INTERACTION BETWEEN THE GALACTIC DISK AND HALO COMPONENTS

Jeremiah P. Ostriker

Princeton University Observatory

I) FRAMEWORK

At least three component parts of the galaxy must be recognized. The Disk Component of the galaxy might be defined as follows. Spatially it is largely confined between the planes ± 1 kpc from the plane of symmetry. With regard to velocities, it is a cold subsystem in that the random motions within it ($\sim$ 20 km/s) are small compared to the systematic flow of rotational motion ($\sim$ 200 km/s). Finally, its composition is largely stellar with stars of all ages and masses being present. Few galaxies are known where the ratio of (gas/stellar) mass is > 10% (cf. Roberts 1975a), and the metal abundance is typically high with at most one percent of the stars having metallicity less than 1/4 that of the Sun (cf. Schmidt 1963). From this point of view the spiral parts are a relatively unimportant (in terms of mass and composition) sub-part of the disk system.

The Inner Spheroidal Component contains the sub-parts termed nucleus, bulge, and halo (with R $\lesssim$ 10 kpc). Spatially it is that part whose equidensity surfaces have axis ratio a_z/a_{ϖ} > 1/2 (cf. Harris 1977). Locally it is quite hot with the random velocities (σ_{π} $\sim$ 200 km/s) according to studies in the solar neighborhood (Oort 1965; Table 5). The ratio of (gas/stars) is still lower than it is in the disk and the metallicity ranges from quite low in the solar neighborhood to normal or metal rich in centers of comparable spiral galaxies (cf. Morgan and Mayall 1957). It appears to be composed entirely of stars older and lower in mass than the Sun.

The Halo Component may be defined (somewhat arbitrarily) as the primary spheroidal component external to most of the visible disk (R $\gtrsim$ 10 kpc). Tracer objects from the Inner Spheroidal Component clearly extend into this region, but there is dynamical evidence that there exists a distinct component (called Corona by Einasto et al. 1974) that extends far beyond these optical tracers. Both the mass and composition are highly uncertain but available evidence (summarized in the next section) indicates that the mass of this component exceeds that of the inner parts and that it is not made up of either gas or normal stars.

Having defined the three subsystems of interest a few more words on their apparent properties may be useful. The surface mass distribution in the disk probably follows the exponential distribution found by Freeman (1970) for the light distribution of external spiral galaxies $\Sigma = \Sigma_0 e^{-\omega/H_D}$ with H = 3 to 5 kpc. Given this form and the local surface mass $\Sigma(R_0) = 80\ M_0/pc^2$ (Oort 1965); the total disk mass is $M_D = 8 \times 10^{10} M_0$ and is rather insensitive to the exact values of R_0 and H_D or the possibility of a hole in the disk with radius ~ 3 kpc. A very important characteristic of the disk is that there are very few low metal abundance stars even among the low mass dwarfs which are so long lived that their number distribution presents a record — as living fossils — of the metal content evolution in the galaxy. Schmidt (1963) noted the difficulty in understanding this feature; if the disk was initially poor in metals, then, in any simple model of galactic evolution, when 1/10 of the metals had been made, 1/10 of the low-mass dwarfs would have been formed, so 10% of G-K dwarfs should have $Z < 0.1\ Z_0$ in violent contradiction to the observational facts (cf. Bond 1970). The mass-to-light ratio of the disk is locally $(\rho/j_V) \approx 3$ to 4 and can be understood if the normal distribution of observable stars (e.g., Van Rijn 1965 luminosity function) is supplemented with 20-30% more mass in gas and dust, 30-45% more mass in degenerate objects (including black "white" dwarfs and neutron stars) and 15-30% more mass in faint companions of luminous stars (computed using van de Kamp 1971). The disk stellar velocity distribution shows the well known property that older and older components have a larger and larger random component (cf. Blaauw 1965); the effect is almost certainly due to dynamical relaxation of some kind, given the form of the relation between dispersion and age. The initial mass function (dependence of birth rate on mass) of stars more massive than the Sun follows approximately a power law with $B(m)dm = m^{-k}$, k = 2.35 (Salpeter 1955) or somewhat steeper (Ostriker et al. 1974).

The inner spheroidal component has a distribution in R-R Lyrae stars, globular clusters and any easily indentifiable tracer that follows to a good approximation the light density law $j_H(r) = j_0\ [1 + (r/H_H)^2]^{-3/2}$ with $H_H \sim 100$ pc. Locally the integrated surface light density is $\sim 1\ L_0\ pc^{-2}$ compared to $\sim 20\ L_0\ pc^{-2}$ from disk stars (cf. Weistrop 1972). Thus one can compute that the inner spheroidal component will dominate the observable intensity within .7 kpc of the center of the galaxy and again at distances larger than 31 kpc. The central mass-to-light ratio is probably like that found in other spirals, 3-10; it is somewhat larger than that for the disk or for globular clusters (which have lost their low mass stars due to evaporation) but much smaller than the integral mass-to-light ratios of galaxies as determined from binary studies (e.g., Turner 1976).

The outer halo presumably has a density distribution $\rho \propto r^{-2}$ in order to produce the flat rotation curves seen in many galaxies (cf. Roberts 1975b), with total masses of giant spirals estimated to be $> 10^{12}\ M_{\odot}$, most of it residing at distances $R > 100$ kpc (Ostriker, Peebles and Yahil 1974). For a flat rotation curve the relation between density and velocity is $\rho = (3/4\pi G)(v_{rot}/R)^2$. The maximum contribution locally of the outer halo can be obtained by setting v_{rot} = 200 km/s, R = 10 kpc; we find ρ_{Halo} (10 kpc) $< 0.022\ M_{\odot}\ pc^{-3}$. The light emissivity distribution in the outer parts of spirals does not obey the r^{-2} law followed by the mass density but shows a steeper falloff, even steeper than would be derived from the Hubble law (r^{-3}) or an extrapolation of the inner spheroidal component (for review of observations see Spinrad et al. 1978); thus the local mass-to-light ratio may exceed 1000 in the outer parts of some spirals. Several studies have shown that the material comprising this component cannot be gaseous H I or H II without violating observational contraints. The nature of this component is quite unknown at the current time.

II) INTERACTIONS

a) Gas Dynamics

At present it is likely that both the Spheroidal and Disk Components are generating enough energy in explosions so that the mass injected into the interstellar medium acquires thermal energy comparable to the local potential thereby generating winds from both components. The mechanism was first proposed by Matthews and Baker (1971) and has been investigated by several authors, for the disk most recently by McKee and Ostriker (1977) who find that disk supernovae can drive a wind in both components, the mass outflow rate being $\sim 1\ M_{\odot}\ yr^{-1}$.

In the past, however, it is likely that flows went in the opposite direction (cf. Larson 1974) and gas ejected by the first generations of stars in the spheroidal component accumulated in the disk. In a quantitative treatment of this problem Ostriker and Thuan (1975) found that approximately 10 $M_{\odot}$ of moderately metal-rich material were ejected early in the history of a galaxy for 1 $L_{\odot}$ current visual luminosity from a group of stars having a power law distribution of number vs. mass similar to the Salpeter function. Using this ratio we can determine the mass lost in early epochs by massive stars of the spheroidal component if we know the current luminosity of that component. With the numbers quoted above they found that approximately 1/10 of the disk mass but 1/2 of the disk metals were secondary ejecta from spheroical component stars. Since this material reaches the disk at essentially t = 0 (galactic time), the G-dwarf problem is simply solved; there never was an era when the disk was metal-poor by much more than a factor of two.

b) Dynamical Stability, Effect of Interactions Among Components

i) Radial Modes. Toomre's (1964) well known result that the velocity distribution σ in the disk must not be too small $\sigma > 3.36$ $G\Sigma\kappa$ (where Σ is the surface mass density and κ the epicyclic frequency) has been modified somewhat by Zweibel (1978) who computed the stabilizing effect of a spheroidal component on the radial modes.

ii) Spiral Modes. So much has been written on this topic that little can be added here. Suffice it to note that, as Mark in several papers (e.g., Mark 1976) has pointed out, disk-halo interactions can have a significantly stabilizing or destabilizing effect on these modes. Thus, it is clear that one ought not to compute spiral modes in a flat one-component galaxy if comparison with observations is intended.

iii) Bar Modes. These have given us the strongest clue that a one-component galaxy is not an appropriate model. Several investigators (whose work was summarized by Ostriker and Peebles (1973)) found that cold disk systems were invariably unstable on the shortest dynamical timescale. The instability is dramatic and leads to bar formation and then (often) the development of a hot disk within which random motions are comparable to the rotational velocity. All of the work known to this author as of the present time can be summarized by saying that cold disks will be unstable on a short timescale unless, coextensive with them, there exist hot components (nucleus + spheroidal component + possible parts of outer halo) which are comparable in mass to the cold disk component. As a so far quite accurate rule of thumb, it is required that the rotational kinetic energy divided by the total gravitational energy (within the sphere defined by the disk distribution), defined to be t, be less than 0.14 for stability to the gross bar mode.

c) Secular Stability, Interactions Among Components

This is not a well defined concept for a stellar system but one can ask if the gaseous component of the disk + spiral system is secularly stable to displacements tending to distort the disk into a shape having a lower energy state (a bar or ring). Since only a small fraction of the total mass is in the gaseous component one must not consider stability of the isolated gaseous system, which is of course much too cold to be stable by itself, but of that system in the force fields produced by the stellar components of the galaxy. One new result recently obtained by Ostriker and Tremaine (1977) and also, independently, by Durisen (1977) is at first surprising and possibly important. The tendency to bar formation of a uniformly rotating cold disk is only weakly, if at all, affected by external forces on a secular, dissipative timescale. That is, a halo cannot prevent the

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slow secular instabilities. The dissipative timescale is essentially determined by cloud-cloud collisions and in our galaxy is less than the Hubble time for radii < 3-5 kpc. In a strongly differentially rotating velocity field the same viscous effects lead to ring formation on the viscous timescale. In both cases gas will tend to be evacuated from the central regions and reformed into either a bar or a ring (depending on the degree of differential rotation) at the viscous timescale. This theoretical result may be related to the fact that the gas density (atomic + molecular) in the inner parts (radius < 3 kpc) of our galaxy is low (cf. Guibert et al. 1977, this conference) and similar results are obtained for other spiral systems.

III) SUMMARY REMARKS

To recapitulate, our galaxy appears to be comprised of at least three rather distinct components. The visually prominent disk is probably less important than the observed spheroidal component with respect to the bulk of nucleosynthesis and it is probably much less important than the extended halo in terms of mass and contribution to the cosmological density. Dynamical interactions amongst these systems are manifold and just beginning to excite the interest of the theoretician; the only general rule apparent is that dynamically cold systems are quite unstable, and that the instabilities if not prevented will produce more or less violent motions which, increasing the random velocities at the expense of the systematic ones, tend to stabilize the resulting hotter stellar system.

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