ROTATION CURVES OF HIGH-LUMINOSITY SPIRAL GALAXIES AND THE ROTATION CURVE OF OUR GALAXY

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ABSTRACT. Rotation curves of high luminosity spiral galaxies are flat, to distances as great as $r=49$ kpc. This implies a significant mass at large r. Rotational velocities increase about 20 km/s across a spiral arm, as predicted by the density wave theory. By analogy, it is suggested that our Galaxy has a flat rotation curve out to $r \sim 60$ kpc, with $V \sim$ constant at near the solar rotational velocity, and $\mathfrak{M} \sim 7 \times 10^{11} \mathfrak{M}_{\odot}$. Values of A and B imply that the sun is not located in a spiral arm.

Knowledge of the structure and dynamics of our Galaxy has come not only from the study of stellar and gas motions within the Galaxy, but also from a comparison of the properties of our Galaxy with those of neighboring spiral galaxies. Until recently, this comparison was hampered by very incomplete observations of rotation curves of external galaxies. Optical observations generally determined velocities only across the nucleus and inner regions; velocities at large nuclear distances were rarely obtained. Radio 21-cm line observations generally integrated all the neutral hydrogen into a single profile; all spatial information was lost. Recently, both optical and radio instrumentation has developed sufficiently so that detailed rotation curves of high accuracy can be obtained across most of a galactic disk. An outstanding recent study of rotation curves from 21-cm line observations is due to Bosma (1978). I shall present results of our optical studies; briefly discuss their implications for spiral dynamics and kinematics, and from them infer an extended rotation curve for our Galaxy. This curve is necessarily speculative. However, unless our Galaxy is very different from the high-luminosity sample which we have studied, the major characteristics of its rotation curve are reasonably well defined.

ROTATION CURVES FOR HIGH LUMINOSITY SPIRAL GALAXIES

For a sample $(n \sim 15)$ of high luminosity spiral galaxies, Hubble types (HT) Sa through Sc, we have obtained accurate rotation curves which extend to about 80% of the deVaucouleurs radii. The galaxies were

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 211–220.

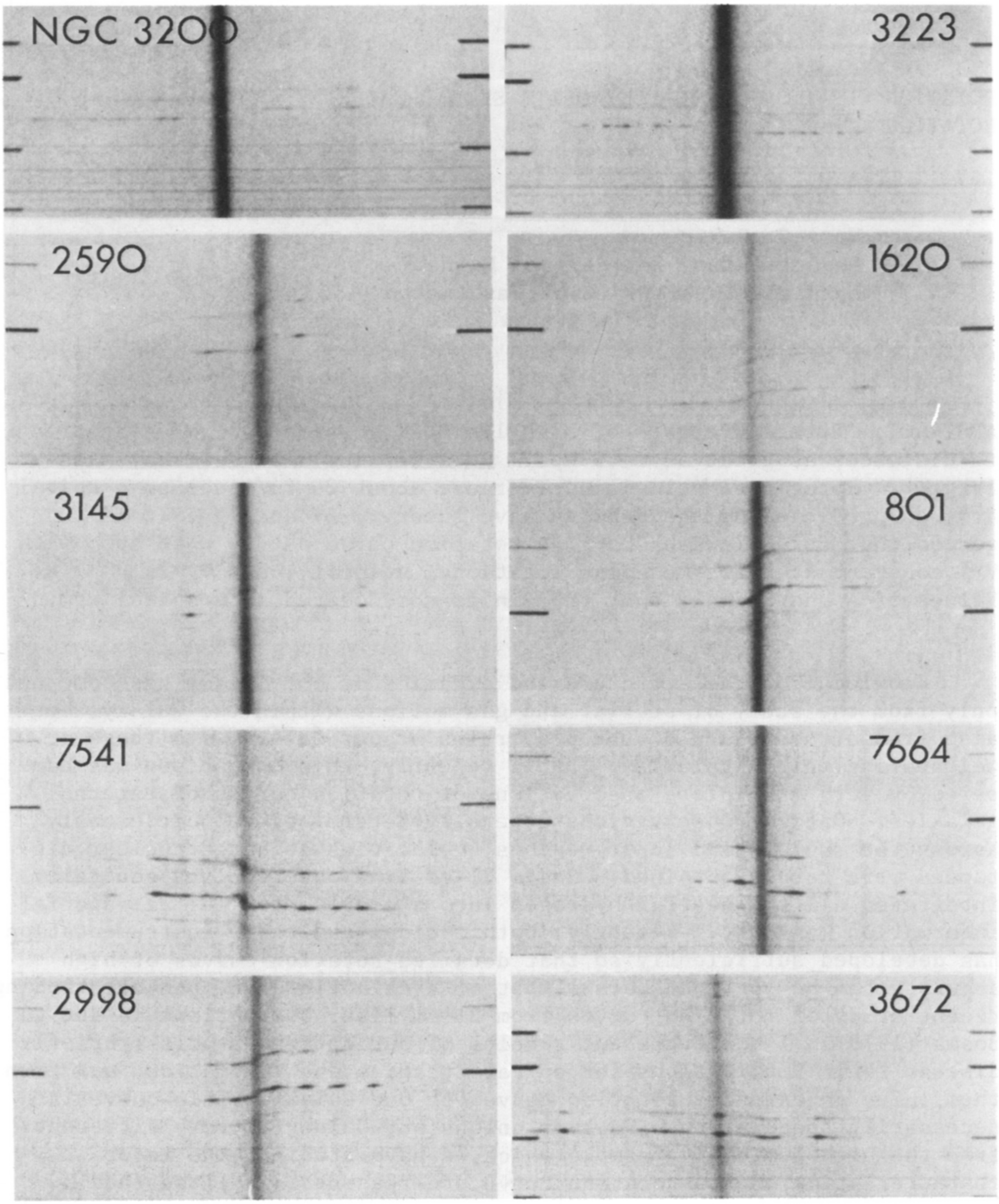

Fig. 1. Hα region of spectra for galaxies of different Hubble types, taken with the KPNO or CTIO 4-m spectrographs plus Carnegie image tube. Exposure times are 90 min. to 200 min., dispersions are 25 or 52 A/mm. Linear extent of emission varies from a radius of 17 kpc (NGC 2590) to 49 kpc (NGC 801). We adopt H = 50 km/s per Mpc.

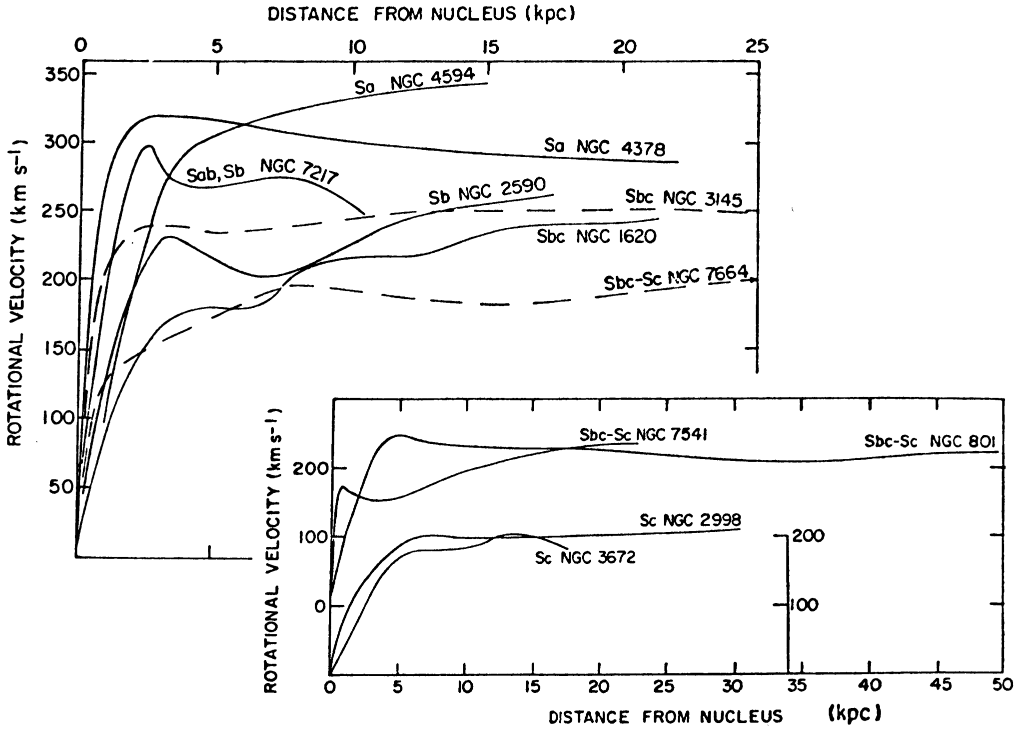

Fig. 2. Rotational velocities for 11 galaxies, as a function of distance from nucleus, Curves have been smoothed to remove velocity undulations across arms and small differences between major axis velocities on each side of nucleus. Early-type galaxies have higher peak velocities than later types.

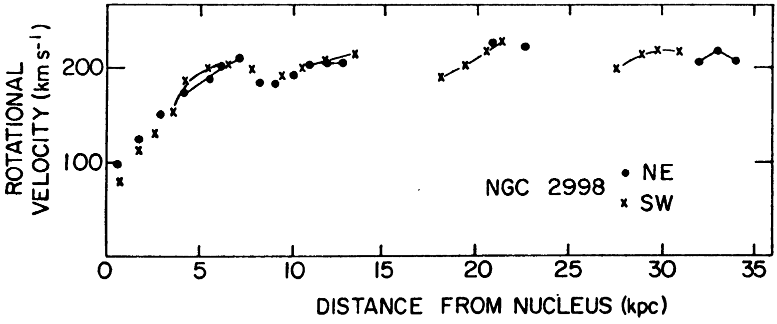

Fig. 3. Rotational velocities in NGC 2998, as a function of distance from nucleus. Velocities for strongest emission are connected with lines. Note fairly good velocity agreement between velocities from NE and SW major axes, and positive velocity gradient across arms.

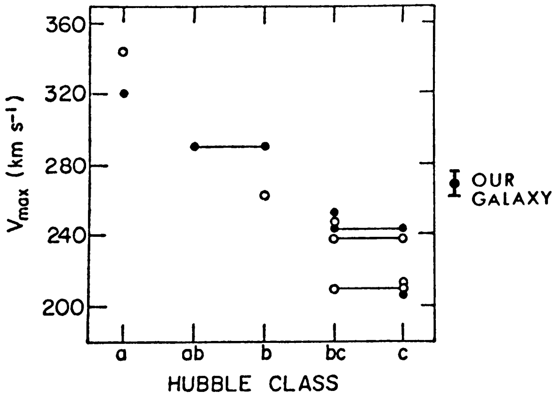

Fig. 4. Maximum rotational velocity, in the plane of the galaxy, as a function of Hubble type. Galaxies with 2 classifications are entered twice with a connecting line. Open circles denote peak velocity at the last measured velocity (i.e., rising rotation curve).

chosen with extreme care: to have angular diameters near 3' or 4' to match the KPNO and CTIO spectrograph slit lengths; to be of high inclinations so that uncertainties in inclinations produce little effect on rotational velocities and hence masses; to be of high luminosity as indicated by the widths of their 21-cm profiles; and to have large linear diameters.

Optical spectra were obtained with the Kitt Peak and Cerro Tololo 4-m spectrographs plus Carnegie image tube, generally at a dispersion of 25A/mm. Errors in the rotational velocities (measuring errors plus projection uncertainties) are generally less than 8 km/s per point. Reproductions of 10 spectra are shown in Fig. 1. Rotation curves are drawn in Fig. 2; data for NGC 4594 come from Schweizer (1978).

The following conclusions come from analysis of these data (Rubin, Ford, and Thonnard 1978): (1) All rotation curves are nearly flat to distances as great as 50 kpc radius. Eight of these 11 galaxies have their maximum velocity at r > 10 kpc. Secondary velocity undulations indicate that rotational velocities are lower by about 20 km/s on the inner edges than on the outer edges of spiral arms. This is especially apparent in NGC 2998, whose velocities are plotted in Fig. 3. This observation confirms a prediction of the density wave theory, and is a major result of our study. While velocity gradients would exist also in any gravitational model with mass concentrations in the arms, the density enhancement would have to be enormous to produce the observed effect; (2) There is a pronounced increase in the maximum rotational velocity, Vmax, with earlier HT; Fig. 4 shows this tight correlation. A correlation between Vmax and HT found earlier by Brosche (1971) lies about 50 km/s below the relation indicated in Fig. 4, and is defined principally by galaxies of types later than Sbc. This suggests that Fig. 4 represents an upper envelope defined by high luminosity galaxies.

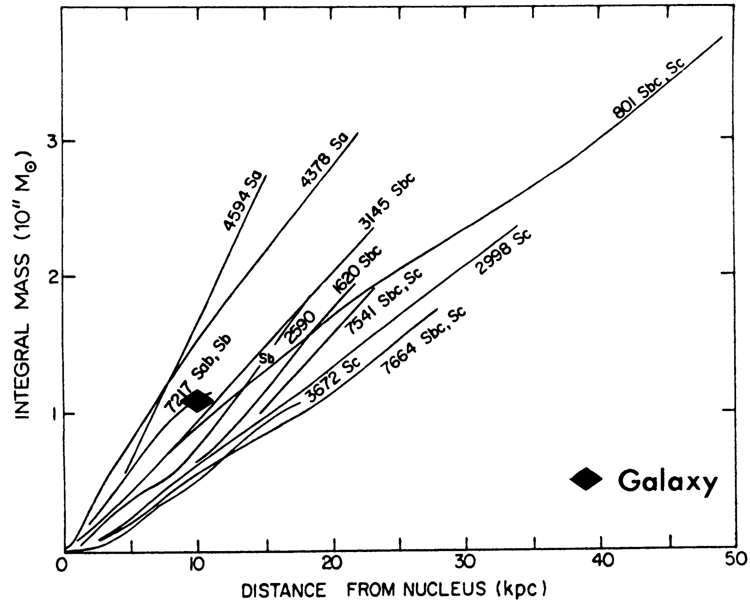

Fig. 5. Integral mass within a disk of radius r, as a function of r, for galaxies types Sa through Sc. Scale gives mass for disk models; masses for spherically modeled galaxies are 1.4 times larger.

A larger sample of rotation curves for galaxies of all luminosity classes must be available before the true scatter of Vmax versus HT and luminosity can be determined; (3) Masses out to the deVaucouleurs radius (25^{m}/□'') have been calculated, and are generally accurate to about 25%. Masses range from $1 < \mathfrak{M} < 7 \times 10^{11} \mathfrak{M}_{\odot}$ for spherical modeled galaxies. Thus some spiral galaxies will have masses approaching $10^{12} \mathfrak{M}_{\odot}$ to their Holmberg radii ($26^{m}.5$/□''). Integrated mass as a function of radius is plotted in Fig. 5. The linear increase in mass with r is a consequence of the flat rotation curves, for $\mathfrak{M} \propto V^2 \cdot r$.

SOME IMPLICATIONS FOR GALACTIC DYNAMICS AND THE DENSITY WAVE THEORY

Spiral galaxies with rotation curves of the forms shown in Figs. 2 and 3 possess interesting dynamical properties. Values of Oort's constants A and B calculated locally for a generally flat but undulating rotation curve (Fig. 3) will oscillate, with $A = -B$ at the local maxima and minima, but with A and $|B|$ slowly decreasing with r. Thus values of A and B determined for stars within any few kiloparsec radius may not indicate the large scale characteristics of the rotation field, but merely the sign of the gradient of the rotation curve locally.

Rotational periods at large r are long, $\sim 10^9$ years, and V/r is only a very slowly decreasing function of r. Hence the old worry of winding up of spiral arms will be less relevant. Within the framework of the density wave theory, rotating gas at large r will encounter a two-armed spiral pattern only at widely separated intervals; stars will form and die long before the next passage through the density wave. Lacking alternative mechanisms for massive star production, such galaxies would have two widely spaced arms, of the  type. One alternative mechanism is proposed by Seiden and Gerola (1977), who suggest that self-propagating star formation in a differentially rotating disk can produce persistent large scale spiral features. Their computer pictures indicate features of a feathery nature. Perhaps different mechanisms of star formation produce galaxies of different morphological types; in some galaxies a combination of mechanisms may participate.

Problems with corotation continue to exist. If corotation is placed at the outer HII regions or at the disk limits, then it occurs at r = 49 kpc in NGC 801, near 35 kpc for other program galaxies. No single pattern speed can account for spiral structure over this distance; solutions involving several spiral modes are required. Theoretical progress (Bertin _et al_. 1977) will have to be rapid to keep pace with observational results.

ARE THERE SPIRAL GALAXIES WITH FALLING ROTATION CURVES?

What was the reason for the earlier belief that disk galaxies had Keplerian velocities at moderate nuclear distances? A search of the literature now reveals little to support this belief. Early velocity measures by the Burbidges and colleagues generally show a large scatter near Vmax, followed by sometimes falling, sometimes rising, velocities. But it is almost impossible to identify a galaxy with a falling optical rotation curve. NGC 4321 may be an example (van der Kruit 1973), although measured velocities cover less than 1/2 the optical disk. From Bosma's 21-cm compilation, M81, M51, and M101 appear to have falling rotation curves. For M81, the intergalactic gas enveloping both M81 and M82 confuses the determination of the rotation curve; for M51 the 21-cm velocities are only marginally falling (Shane 1975; r = 12 kpc) and conflict with the optical velocities which are constant (Burbidge and Burbidge 1964; r = 14 kpc). We conclude that nearly constant velocities and significant mass at large r are the rule, at least for high luminosity spiral galaxies. Exceptions have yet to be confirmed.

THE EXTENDED ROTATION CURVE OF OUR GALAXY

Based on observations of high luminosity spiral galaxies, and on the premise that our Galaxy is of luminosity class I or II, we suggest the following rotational properties for our Galaxy. Incomplete justification is given for most of the assumptions; this is due to a lack of space and knowledge. We adopt $R_\odot$ =10kpc and $V_\odot$=250km/s for the solar neighborhood, although recent work suggests that Ro is less than 10kpc

(Oort and Plaut 1975, Harris 1976) and Vo is greater than 250 (Lynden-Bell and Lin 1977) and less than 250 (Knapp, this Symposium).

Current values of Oort's constants are A = 15.6±2.8, B = -11.4±2.8 km/s per kpc (Fricke and Tsioumis 1975), although O-B2 stars produce values as discrepant as A = +26, B = -37 (Asteriadis, 1977). At the 1σ level, A = -B is not excluded, i.e., the rotation curve could be flat in the solar vicinity. More likely, there is a negative velocity gradient at the position of the sun. Because spiral arms show positive velocity gradients, the sun is probably not located in a spiral arm. Lin et al. (1977) conclude that the sun is situated between spiral arms, from a comparison of stellar motions with predictions from the density wave theory.

Interior to the solar circle, HI (Sinha 1978) and HI plus CO (Burton and Gordon 1978) velocities at the tangent points are used to derive new rotation curves similar to the Schmidt (1965) rotation curve, r>4kpc. (Fig. 6). Differences between HI velocities in the 1st and 4th quadrants of ∿10 km/s are attributed by Sinha to streaming motions. Exterior to the solar circle, HII regions (Georgelin and Georgelin 1976), OB stars (Rubin 1965), OB stars with Walborn distances (unpublished), stellar aggregates associated with Sharpless regions (Jackson, this Symposium) and HII region recombination line velocities (calculated from Silverglate and Terzian 1978) suggest generally flat or rising velocities, 12 < r < 18 kpc, with perhaps a shallow minimum, r∿11kpc. (Fig. 7).

How far does the galaxy extend? The surface brightness at the sun compared with appropriate external galaxies, the hydrogen radii of late-type galaxies which are often twice the optical, and the extent of the globular cluster system (r∿40 kpc, Harris 1976) all suggest that our Galaxy could have a radius ∿50 kpc. Faint anticenter blue stars

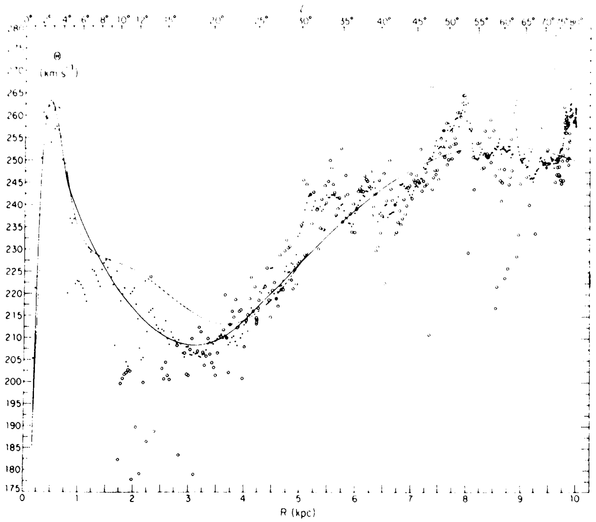

Fig. 6. Linear velocity as a function of distance from the center of our Galaxy, from terminal velocities of CO and HI (Burton and Gordon 1978).

identified by Rubin and colleagues (1971, 1974) show no proper motions (Cudworth 1974, 1975, 1977), and have photometric distances $\sim$20 - 30 kpc from the center (Chromey 1978). Spectroscopic data confirm these distances; one O5 star (R152, $\ell = 219^\circ$, $b = +7.6^\circ$) is located 48 kpc beyond the sun, 56 kpc from the center, with $z = 6$ kpc. Such stars may belong to the 50% of all early O stars which are located in regions free of nebulosity (Torres-Peimbert et al. 1974) and may constitute a fraction of the high velocity halo population. If part of a more normal disk population, they will be valuable for determining the rotation curve at large nuclear distances. However, lack of HII regions at large galactocentric distances constitutes a problem for the extended galaxy model.

For a rotation curve, flat at near the solar velocity to $r = 60$ kpc, then $\mathcal{M} \sim 7 \times 10^{11}\, \mathcal{M}_\odot$, which is just the Galaxy mass out to $r = 60$ kpc derived by Hartwick and Sargent (1978) from velocities of intergalactic tramp clusters and satellite galaxies (assuming an isothermal velocity dispersion). If V is constant out to $r = 75$ kpc, $\mathcal{M} \sim 10^{12}\, \mathcal{M}_\odot$, close to the mass at $r = 75$ kpc derived by Einasto et al. (1976). A small Galaxy, $\mathcal{M} \sim 3 \times 10^{11}\, \mathcal{M}_\odot$ with $\mathcal{M} \propto r$ out to $r = 28$ kpc and no significant mass beyond, would have a Keplerian velocity decrease to $V \sim 165$ km/s at $r = 60$ kpc, and still be at the lower limit of the Hartwick-Sargent mass determination. But such a galaxy would be atypical. We believe that we live in a high luminosity massive galaxy which extends to $r = 60$ or 75 kpc. Studies of the extent of star formation and the spiral pattern of the outer regions should occupy observers for many years.

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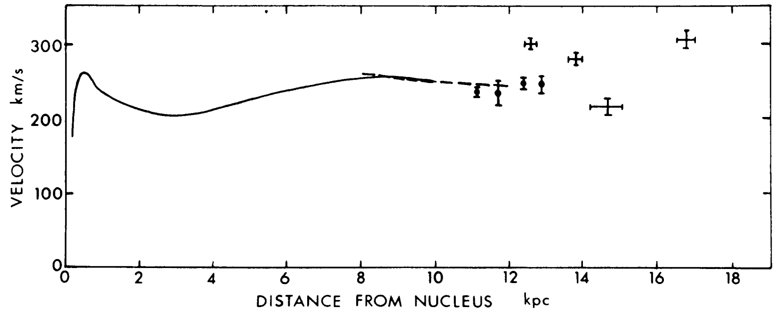

Fig. 7. Schematic rotation curve for the Galaxy, compiled from Burton and Gordon (1978, $r < 10$ kpc): Georgelins (1976, $8 < r < 12$): Rubin (1965, $r \sim 12$); Walborn (unpublished, $r \sim 12$); Silverglate and Terzian (1978, $r \sim 12$); and Jackson (this Symposium, $13 < r < 17$kpc).

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DISCUSSION

Greyber: Is there evidence to indicate how the nature of the rotation curves changes going towards types with enhanced emission, such as Markarian and Seyfert galaxies and radio galaxies like Centaurus A and Fornax A?

Rubin: Only very limited observations are available for these exotic objects. For a few Seyfert galaxies, rotational properties seem relatively normal. For radio galaxies, velocities are seldom available beyond the nucleus.

Innanen: A comment: The velocity dispersions of the points in the rotation curves appear remarkably small.

Rubin: Except for the nuclear regions, all line widths are probably instrumental, and thus less than 50 km s^{-1}.

van Woerden: Could one of our spectroscopic experts estimate the luminosity of HD 46150, and its uncertainty? I note that, at ℓ ∿ 260°, b ∿ +8° as given by Dr. Rubin, HD 46150 would not be in the well-known warp. (However, z(R) in warped disks may be oscillating.)

Rubin: Fred Chromey will discuss his results on "Spectroscopy of Distant Blue Stars near the Galactic Anticenter" at the Madison AAS meeting; details of the work will be available shortly (B.A.A.S., 1978).

Sanders: Several of the rotation curves which you show have two principal peaks. Indeed, the rotation curve of our own Galaxy has a conspicuous inner peak. Is the existence of an inner peak in the galaxies which you observe associated with any other galactic morphological characteristic, such as a conspicuous bulge?

Rubin: Unfortunately, we do not have direct large-scale plates of most of these galaxies. Some of them are not even in the revised de Vaucouleurs Catalogue. The prints from the Palomar Sky Survey are not adequate to answer your question.

van Woerden: Because M51 and M101 are both only little inclined to the sky, the rotation curves derived for both these galaxies are quite sensitive to a possible warp in their disks. Both Sancisi and Bosma have found that major warps occur frequently. Therefore, we should not attach much significance to the finding that the rotation curves of M51 and M101 are falling outwards.

Rubin: You are correct; I meant to suggest that M51, M81, and M101 are all slightly peculiar galaxies.

Pişmiş: I would like to know how you used the rotation curves to obtain masses of those galaxies where the rotation curves show wiggles or "waves". Did you take the upper envelope of the curve, an average curve, or a polynomial representing the details of the curve?

Rubin: The masses shown were derived from the observed velocities, smoothed only to take out local undulations, and from the assumption of an infinitely thin (Kuzmin) disk scaled by the factor 1.1. However, because the rotation curves are so flat, an expression of the form $M = 1.5\times10^5\ V^2r$ (V in km s^{-1}, r in kpc) reproduces all 11 masses to within 20%, and 7 of them to within 10%. Spherically modeled galaxies have masses well described by $M = 2.1\times10^5\ V^2r$.