GAS DYNAMICS AND DISK-GALAXY EVOLUTION

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I. INTRODUCTION

Gas dynamics plays a vital role in the formation and ongoing evolution of a disk galaxy through its ability to have dissipative collisions. In this paper the simplest possible gas physics which provides a description of a gaseous component is incorporated into N-body experiments to investigate the formation of a disk galaxy.

II. DISSIPATIVE COLLAPSE IN A DARK HALO

It is necessary to maintain star formation over a Hubble time for a viable model of a disk galaxy, a problem identified in the pioneering models of Larson (1976). If all the gas collapses into a thin disk, the density is so high that star formation uses the gas up in a few rotation periods. The view of this paper is that the disk of the galaxy usually contains only a fraction of the gas present in the system, the rest being dispersed in the halo. The danger of ejecting gas from the disk is that it will never return, but help comes from the dark halo which provides a deep potential well. Dark halos also provide a theoretically attractive dynamical arena in which to form a disk galaxy (White and Rees 1978, Fall and Efstathiou 1980). In this paper a physical simulation for the formation of a disk galaxy is constructed, using the extreme assumption that the whole unit was present at the initial instant, with no pre-galactic conversion of gas to stars.

As the starting condition for the model we take a static dark halo with $\rho(r) \sim r^{-2}$. All computational units are dimensionless, with the outer radius of the protogalaxy being r = 1, containing a total mass of 1. The halo is filled with 10000 gas clouds having a combined mass equal to 10% of the static halo mass. The initial velocity distribution is an equilibrium isotropic velocity ellipsoid with a flat rotation curve such that $v/\sigma = 0.2$. In the absence of collisions these clouds and any stars present orbit under the combined gravity of the halo and their own self-gravity, neglecting nonaxisymmetric forces.

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The clouds collide to change direction, lose energy and form stars. The collision rate per cloud is modelled following Larson (1976), as $An_c^p\sigma$; where A is an adjustable parameter giving the effective cross-section, the rate of collisions increases linearly with the velocity dispersion σ of the gas, and p determines how the cross-section varies with the local density of gas clouds n_c. After a number of tests and comparison with models of elliptical galaxies the value of $p = \frac{1}{2}$ was chosen, although values in the range $1/3 < p < 2/3$ seemed to be suitable. An important point here is that the various phases of the interstellar medium present are assumed to be closely coupled, i.e. that the hot gas cannot slip by the cool gas out of which stars form. This would seem reasonable on the basis of the theory of McKee and Ostriker (1977), but in our galaxy molecular clouds are in a very thin layer, whereas there is evidence of hot gas in a much thicker layer suggesting that at some level the coupling breaks down.

When clouds collide, their random velocity about the centre-of-mass velocity is reduced by a factor f (<1), and randomly redirected. At the time of a collision there is a probability ε_* that a star will form from the gas cloud. When a star does form, it immediately ejects a metal-enriched gas cloud, with a random velocity S. The magnitude of S is estimated from the injection of 10^{51} ergs per supernova, and one SN per 100 $M_\odot$ of stars formed. Even at a 10% efficiency of conversion of the SN energy to thermal and kinetic energy this corresponds to a velocity of several hundred kilometers per second, i.e. comparable to the velocity dispersion in the dark halo.

The two major parameters describing the model then are the cross-section parameter A and the energy-ejection parameter S. These parameters can be constrained to about an order of magnitude from simple considerations. In order that any disk at all develop, the mean free path of gas clouds must be much smaller than the size of the system, and at least as short as the thickness of the disk. If S is taken to be so small as to be negligible, then the gas simply settles into a plane in one or two orbital times and turns into stars. A mean free path larger than the system size produces a very slowly growing ellipsoidal galaxy, and a very short mean free path in the halo quickly turns all the gas clouds into stars, more or less with their initial orbits, once again making an ellipsoidal galaxy. Both of these ellipsoids are flattened by rotation. If $S \approx 1$ and the mean free path is adjusted to be about equal to the thickness of the disk, then the gas is constantly ejected out of the disk into the halo, where the density is so low that no stars can form until the gas returns to the disk region. This is similar to the fountain advocated by Bregman (1980). Thus in order to get a reasonable disk galaxy, the parameters are determined to within an order of magnitude, all have straightforward physical interpretations, and most are open to observational investigation. The particular model to be discussed below has A = 10, S = 2, f = 0.95, and $\varepsilon_* = .01$. A scaling to galactic dimensions would typically take a total mass inside of 100 kpc as $10^{12} M_\odot$, the time unit is then 5×10^8 years.

The distribution of stars in the model at t=5.5 is shown in an edge-on view in Figure 1, and the galaxy clearly has a reasonably thin disk imbedded in a spheroidal component. At this time 15% of the mass is still in the form of gas, and star formation is continuing at a rate of 2.0% of the original gas mass per dynamical time, or with the suggested scaling, 4 $M_{\odot}$ per year.

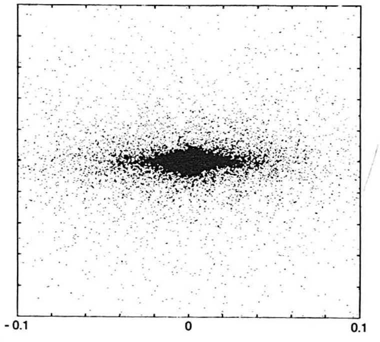

Figure 1. Edge-on view of stars in the final model.

In Figure 2 the metallicity (normalized to the yield) of stars forming in the halo, and in the "solar neighbourhood" ($|z| < .1$, $.05 < r < .1$), is shown as a function of the time of formation. Most of the halo stars are formed at early times, with a mean metallicity of around log (Z/y) = -1, with a very large scatter. The continuation to very high metallicities in the halo is only marginally consistent with the data for our Galaxy, and may indicate that one should include a cutoff minimum density for star formation.

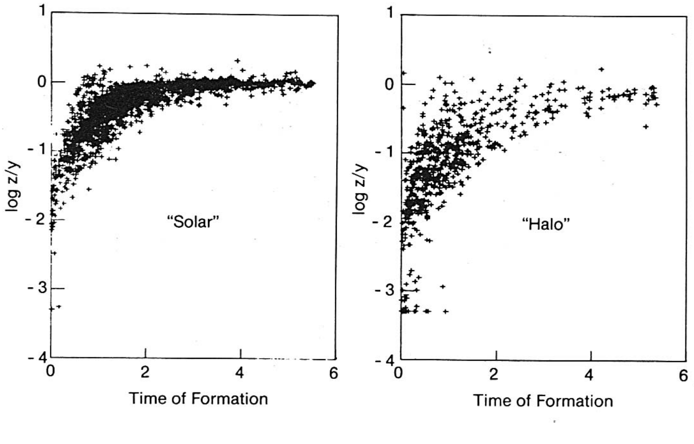

Figure 2. Age-metallicity relation in two regions.

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Figure 3 shows the metallicity of stars in the spheroid of the galaxy as a function of radius (the gap near .01 is an artificial selection effect). It should be noted that there is very little gradient of abundance beyond the end of the disk at r = .1, but a very large scatter is present, as in the observations of outer-halo objects by Searle and Zinn (1978) and Zinn (1980). The reason for the lack of

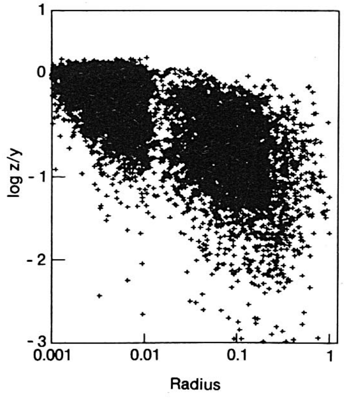

Figure 3. Spheroid radial metallicity distribution.

a gradient in the outer halo is twofold. The bulk of star formation occurs near the disk where the density is high, but the mean free path is long enough that the metals produced mix back up into the halo. There is a significant abundance gradient in the gas but also a considerable scatter about the trend. The halo objects are mostly formed between the start of the experiment and two dynamical times, which encompasses a large range of gas metallicities in the halo. Objects formed at the same time do not reflect the abundance gradient in the halo gas, but once the range of times is added together, and the orbits start mixing the stars around the galaxy, essentially no gradient is discernible.

The model has the large-scale characteristics of a disk galaxy, with clearly differentiated disk and spheroidal components, and star formation which extends over 20 rotation periods measured at the half-mass radius of the disk. However it is not possible to have the gas settle into a very thin plane and simultaneously keep the star-formation rate fairly low. The root of the difficulty may be in the assumption that the hot gas ejected from stars cannot slip past the cooler clouds out of which stars form, requiring a more detailed treatment of the interstellar medium.

III. SUMMARY

Gas-dynamical experiments modelling the formation of a disk galaxy in a dark halo are capable of producing an acceptable object under a limited range of conditions. Formation of a thin disk requires considerable dissipation without star formation. Supernovae and other stellar events eject gas from the disk back into the halo, regulating the gas content of the disk so that star formation is extended over many dynamical times. On the basis of these experiments an extensive dark halo is a necessary component of an actively star-forming disk galaxy.

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DISCUSSION

K.C. Freeman: In your metallicity-radius diagram, you had a number of very metal-weak stars near the centre. Should we take that seriously?

Carlberg: Yes, in that the low-metallicity stars are simply the first stars formed in the bulge region. The overall high mean metallicity is a result of the large amount of infall of metal-enriched gas from elsewhere in the protogalaxy. One notes that the presence of RR Lyrae stars in the bulge is an indicator of the presence of a low-metallicity component.

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Gathering for dinner at Lauswolt. In foreground, left to right by rows: Mrs. Wielen; Wielen; Denoyelle, Maurice; Mrs. Pismis (hidden); Van der Laan, Oort, Gingerich. LZ

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