I

KINEMATICS OF GAS AND THE UNDERLYING MASS DISTRIBUTION

SYSTEMATICS OF HII ROTATION CURVES

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ABSTRACT. Systematic rotational properties of field spiral galaxies are presented, as a function of Hubble type and of luminosity. Within a Hubble type, radius, nuclear velocity gradient, rotation velocity, mass, and mass density increase with luminosity, while $\mathcal{M}/L$ is constant. At fixed luminosity, V(max), mass, density, and $\mathcal{M}/L$ decrease from Sa through Sc. These variations are so systematic that it is possible to display them on a single diagram.

1. SYSTEMATIC ROTATIONAL PROPERTIES OF FIELD SPIRALS

During the several years since the last conference on galaxy dynamics, we have increased our knowledge about the dynamical properties of spirals and ellipticals, bulges and disks. Progress has been due to systematic observational programs which have exploited the avilability of modern detectors on large telescopes. This paper will describe the

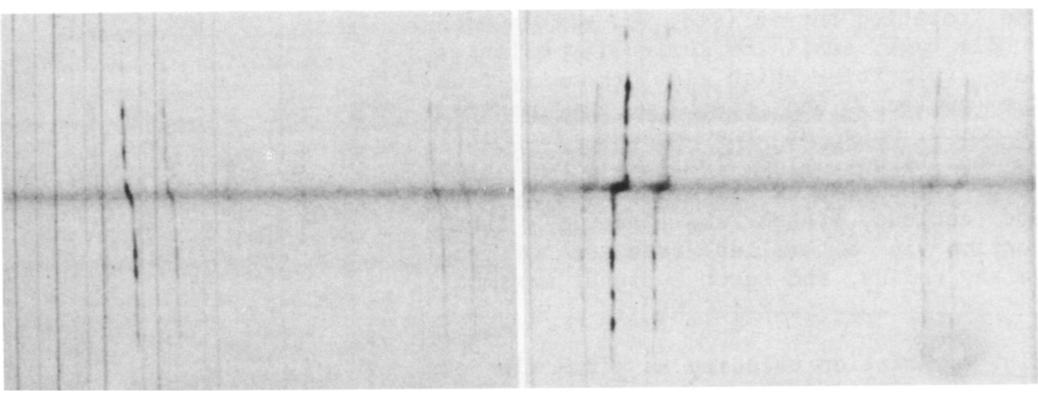

Fig. 1. Spectra near Hα of Sc galaxies of moderate and high luminosity. (left) NGC 2742, M = -20.5. (right) NGC 7541, M = -22.3. Kitt Peak 4-m spectrograph + Carnegie image tube; exposures 120 and 114 min. Note steeper nuclear velocity gradient in higher luminosity Sc.

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results which my colleagues, W. Kent Ford, Jr., and Norbert Thonnard, and I have obtained from a study of rotations of field spirals.

Optical spectra for about 60 Sa, Sb, and Sc galaxies have been obtained with the 4-m telescopes at Kitt Peak and Cerro Tololo Observatories at high dispersion (25A/mm) and high spatial scale (25"/mm). A few spectra were also taken with the 100-in Las Campanas telescope. The spectra are centered at Hα. Fig. 1 shows spectra of two of the Sc galaxies. Program galaxies are relatively isolated, of high inclination, non barred, and have diameters of a few seconds, so that a single spectrograph slit subtends the optical image out to R(25), the isophote of 25th mag (arc sec)^2. For each Hubble type we have made every effort to observe galaxies with as large a range of luminosities as we could identify. Details and results are available elsewhere (Sc: Rubin, Ford and Thonnard 1980; Burstein et al. 1982; Sb: Rubin et al. 1982; comparison of Sa, Sb, and Sc: Rubin, Thonnard, and Ford 1982). Throughout the discussion, we use H = 50 km s^{-1}Mpc^{-1}.

Velocities from the advancing and receding major axes, measured from the Hα and [N II] lines, are smoothed to form the rotation curves (Fig. 2). Within each Hubble type, small low luminosity galaxies have velocities which rise gradually from the nucleus, and reach a low maximum velocity only at the galaxy isophotal radius. Large, high luminosity galaxies have velocities which rise steeply from the nucleus, reach the "nearly flat" portion in a smaller fraction of the galaxy radius, and reach a higher maximum

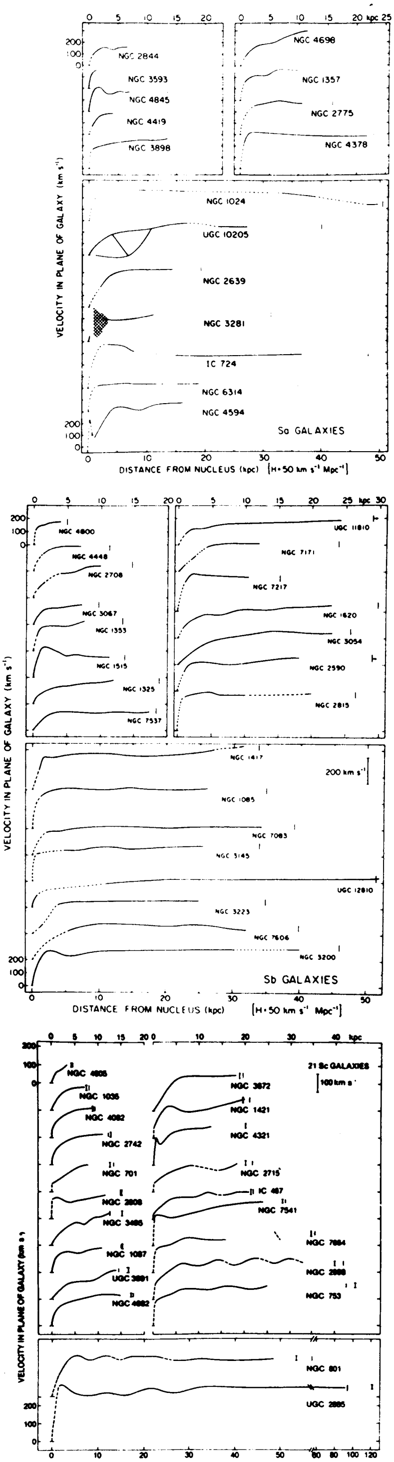

Fig. 2. Rotation velocity as a function of nuclear distance for 16 Sa, 23 Sb, and 21 Sc galaxies. Within each Hubble type, galaxies are arranged by increasing luminosity. Vertical lines: isophotal radius. Dashed lines: no measurements.

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velocity. Virtually all rotation curves continue to rise with distance from the nucleus. For both Sb's and Sc's, in the mean, $V \propto R^{0.1}$ or $\propto R^{0.2}$. Sa's exhibit more individuality, due to increasing bulge importance. Because of the weaker emission, we have less radial coverage for the Sa galaxies. In the correlations we discuss below, we include only Sa galaxies with observations over at least 67% of R(25).

From these rotation velocities, we form "synthetic rotation curves" for galaxies of a given Hubble type, which show rotational velocity as a function of fractional isophotal radius. The procedure for forming these curves is described elsewhere (Thonnard and Rubin 1981). Figure 3 plots such a set for Sb galaxies. There is a neat progression with luminosity from a small nuclear velocity gradient, low rotational velocity to a steep nuclear gradient, high rotational velocity. Within a Hubble type, the form of the rotation curve is a clear luminosity indicator. A comparison of an Sb rotation curve with the set shown in Fig. 3 will permit the absolute magnitude to be deduced, even if only a fraction of the rotation curve is available.

The variation of rotational properties from one Hubble type to another is equally systematic. At a fixed luminosity, the rotation curve of an Sa is higher than that of an Sb, which in turn is higher than that of an Sc. This is illustrated in Fig. 4, where I plot synthetic rotation curves for Sa and Sc galaxies.

The increase in rotational velocity with luminosity produces the Tully-Fisher (TF) relation. However, note the significant displacement of galaxies of different types. This is illustrated in Fig. 5, a plot of M_B versus V(max) for program galaxies. Each Hubble type alone produces a TF line with a slope near 10, but the offset from type Sa to type Sc is over 2 magnitudes at any V(max). Or at fixed blue luminosity, the rotational velocity of an Sa is 1.6 times that of an Sc. A corresponding

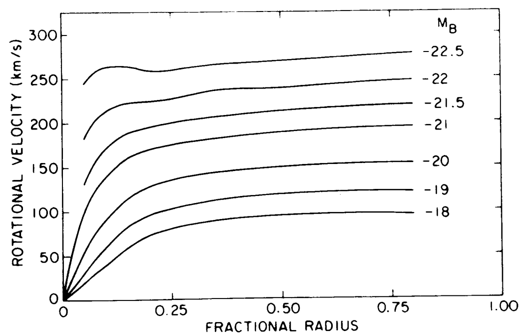

FIG 3. Synthetic Sb rotation curves, formed from observed velocities. Rotational velocity as a function of fractional isophotal radius is shown.

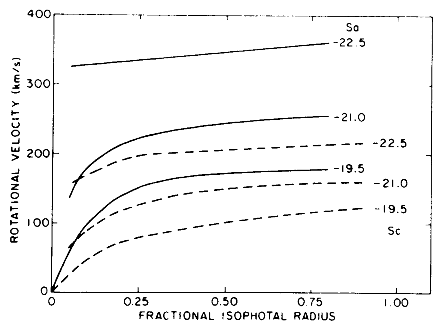

Fig. 4. Synthetic rotation curves for Sa and Sc galaxies. Curves are calulated with H=50 km s Mpc . For H=100, M is fainter by 1.5 mag.

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correlation between V(max) and R(25) exists, but with slightly larger scatter. The agreement of these correlations with those based on red magnitudes (Aaronson, Huchra, and Mould 1979) is still under study.

For all of the program galaxies, luminosity is correlated with isophotal radius, with no type dependence (Fig. 6). Although Hubble (1936) knew this relation, it continues to be rediscovered annually.

2. SYSTEMATIC MASS PROPERTIES FOR FIELD SPIRALS

In the most simple spherical mass models, the mass $\mathcal{M}$ interior to R(25) is given by $G \cdot R(25) V^2(R25)$; G is the constant of gravitation. For flat rotation curves, integral mass rises linearly with R; for velocities rising as $R^{0.15}$, mass increases faster then R, $M \propto R^{1.3}$. Here I discuss the mass interior to R(25).

Within a Hubble type, velocity and hence mass and mass density increase with increasing luminosity. At a fixed radius and luminosity, early type galaxies have higher rotational velocity and hence higher density. But note the interplay of luminosity and Hubble type. An extremely luminous Sc galaxy can mimic the velocity, mass, and mass density of a mid-luminosity Sa, but the radius of the Sc must then be enormous.

For each Hubble type, there is a fairly tight correlation of mass with luminosity, i.e., <u>$\mathcal{M}/L$ is independent of luminosity</u>. This is

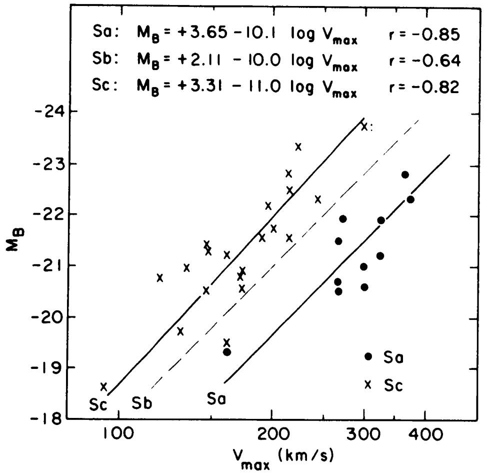

Fig. 5. Correlation of luminosity with V(max) for Sa, Sb, and Sc galaxies. Note slope near 10 for each type, but the displacement between Hubble classes.

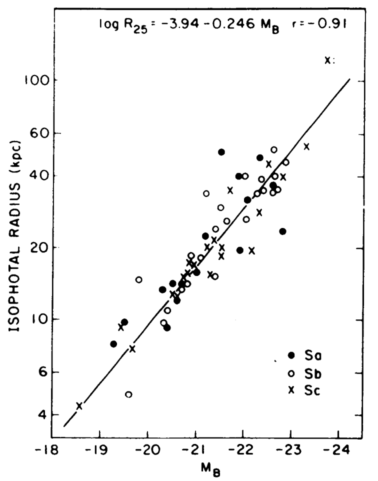

Fig. 6. Correlation of radius with luminosity, for Sa, Sb, and Sc galaxies. The slope of the relation means that luminosity increases slower than surface area, $L \propto R^{\sim 1.7}$.

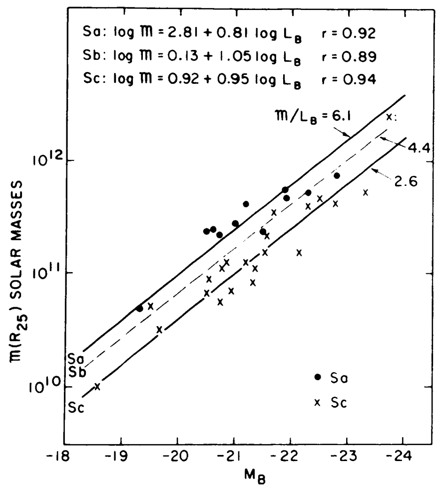

Fig. 7. Correlation of mass with luminosity for Sa, Sb, and Sc galaxies. At fixed Hubble type, $\mathcal{M}/L$ is independent of luminosity, as shown by the lines of constant $\mathcal{M}/L$.

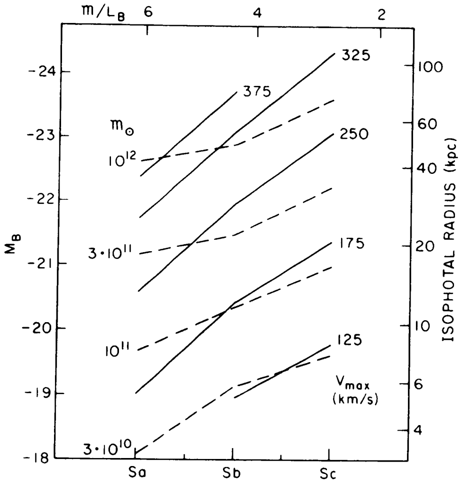

Fig. 8. Interrelation of 6 parameters; lines of constant V(max) and constant mass are shown. For H = 100, M is brighter by 1.5 mag, radius and mass decrease 1/2, $\mathcal{M}/L$ increases x 2.

displayed in Fig. 7, where lines of constant $\mathcal{M}/L$ = 6.1 (Sa), 4.4 (Sb), and 2.6 (Sc) are shown. At a fixed Hubble type, the velocity, radius, mass, and mass density all increase with luminosity. The ratio of mass to luminosity is unique, being one important galaxy parameter which does not vary with luminosity, but does vary with Hubble type.

The correlations between luminosity, radius, mass, V(max), $\mathcal{M}/L$, and Hubble type can be combined into a single diagram, which illustrates the systematic interrelations of these parameters. I show such a diagram in Fig. 8. It contains, in extremely compact form, much of what we now know concerning the dynamics of galaxy disks. It also indicates that at least two parameters are necessary to locate a galaxy on this plane.

Finally, I point out that the curves of integral mass with radius of most Sc and Sb galaxies are remarkably similar, and can be generated from a single mass form, with suitable radial scaling. This follows from the rotation curve forms, which themselves can be transformed one into another with radial scaling (see discussion in Burstein et al. 1982).

3. ROTATIONAL PROPERTIES OF CLUSTER SPIRALS

The results discussed above come from observations of field spirals. We are presently engaged in an observing program to determine rotation curves for cluster spirals. Our aim is to see if the structure of galaxies is altered by the denser cluster environment, and if such altered structure leads to altered dynamical properties. For example, the high rotational velocities at large radial distances observed for field galaxies is one piece of evidence that spirals have massive halos extending to large radial distances. In the denser cluster environment, extended halos might be disturbed by the neighboring galaxies. A comparison of the rotational properties of field and cluster galaxies should enable us to infer the importance of environmental effects in galaxy evolution and dynamics.

To date, we have derived rotation curves for 8 galaxies in the Cancer and Pegasus I clusters, of Hubble types Sab through Sc. The dynamical properties of these galaxies are in no way different from those of the field spirals. These clusters, chosen because they were observed in the infrared by Aaronson et al. (1980), are not especially dense ones. We are now observing galaxies in two denser cluster (Hercules and DC 1842-63; Dressler 1980). If the remaining observations and analysis confirm the preliminary conclusion that field and cluster spirals are indistinguishable by their rotational properties, then we will have placed significant constraints on the properties of spiral halos.

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DISCUSSION

INAGAKI : Is it possible to separate the disk mass from the halo mass observationally, for example using statistical methods ? Are there any rotation curves from absorption lines measurements i.e. stellar rotation curves ?

RUBIN : For the simple analysis we employ, the total mass interior to any radial distance R is derived, but not the distribution of that mass. However F. Schweizer, B. Whitmore and I have observed a galaxy with a polar ring, A0136-080, and have velocities in the S0 disk galaxy (from absorption lines) and in the polar ring (from emission lines). The polar ring extends to radial distances about three times as great as the S0 disk. So for this case we are able to sample the gravitational potential beyond the optical disk. The results indicate that the distant polar material is feeling a spheroidal, rather than a disk potential. We have no stellar rotation curves for our program galaxies, but absorption line rotation curves for E's and S0's will be discussed later in this program.

GOTTESMAN : In A0136-080, what is the effect of tidal phenomena on the halo of the galaxy ?

RUBIN : This depends on the mass ratio between the halo and the disk in the S0 galaxy. From the flatness of the rotation curve in the outer ring, we infer that the halo is massive and that it probably determines the dynamics of the system. The outer ring itself contains so little material that it probably reacts to the combined halo-disk potential like an ensemble of test particles,and it seems unlikely that it can have any appreciable effect on the massive halo.

SANDAGE : You have shown so convincingly here that the Tully-Fisher relation is very dependent on Hubble type in M_B magnitudes, despite certain contrary infrared data sets. Have you ever looked to see if this dependence exists in the infrared observers' apparently magic H magnitudes, or whether it disappears for your galaxies when H is used ? I think that Tully-Fisher diagrams should be type dependent. Use of H magnitudes, although reducing internal absorption problems, cannot conceal the large difference in mass distribution that exists along the sequence Sa to Sb to Sc to Sd galaxies.

RUBIN : We do not yet have H magnitudes for any of our galaxies but Aaronson has been observing them and we hope his results will be available soon. However I agree with your comment. To make the Hubble type dependence that we observe in the blue disappear at the H magnitudes requires that differential B-H colors be larger than two magnitudes between types Sa and Sc, independent of luminosity. This seems like an excessive amount but I am willing to wait for the observations.

AOKI : There will be a difference in the mass estimate depending on whether you assume spherical symmetry or allow for flattened shapes.

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How does this influence your estimated M/L ratios ? I think your data are good enough to permit a fine analysis to bring out the difference.

RUBIN : Because we lack information concerning the distribution of the non-luminous matter, we have chosen to model all of the galaxies in the most simple fashion, as spheres. The M/L ratios we derive then follow. If instead the mass distribution is in a flattened ellipsoid, then the masses will be decreased by a small factor (∿ 20 or 30 %), but the relative M/L ratio will stay the same. However, if the mass distribution differs in galaxies of different Hubble types, or in galaxies of different luminosities, then the relative M/L values will change. We presently have no way to get the detailed distribution of the non-luminous matter, so a more detailed analysis is not yet warranted.

WIELEN : Some of the correlations you find could be caused by systematic errors in the galaxy inclination as a function of Hubble type or absolute magnitude. Can you exclude significant systematic errors of this kind in the inclinations you use ? What is the typical inclination of a galaxy in your sample ?

RUBIN : With only very few exceptions, inclinations for program galaxies range roughly from 50° to 80°. Hence errors as large as 10° in the adopted inclination will produce velocity errors no larger than 10 %, and generally smaller. I do not think this is a problem for this set of galaxies.

TOHLINE : I would like to emphasize at the opening of this symposium that the often quoted ratio M/L is in fact the ratio V^2r/L of the directly observable quantities V, r and L. This ratio V^2r/L can only be interpreted as an indicator of mass to light ratio if we assume that Newton's law of gravitational attraction is correct on the scale of galaxies. Since Keplerian behavior is essentially never seen in extragalactic systems, I might be so bold as to suggest that the validity of Newton's law should now be seriously questioned. I hope that observers who have definitive evidence that Keplerian behavior has been observed in any system will emphasize that evidence at this meeting.

RUBIN : While we have observed that most Sa, Sb and Sc, galaxies have flat or slightly rising rotation curves, a few have slightly falling curves. However, I know of no isolated galaxy with rotation velocities decreasing as rapidly as $V \propto r^{-1/2}$. The point you raise is worth keeping in mind although I believe most of us would rather alter Newtonian gravitational theory only as a last resort.

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