to 0$, is $Z_g = 1 - \mu^y$ (eq. [40] of Talbot and Arnett 1971).

For a system whose mass increases because of gas inflow while the stars are forming, Z_g tends asymptotically to a value of order $y + Z_f$, where Z_f is the metallicity of the infalling gas. More exactly, if the ratio of star formation rate to gas inflow rate is k, it can be shown that

$$Z_g \to ky + Z_f\,, \tag{2}$$

a generalization of Larson's (1972) result, which had $k = 1$. The star formation rate (SFR) used here is the net rate, excluding matter immediately returned to the interstellar medium by short-lived stars. If delayed return of gas from long-lived stars is significant, its effect is similar to that of infall, with a Z_f equal to the mean metallicity of the old stars.

During the early stages of formation of a galactic disk by infall of gas, the infall rate is large compared with the SFR (i.e., $k \ll 1$ in eq. [2]), so Z_g is approximately equal to Z_f. The burst of star formation occurring in the models during the initial collapse produces a rapid rise in Z_f, and hence in Z_g; but Z_f quickly drops again as star formation outside the disk subsides, and this can cause a drop in Z_g. Thereafter, the infall rate slowly declines, and it eventually becomes somewhat less than the SFR in the disk, so that Z_g approaches a slowly varying value $\sim ky$, with $k \gtrsim 1$. If infall were to stop altogether, Z_g would increase according to $\Delta Z_g \approx y\Delta \ln \mu^{-1}$ as in a closed model, possibly reaching much greater values than with even a small amount of infall.

More detailed analytical approximations for infall models with $Z_f = 0$ have been derived by Lynden-Bell (1975). His "Best Accretion Model" has a steadily declining infall rate and a gas mass that first builds up and then declines to zero. Correspondingly, Z_g first rises to approach an asymptotic value but later increases more steeply as the gas is used up; in terms of the above approximations, k is at first less than 1 but later increases rapidly. Qualitatively similar effects are seen in some zones of the models of Paper I. However, a difference from Lynden-Bell's model is a finite Z_f, which considerably enhances the initial rapid rise in Z_g.

III. PROPERTIES OF THE COLLAPSE MODELS

a) *Evolution of Metallicity*

Figure 1 shows the time variation of the metallicity of the gas at several radii in the disks of models 6 and 9 of Paper I. The quantity plotted is Z_g/y, where Z_g is the abundance of any primary element made in stars above 5 $M_\odot$ (e.g., Fe or O) and y is the yield for that element. These curves all show the initial rapid rise and, except in the outermost zones, the subsequent drop in metal abundance predicted by the analytical approximations of § II. The metallicity later rises slowly as the infall rate declines and k becomes greater than $\sim$1. The cross marks on the curves indicate when 10%, 50%, and 90% of the final number of stars have been formed at each radius, and they show that, at small radii, most of the stars

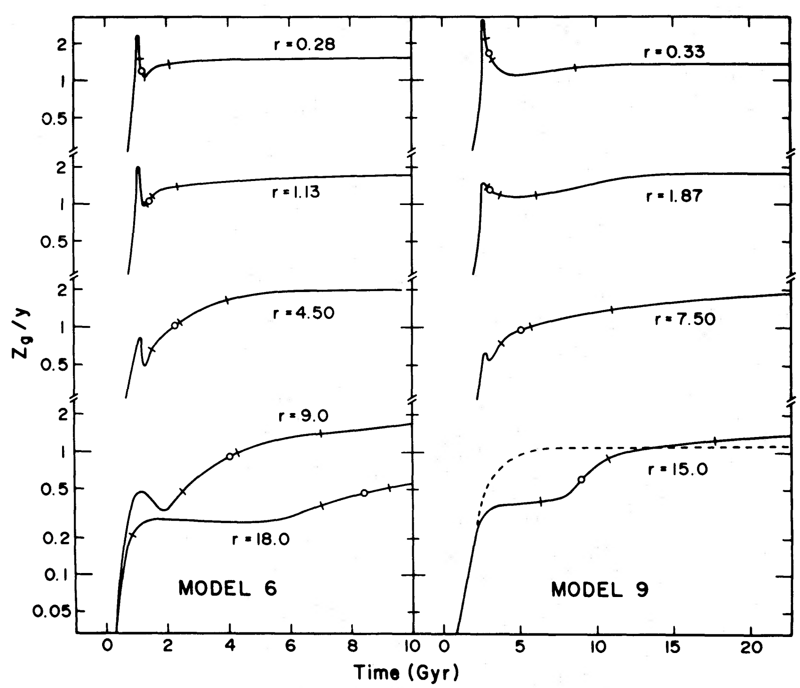

FIG. 1.—Evolution of metal abundance (scaled to the yield, which depends on the element considered) in the gas at several radii in (*left*) model 6 and (*right*) model 9. The zero point of time is the start of collapse. Curves are labeled by the radius in kpc. Cross marks on each curve denote the times at which 10%, 50%, and 90% of the final mass of stars has been formed; open circles denote the time of maximum gas density. The dashed curve for the region at 15 kpc in model 9 is for an ad hoc variant in which the gas density is held constant after 2.3 Gyr.

form very early and have nearly the same metallicity as those formed later; half of the stars at the innermost radius in model 9 are even super-metal-rich relative to younger stars. At larger radii, the early maxima in Z_g involve only a small fraction of the stars, and these are not more metal-rich than the youngest stars. Most stars in the outer regions form while the disk is gradually gaining mass by accretion and while the metallicity is rising slowly from a value somewhat below the yield to a value somewhat above it.

In all cases shown in Figure 1, less than 10% of the stars form when Z_g is below half the final mean stellar metallicity. The resulting narrow metallicity distributions are characteristic of chemical evolution models in which infall is important (Tinsley 1975) but not of simple closed models, which predict that ~40% of the stars have less than half the mean metallicity (e.g., Schmidt 1963). The effectiveness of infall here is due to the slow disk formation, by gradual accumulation of gas over billions of years, that occurs in the models of Paper I because of the long gaseous dissipation time scale at low density. A long time scale for disk formation could also occur if gas falls in from distances larger than those considered in the models, i.e., greater than ~100 kpc. If, on the other hand, the infall and dissipation time scales are short, most of the gas can fall into a disk before significant star formation has taken place; we have calculated the chemical evolution of a model of this type (not published in Paper I), and we find that it resembles more closely a simple closed model.

The chemical evolution of the gas depends sensitively on the amount of gas remaining at any time, and hence on the exact relation between the SFR and the gas density. In the present models, the SFR varies approximately as a power of the gas density; as a result, the gas density first rises and then declines again after a time indicated by the circle marked on each curve in Figure 1. Another possibility is that there is a threshold gas density such that star formation does not occur at lower densities but is very rapid at higher densities (e.g., Quirk 1972); then the gas density will be maintained near the threshold value by a close balance between star formation and infall. To illustrate the effect of such a threshold density on chemical evolution, we have recalculated the properties of the zone at $r = 15$ kpc in model 9, assuming that the gas density remains constant after 2.3 Gyr while infall continues at the rate given by the dynamical calculations; the result is shown as the dashed curve in Figure 1. This case resembles an "extreme infall model" (Larson 1972) in producing a rapid rise of Z_g to a nearly constant asymptotic value. If this behavior were to occur at all radii, it would result in narrower metallicity distributions and flatter radial abundance gradients (see below).

b) Metallicity Gradients

Figures 2*a* and 2*c* show the radial variation of both the final metallicity of the gas, Z_g, and the average metallicity of all stars ever formed, Z_*. Since most stars are formed early, Z_* corresponds observationally to the metallicity of the old stellar component of galactic disks. In both models, Z_* decreases monotonically outward, in qualitative agreement with observations of old disk stars in our Galaxy (Janes 1975; Mayor 1976) and several S0 galaxies (Strom *et al.* 1976; Faber 1977). Although quantitative comparisons are difficult because of calibration uncertainties, we note that the predicted decrease in Z_* out to $r =$ 15 kpc is about a factor of 2, in rough agreement with the factors of ~2–4 estimated from observations for the radial variation of Z_* in S0 galaxies.

The models predict stellar age gradients that could also contribute to the observed gradients of color and line strength in S0 galaxies. For example, if star formation were terminated several Gyr before the present time, the mean stellar age would be several Gyr younger in the outer part of the disk than near the center; this would produce a radial color change of up to ~0.1 in $B - V$ or ~0.2 in $V - K$, possibly contributing significantly to the observed gradients that have been ascribed entirely to metallicity.

The metallicity Z_g of the gas decreases with increasing radius over most of the disk in these models, because the completeness of conversion of gas into stars decreases outward. However, infall of metal-poor gas produces a shallower gradient than would occur without infall. This effect is illustrated for model 6 in Figure 2*b*, where the solid curve reproduces Z_g from Figure 2*a*, while the short-dashed curve shows the radial dependence of Z_g that would be predicted by equation (1) if each annulus evolved as a closed system. It is evident that infall reduces Z_g by an amount that is largest at the center, where the relative importance of infall is greatest; the source of this infall in the model is gas loss from low–angular-momentum bulge stars formed early in the collapse (cf. Ostriker and Thuan 1975). An intermediate result is found if infall is initially important but is later cut off—for example, by a galactic wind (Faber and Gallagher 1976). The long-dashed curve in Figure 2*b* shows what happens if infall is arbitrarily stopped after 90% of the final mass at each radius has fallen into the disk; it is seen that Z_g in the innermost few kpc is still sensitive to infall after most of the mass is already present. Thus gas-dynamical effects can strongly alter Z_g during the later stages of galactic evolution, and therefore the predicted abundance gradient in the gas is considerably more uncertain than that in the stars.

Gradients qualitatively similar to those predicted here for Z_g are observed in the oxygen abundances of H II regions outside the central few kpc of spiral galaxies (e.g., Searle 1971; Shields 1974; Smith 1975; Jensen *et al.*). The most detailed data are for M101, for which Shields and Searle (1978) derive a gradient $d \log (O/H)/d \log r \approx -1.8$, which corresponds to a total range in O/H of a factor of ~10 between radii of 7 and 24 kpc. The predicted gradients are somewhat less steep than this, except in the outermost very gas-rich regions of the models. Several factors might

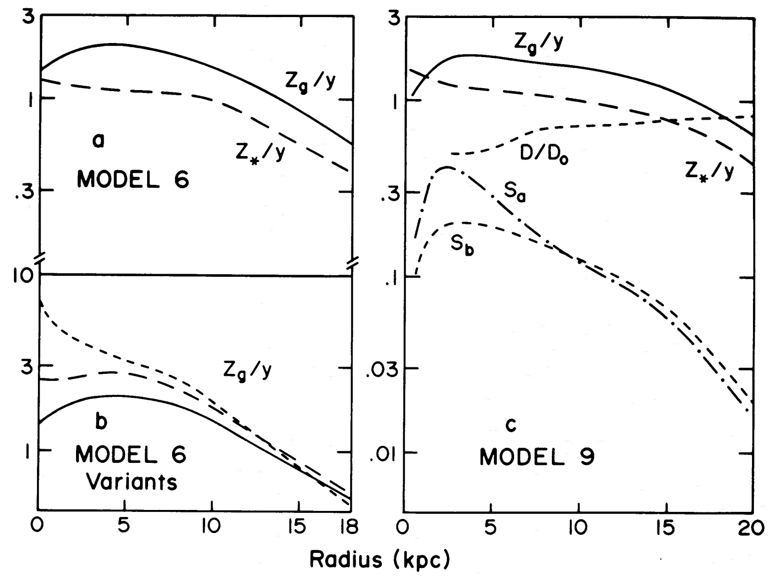

FIG. 2.—Composition gradients in (*a*) model 6 at age 10 Gyr, (*b*) some variants on model 6, and (*c*) model 9 at age 15 Gyr. Z_g/y is the metallicity of the gas relative to the yield; Z_*/y is the average metallicity of stars; S_b is the abundance in the gas of secondary elements formed in stars above 5 $M_\odot$; S_a is the corresponding quantity for low-mass stars; and D/D_0 is the abundance of deuterium relative to its primordial value. In panel (*b*), all curves are for Z_g/y: The solid line is the unaltered model 6; the long-dashed line is a case where infall is stopped after 90% of the normal mass has been accreted at each radius; and the short-dashed line is the result of approximating each annulus by a "simple" model for a closed system (eq. [1]).

contribute to making gradients in Z_g steeper than are predicted by the collapse models. The yield y depends on the stellar mass spectrum and would decrease outward, if the proportion of massive stars in the initial mass function (IMF) decreases outward. (A change in the shape of the IMF would be required, since an outward decrease in the upper mass limit does not seem to be allowed by an analysis of the temperatures of H II regions [Shields and Tinsley 1976].) A radially inward gas flow in a galactic disk, caused by loss of angular momentum from the gas through viscosity or through interaction with a bar or spiral density wave, could also produce or enhance a radial abundance gradient. It can be shown that a radial inflow produces, after a time of order (gas mass)/(inflow rate), a gradient of the order

$$\frac{d(Z/y)}{d \ln r} \sim -\frac{\text{SFR}}{\text{inflow rate}} .$$

For example, in the solar neighborhood this implies that a significant gradient $[d(Z/y)/d \ln r \sim -1]$ can be produced by a radial inflow velocity as small as $\sim 5 \text{ km s}^{-1}$; a drift velocity of this magnitude cannot be excluded for most spiral galaxies.

c) *Other Abundance Gradients*

Abundance gradients in the gas for elements with various other origins are also shown for model 9 in Figure 2*c*. Here S_b is the abundance of secondary elements produced in stars above 5 $M_\odot$, and S_a is the abundance of secondary elements from less massive stars, both on arbitrary scales (Tinsley 1977). For the former elements the radial variation follows approximately the relation $S_b \propto Z_g^2$, as predicted for secondary elements in simple models; however, delayed recycling from long-lived stars causes S_a to continue increasing steeply inward to $r \approx 2$ kpc, where Z_g and S_b have already begun to decline. A primary element from low-mass stars would behave more like S_a than like Z_g. Thus the fact that the nitrogen gradient in spiral galaxies appears to be somewhat *shallower* than $N/H \propto (O/H)^2$ (Smith 1975; Peimbert, Torres-Peimbert, and Rayo 1977; Shields and Searle 1978) implies that nitrogen comes mainly from relatively short-lived stars and may be partly a primary element.

The predicted abundance of deuterium, also shown in Figure 2*c*, is calculated on the assumption that deuterium is of primordial origin and is completely destroyed in stars. Its abundance decreases inward over most of the disk, owing to the increasing degree of stellar processing. (A gradient of the opposite sign would be predicted if deuterium were of galactic origin [Ostriker and Tinsley 1975].) The overall gradient is small, because continuing infall of almost primordial gas replenishes deuterium in the inner regions. The deuterium abundance in the innermost 3 kpc is very sensitive to the source of infalling gas, so it has not been plotted; infall from halo stars would give a very low deuterium abundance (Ostriker and Thuan 1975), while a local production mechanism (Audouze *et al.* 1976) or extragalactic infall could give a high deuterium abundance, as is observed at the center of our Galaxy (Penzias *et al.* 1977).

d) *Color Gradients*

The radial variation of $B - V$ for the disk of model 9 is shown in Figure 3, as derived from the

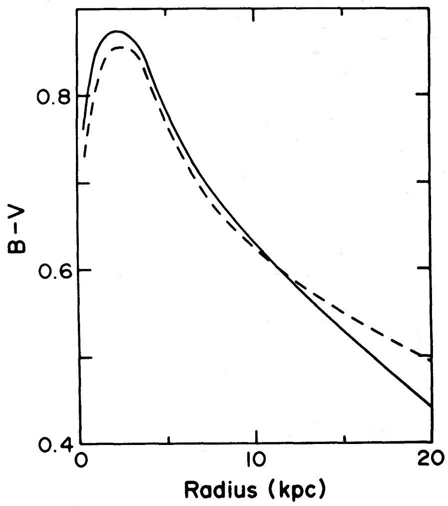

FIG. 3.—Color gradients in model 9. The dashed line includes the effects of the star formation rate only, and the solid line includes corrections for the stellar metallicity gradient.

relation between $B - V$ and SFR given by Larson and Tinsley (1978). The dashed curve shows the effect of the SFR only, and the solid curve includes the effect of variation in the mean stellar metallicity Z_*. The model generally becomes bluer with increasing radius, owing to the increasing proportion of young stars and (less importantly) to the decrease in Z_* with radius. In the innermost regions ($r \leqslant 2$ kpc) the color gradient is reversed, and the model becomes bluer toward the center because of a relative increase in the infall and star formation rates toward the center. The results for the outer regions are consistent with observed colors, in that spiral galaxies generally become bluer at larger radii (de Vaucouleurs 1961). The nuclei of spiral galaxies are usually redder than their disks but show a very wide range in colors, including some that are as blue as a system experiencing an intense burst of star formation (several tenths of a magnitude bluer than the central part of model 9). Such very blue nuclei may be explainable by infall or a radial inflow of gas at an even higher rate than that in the present models. Red nuclei, on the other hand, may result when gas inflows are cut off by a galactic wind.

IV. COMPARISON WITH THE SOLAR NEIGHBORHOOD

Although no attempt was made in Paper I to reproduce any detailed properties of our Galaxy, it is nevertheless interesting to see whether there is any resemblance between the characteristics of the models at some appropriate radius and those of the solar neighborhood. Of particular interest is the effect of infall on the metallicity distribution (§ I), but some features of the star formation history and kinematics can also be compared.

a) *Constraints on Abundances and Ages*

Table 1 lists some properties of the solar neighborhood that can serve as constraints on models. The tabulated quantities, which refer to a zone of height 400–800 pc, are mostly taken from Tinsley (1977), where original references are given. The quantity τ_g is the time required for star formation to use up the

TABLE 1

COMPARISON WITH PROPERTIES OF THE SOLAR NEIGHBORHOOD

Region	Solar neighborhood	Disk of model 9, age 15 Gyr 7.5 kpc	15 kpc	15 kpc*
(1) Gas fraction, $\mu = m_g/m_{tot}$	0.055 - 0.11	0.076	0.27	0.064
(2) $\tau_g \equiv m_g$/SFR	0.6 - 10	4	6	1.8
(3) $\tau_f \equiv m_g/f$ (Gyr)	>3	8	10	2.3
(4) Median age of stars (Gyr)	<5	9	6	7
(5) Fraction of stars with $Z < Z_*/3$	<0.1	0.009	0.02	0.02
(6) Relative evolution of Z for 90% of stars+ ...	<1.5	2.5	2.9	1.1
(7) Mean age (Gyr) of elements 5 Gyr ago	$\gtrsim$1.3($\gtrsim$4?)#	2.1	1.7	0.7

* With m_g held constant after 2.3 Gyr.

+ (Present Z_g)/(value of Z_g when 10% of stars were formed).

\# The empirical quantity (Δ^{max}) derived model-independently from solar system abundances and nuclear data on long-lived radio-nuclides.

gas if stellar mass loss and infall are neglected; τ_f is the time required for infall at rate f to replenish the gas; and the quantity in row (6) measures the variation of metallicity with age for disk stars. A new constraint, the median stellar age (row [4]), is based on the work of Demarque and McClure (1977). They find an age of 5 ± 1 Gyr for NGC 188 and suggest that this is an upper bound for the ages of most disk stars, since the H-R diagram of NGC 188 forms a lower bound to that for field stars (Wilson 1976); however, older stars could be present if they were metal-poor. Demarque and McClure also find ages between 12 and 15 Gyr for globular clusters, which indicates that the disk of our galaxy is considerably younger than the halo. A similar range of ages for globular clusters has been obtained by Saio (1977), while Saio, Shibata, and Simoda (1977) find an age of 8 ± 1 Gyr for NGC 188; the latter would agree with Demarque and McClure's value, had the same revised Hyades distance been used. These results lend support to the models of Paper I, in which the formation of the halo requires somewhat more than one free-fall time and the formation of the disk takes much longer, especially in the outer parts.

The properties of two annular zones of model 9 at age 15 Gyr are listed in Table 1 (cols. [2] and [3]) for comparison with those of the solar neighborhood. The agreement is seen to be satisfactory in most respects. The stars are too old in the zone at radius 7.5 kpc, and there is too much gas at 15 kpc, but an intermediate radius would roughly satisfy both criteria. However, both zones apparently show too much evolution of metallicity, which indicates that the infall rate and SFR are not closely enough matched to provide the nearly constant Z_g characteristic of "extreme" infall models. Nevertheless, the present models do give a sufficiently small fraction of metal-poor stars (row [5]), which is a firmer constraint because of the difficulty of establishing accurately the relation between stellar ages and metallicities (McClure and Tinsley 1976). With no infall the fraction of stars having $Z < Z_*/3$ would have been about 25%, far in excess of the observed proportion (Bond 1970).

The last column of Table 1 shows the results for the variant of the 15 kpc zone in which the gas mass is held constant after 2.3 Gyr (§ III*a*; *dashed* curve in Fig. 1). In this case there is no longer too much evolution of Z_g; but now the infall time scale is somewhat too small, and the mean age of the elements at the time of solar system formation is too young because most of the gas then present is recently accreted material. The examples shown are merely illustrative; although it is possible to construct more contrived models that simultaneously satisfy all of the constraints in Table 1, we suspect that attempts to do so are probably not very meaningful, pending further study of the observational constraints which may well need further revision. We conclude that the collapse models, or plausible variants of them, show good promise of being able to account for most of the age and abundance characteristics of solar neighborhood stars.

b) *Kinematics*

Another constraint on dynamical models of galaxy evolution is provided by the kinematics of solar neighborhood stars. In particular, it is of interest to see whether the present models, with relatively long collapse time scales, can account for the observed correlations between velocity dispersion and metallicity that have been interpreted in terms of a rapid initial collapse of the galaxy (Eggen, Lynden-Bell, and Sandage 1962).

Figure 4 shows the time dependence of the velocity dispersion σ_v and the metallicity Z_g (from Fig. 1) of the gas and newly formed stars in the 15 kpc zone of model 9. The model velocity distribution is assumed to be isotropic and contains no effects of mixing of orbital motions parallel to the galactic plane, so it is probably most directly comparable with the z component of observed velocity dispersions. The velocity dispersion of disk stars is illustrated for times later than 3 Gyr, which is approximately the time when a well-defined disk component begins to form at $r =$ 15 kpc; prior to this time there are only halo stars at this radius, and their velocity dispersion of ~75 km s^{-1} is indicated on the left side of the diagram. Also indicated at the right edge of Figure 4 is a Gaussian distribution in $\log Z$ with dispersion $\sigma(\log Z) = 0.15$, representing a likely minimum value for the dispersion in Z (both real and observational) at a given time.

It is clear from the figure that the dispersion in Z at a fixed time will tend to weaken the correlation between Z and velocity dispersion. Regressions of σ_v on Z including the dispersion in Z are shown in Figure 5 for the two versions of the 15 kpc zone of model 9. Also shown are data of Janes (1975) for solar neighborhood G and K giants, plotted on the

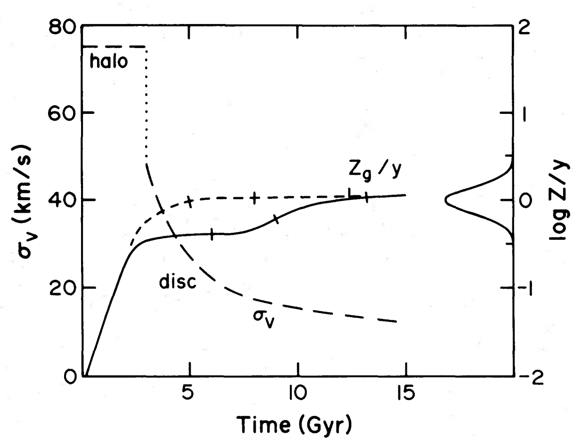

FIG. 4.—The stellar velocity dispersion (σ_v) and metal abundance in the gas (relative to the yield), plotted versus time for the 15 kpc region of model 9. The solid and dashed metallicity curves are as in Fig. 1. Cross marks denote the times when 10%, 50%, and 90% of the mass of stars present at 15 Gyr have been formed. The inset curve on the right is a Gaussian distribution of $\log Z$, with $\sigma(\log Z) \equiv \sigma_Z = 0.15$, indicating a possible dispersion in metallicities of stars formed at a given time.

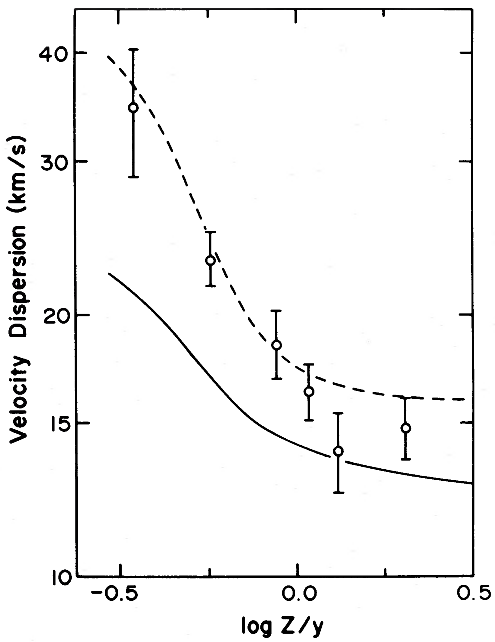

FIG. 5.—Theoretical and empirical correlations between metallicities and velocity dispersions for disk stars. The curves are for model 9 at 15 kpc and are derived from the evolution of each quantity shown in Fig. 4, including the dispersion $\sigma_Z = 0.15$: *solid line*, unaltered model (solid line for Z_g in Fig. 4); *dashed line*, model variant (dashed line for Z_g in Fig. 4). The circles are binned data on G–K giants from Janes (1975), with statistical error bars.

assumption that the sample mean [Fe/H] of -0.19 can be equated to [y/H], which may introduce an uncertainty of $\sim$0.1 in the abscissa. Another uncertainty in this comparison is that Janes's sample may be biased toward relatively old stars and high z velocities compared with the models. Nevertheless, Figure 5 shows good agreement between the model predictions and the observations, favoring the case where the gas mass is constant after 2.3 Gyr and Z_g is nearly constant after 5 Gyr (*dashed curve*). Qualitative agreement is found also with the data of Mayor (1976) for dF stars, if those younger than 10^9 yr are excluded from Mayor's sample; as discussed below, the kinematics of younger stars may not be correctly described by the present models.

For halo stars formed during the first 3 Gyr, the model predicts no correlation between velocity dispersion and metallicity (although a more detailed calculation following the orbits of stars formed in different locations might show some correlation). In agreement with the model, very metal-poor stars are observed to have a much larger velocity dispersion than disk stars, but for stars with less than one-tenth of the solar abundance there is no clear correlation between velocity dispersion and metallicity (Eggen *et al.*; Bond 1970).

Thus the kinematic properties of the model appear to be consistent with the observed correlations between metallicity and velocity for both halo and old disk stars. In the model, the correlations for old disk stars are due to gradual dissipation and settling of the gas into a thinner and cooler layer during a slow chemical enrichment. This slow dissipation is not necessarily inconsistent with the observed rapid variation of velocity dispersion with age for young stars, if the gas actually collapses to a thin but warped and undulating layer, and if the dissipation in question refers to gradual settling of the vertical motions of this gas layer. The locally measured velocity dispersion of the youngest stars is then just the internal velocity dispersion of the gas layer, while that of stars older than about one galactic rotation reflects, in addition, the vertical motion of the gas layer and so could be considerably greater. This effect would eliminate the need for a secular acceleration of stars to explain the increase of velocity dispersion with age.

V. CONCLUSIONS

The collapse models of Paper I were calculated with assumptions chosen to reproduce the basic structure of galaxies with disk and bulge components, but not the chemical properties of spiral galaxies or the solar neighborhood. Thus it is significant that, when their chemical evolution is calculated, these models also show at least qualitatively many of the relevant characteristics of spiral galaxies. Over most of the disk the predicted metal abundances of both gas and stars decrease with increasing radius, and the color also becomes bluer outward, as observed. At radii of $\sim$10–15 kpc, the models resemble the solar neighborhood in having approximately the observed gas content and star formation rate, very few metal-poor stars, and a median stellar age less than half that of the oldest halo stars. In addition, the models predict a correlation between velocity dispersion and metallicity similar to that observed for solar neighborhood stars, which shows that the observed correlation can arise from a gradual settling of the gas into a plane.

Our results also demonstrate the sensitivity of chemical evolution to gas flows and to the exact relation between the gas inflow rate and the star formation rate. The occurrence of infall can, for example, make a large difference to the metallicity in the inner part of a spiral galaxy (Fig. 2*b*). The early infall of gas enriched by halo star formation produces a rapid initial rise of metallicity, as in the models of Ostriker and Thuan (1975); but gas that falls in later is less enriched and tends to suppress any further increase in metallicity. The gradual buildup of the disk toward larger radii by continuing gas infall (see Fig. 6 of Paper I) also allows the outer part of the disk to be younger than the halo, which may account for the young disk age found by Demarque and McClure (1977). In general, it seems unlikely that any complete picture of the chemical evolution of galaxies can neglect the effects of gas flows, whether from outside or inside the system.

To summarize, we conclude from a study of the chemical properties of collapse models that the process of disk formation by gradual accumulation of gas into a plane may account in a natural way for many properties of our own and other galaxies.

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