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A CENTURY OF GALAXY SPECTROSCOPY[1]

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ABSTRACT

The first successful spectrum of a galaxy, M31, was obtained in 1898 and published in a two-page paper in the young *Astrophysical Journal* (Scheiner 1899). Thus the first century of galaxy spectroscopy and the first century of the *Astrophysical Journal* are almost coincident; I celebrate both in this paper. I describe the very early history of the determination of internal kinematics in spiral galaxies, often by quoting the astronomers' own published words. By mid-century, observations with improved optical and radio telescopes offered evidence that much of the matter in a galaxy is dark. As the century ends, research interests have enlarged to include study of spheroidal and disk galaxies with complex nuclear (and other) kinematics. These complicated velocity patterns are understood as the result of interactions, acquisitions, and mergers, and offer clear evidence of the important role of gravitational effects in galaxy evolution.

Subject headings: dark matter — galaxies: evolution — galaxies: kinematics and dynamics — galaxies: nuclei — history and philosophy of astronomy

1. INTRODUCTION

Virtually all of our knowledge concerning galaxies has come during the 20th century. From the work of Russell, Payne-Gaposchkin, Oort, Morgan, Hubble, Shapley, and others, we know that we live in a Galaxy, that the solar system orbits about the distant Galactic center, and that galaxies are expanding one from the other. But Hubble's concept of "island universes" evolving in splendid isolation has given way to knowledge of a dynamic universe. Astronomers now recognize that a galaxy is a continuously evolving structure which will acquire stars or lose stars through gravitational interactions, will acquire gas or lose gas through infall or galactic winds, will be actively forming stars or quiescent depending upon its most recent history, and will look like an elliptical or a spiral depending upon the eyes of the beholder, the limiting magnitude of the telescope exposure, and the spectral band. Just as continents are moving and evolving beneath our feet, so too galaxies are assembling and transforming over our heads.

My family is fond of a Peanuts cartoon in which Lucy is asking, "On the good Ship of Life, Charlie Brown, which way are you going to place your deck chair? To see where you have been or to see where you are going?" And Charlie Brown replies, "I can't seem to get my chair unfolded." Well, my chair is unfolded, and I am going to discuss our increasing understanding of galaxy kinematics over the last century. Certainly the last century is not more important nor more interesting than the next. In fact, we are all aware that we are living at the start of a remarkable era during which our knowledge of the universe will escalate, due to new telescopes, new detectors, new techniques, new computers, and especially new ideas. However, it is clear that every major problem of extragalactic astronomy that we have attacked during the 20th century is still unsolved; unknown are the amount and distribution of dark matter, the rate of expansion of the universe, the magnitude and significance of large-scale motions, and the detailed motions of gas and stars within galaxies. Some of you whose careers will develop during the next century will work on problems whose history starts with the papers I mention today.

2. THE EARLY YEARS

One hundred years ago, no one knew what a galaxy was. But 96 years ago, Scheiner (1899); reported the first successful spectrum of a galaxy, in a two-page paper in volume 9 of the *Astrophysical Journal*, "On the Spectrum of the Great Nebula in Andromeda"

> The continuous spectrum can be clearly recognized on it from F to H, and faint traces extend far into the ultraviolet. A comparison of this spectrum with a solar spectrum taken with the same apparatus disclosed a surprising agreement of the two, even in respect to the relative intensities of the separate spectra regions... No traces of bright nebular lines are present, so that the interstellar space in the Andromeda nebula, just as in our stellar system, is not appreciably occupied by gaseous matter.

Scheiner had discovered that M31 is a stellar assemblage. Scheiner did not publish the spectrum, and over the years I repeatedly asked astronomers from Potsdam Observatory to attempt to locate it. In 1987 Hans Oleak wrote me that he had found the plate (incredible, he said, after two major wars and numerous upheavals), traced it, and was to publish it (Bronkalla & Oleak 1987). A handwritten note on the plate envelope said the plate had been chemically enhanced to increase its intensity, but the enhancement had disappeared by 1906.

By 1912, Slipher at the Lowell Observatory was obtaining spectra of galaxies, objects he thought to be planetary systems in formation. By 1914 he had confirmed that M31 and NGC 4594, the Sombrero, exhibited inclined lines (Slipher 1914; see also Wolf 1914). Inclined spectral lines were familar to astronomers because of their knowledge of planetary rotation. A spectrum obtained along the equator of Jupiter shows each line to be inclined. Light from one limb is blueshifted, and from the other limb it is redshifted with respect to the center, as the planet's rotation carries one limb toward and one away from

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the observer. Hence, inclined lines in a galaxy spectrum were evidence that galaxies are rotating. By 1929, velocities for 46 galaxies were available (Hubble 1929), all but a few of them due to Slipher. Slipher deserves more credit than he generally gets in histories of astronomy.

Within a few years, Pease (1918) confirmed that M31 was rotating. Using the Mount Wilson 60 inch (1.5 m), he exposed a spectrum along the minor axis during 84 hr in August, September, and October of 1916 and along the major axis for a total of 79 hr in August, September, and October of 1917. The lack of significant velocity gradient on the minor axis and the steep velocity gradient over the inner 2'.5 along the major axis were evidence of rotation. It is curious, and interesting, that Pease took the minor axis spectrum before the major axis one. Pease apparently chose to make the first exposure along the minor axis, knowing that inclined lines were observed by Slipher along the major axis. A misprint in Pease's paper lists the wavelength interval as $\lambda4930$ (rather than the correct 3930) to $\lambda4950$. When Rubin & D'Odorico (1969) divided by the 5.3 mm extent, they noted an erroneous dispersion. N. U. Mayall and R. Minkowski both wrote to me to point out the error, with Minkowski stating "It would have been a miracle if Pease had been able to observe M31 with 3.8 Å/mm."

The 1920s was a decade of rapidly increasing uderstanding of galaxies. Using the velocity curve of M31 from Pease, Oepik (1922 [as spelled in the ApJ]) published "An Estimate of the Distance of the Andromeda Nebulae," which I consider to be one of the most original papers of this century. By now, the *Astrophysical Journal* had abstracts, and his begins,

> *Andromeda Nebula.*—Assuming the centripetal acceleration at a distance r from the center is equal to the gravitational acceleration due to the mass inside the sphere of radius r, an expression is derived for the *absolute distance* in terms of the linear speed v_0 at an angular distance ρ from the center, the apparent luminosity i, and E, the energy radiated per unit mass. From observations, v_0 comes out 15 km s^{-1} for $\rho = 150''$; and giving i a value corresponding to 6.1, and assuming E the same as for our Galaxy, the distance is computed to be 450,000 parsecs. This result is in agreement with that obtained by several independent methods. If it is correct, the *mass* within 150" is 4.5×10^9 times the Sun's mass, and the nebulae is a stellar universe comparable with our galaxy."

Oepik determined a distance for M31 such that when angular distances within M31 were transformed to linear distances, the mass-to-luminosity ratio (in today's notation) was equal to that of the solar neighborhood, a quantity Oepik had also to derive. His analysis indicated that M31 is a massive distant galaxy. But Oepik was too modest. The derived 450 kpc distance is closer to the 700 kpc used today than the 210–250 kpc distances that Hubble and other astronomers were using until the 1950s.

In 1927, Oort (1927) explained observed stellar motions within our Galaxy as the result of a differentially rotating galaxy, with angular velocity decreasing with nuclear distance. In 1929, with velocities available for 46 galaxies but distances for only 18, Hubble (1929) determined the motion of the Galaxy and the expansion rate of the universe, over 500 km s^{-1} Mpc^{-1}. This result, more credible than earlier solutions (e.g., Wirtz 1925), was enshrined in the literature by Hubble's (1936) enormously influential book, "The Realm of the Nebulae," from which my generation of students learned about galaxies. Rarely mentioned is Oort's (1930) analysis of the same data, but with two original differences. Distances were measured in units of A, the (then uncertain) distance to M31. The expansion term he found is $L = 140$ km s^{-1} A^{-1}; with the present M31 distance this corresponds to ≈ 200 km s^{-1} Mpc^{-1}. But forward thinking, Oort concludes his paper,

> In order to see whether the factor with which the recession increases with distance is the same in different parts of the sky the nebulae may suitably be divided into two groups: those south of the galactic plane and those north of it. Assuming the solar velocity as found in solution (A) I find from the 13 objects south of the galactic plane $L = 142$ km/sec.A $\pm$ 21(m.e.). The whole material gave +140 km/sec.A; L is thus found to be practically the same for northern and southern nebulae, that is for two regions of the sky which are separated by about 120°.

Possibly without intending to, Oort had founded the study of large-scale motions in the universe. The next discussion of galaxy velocities as a function of position on the sky would apparently wait 20 yr (Rubin 1951).

Spectrographs were slow, exposures were long, and velocities were uncertain due to instabilities in the instruments, low dispersions, and low signal-to-noise ratios. For his thesis, Babcock (1939) determined velocities of rotation within M31 using the Lick Observatory Crossley telescope, observing diffuse nebulosities near the nucleus, and 4 H II regions located 300" to 100" distant. Exposure times were as great as 20 hr. Velocities, which continued to rise with distance rather than to fall as expected from a Keplerian inverse square law, were imprecise but still revealed a bit of the truth. The apparent solid body rotation pattern beyond the nuclear region puzzled theorists, but was neatly explained in terms of Newtonian gravitational theory by Holmberg (1939).

Mayall (1951) continued the observation of rotation velocities within M31, from 31 H II regions (Fig. 1). Exposure times with the Crossley had decreased to ~10 hr; a distance for M31 of 230 kpc was assumed. A comparison of this rotation curve with that known for our Galaxy, convinced Mayall that something was wrong. He ended:

> Conclusion: It thus appears that either (1) the main bodies of M31 and the Galaxy are appreciably dissimilar in size, or (2) the accepted distance of M31 is too small, or (3) the present simplified analysis of Cepheid radial velocities is misleading. Whether any of these three alternatives, separately or in combination, is correct probably cannot be decided until more precise data are available for distances of Cepheids in the Galaxy and in M31.

By mid-century, radial velocities for ~800 galaxies were available from Humason, Mayall, & Sandage (1956). A value of $H = 180$ km s^{-1} Mpc^{-1} was derived. Other questions, such as evidence of large-scale structure and large-scale motions, were still to be asked. But even for those questions which had been asked, answers were not imminent. The distance scale was still in question. The forms of rotation curves, dozens compiled by Burbidge & Burbidge (1975, although manuscript submitted 1969) and generally covering only the inner parts of galaxies, were assumed to be falling and free of complication. Very few voices were raised in query. One of these few was Oort's (1940); his presentation at the dedication of the McDonald Observatory discussed the distribution of light and the distribution of matter in NGC 3115. He wrote in the abstract:

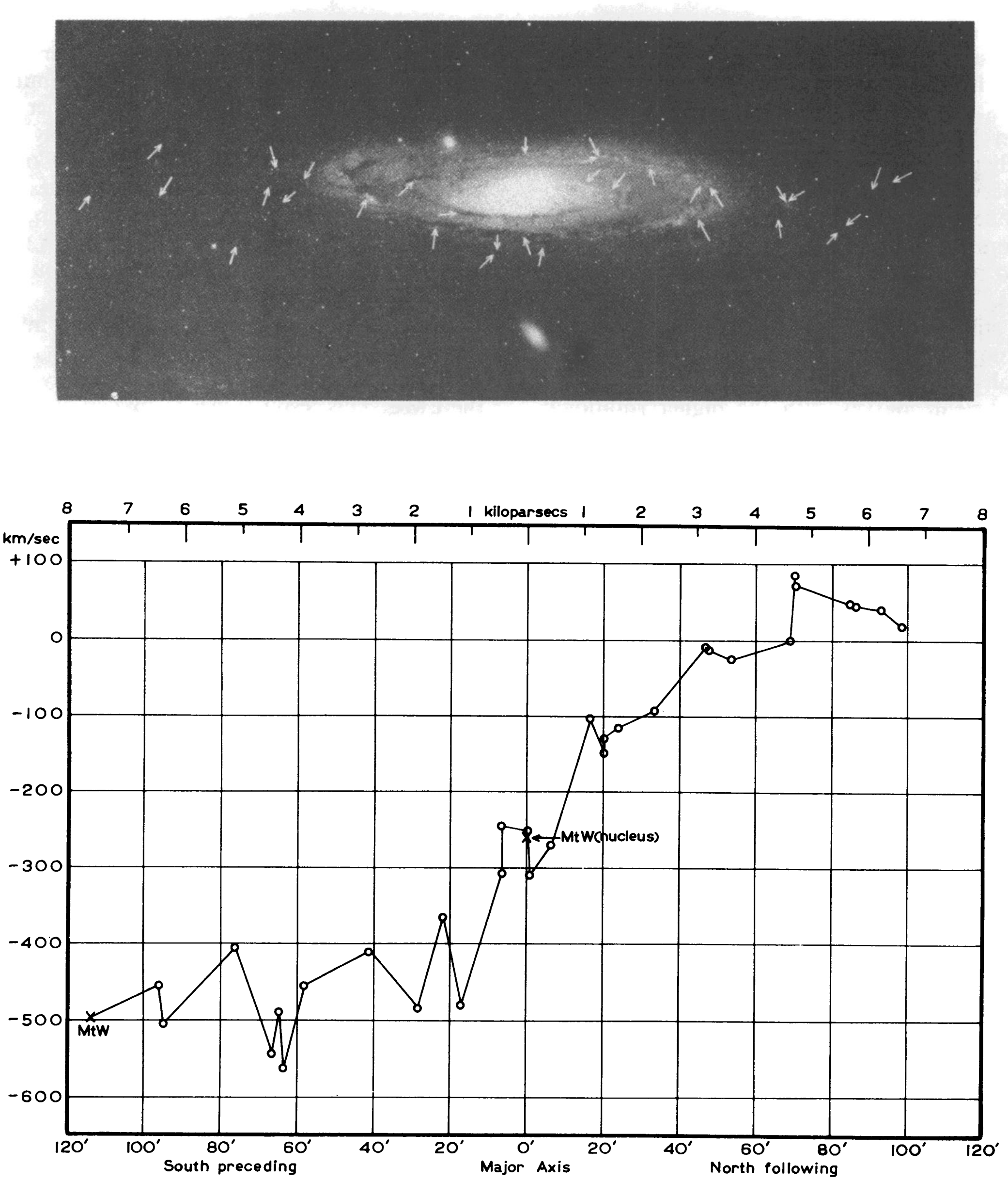

FIG. 1.—Observed velocities in M31, from Mayall (1951). The H II regions with measured velocities are indicated on the image. Note that some indication of the complex nuclear velocities are indicated in these early observations.

> It is found that beyond about 10″ from the center in the equatorial plane the mass density must be about constant. The actual density depends on the unknown flattening of the attracting mass, but it should be at least of the order of 140 solar masses per cubic parsec (10^{-20} gm/cm^3), or 2000 times that near the sun. In this region of constant mass density the light-density diminishes with a factor of at least 10: the distribution of mass in the system appears to bear almost no relation to that of the light.

This statement is the earliest statement I know which identifies the necessity for dark matter in individual galaxies. Thirty years later, Freeman (1970) raised a similar caution for NGC 300, now with better velocity information available:

> The H I rotation curve has $V_{\max}$ at $R \approx 15'$, which also happens to be the photometric outer edge of the system. If the H I curve is correct, then there must be undetected matter beyond the optical extent of NGC 300; its mass must be at least of the same order of magnitude as the mass of the detected galaxy.

Yet it is important to remember that these few sentences were lost in the mass of publications which "detected" Keplerian falling velocities. The unexpected relation between luminosity and velocity was noted by very few, even though Ostriker & Peebles (1973) had suggested a halo as a means of stabilizing a galaxy disk.

During the 1970s, accurate rotation velocities in galaxies accrued rapidly, due principally to more sophisticated observing instrumentation and techniques, both in the optical and in the radio spectral regions. By 1975, there was an optical rotation curve for M31 that was flat beyond the nucleus and believable, with accurate optical velocities (Rubin & Ford 1970) which extend to 120″, matching precise radio velocities which extend to 170″ (Roberts & Whitehurst 1975). High-resolution optical spectra across the nucleus still took 6 hr to obtain, even using a spectrograph which incorporated an image tube. The telescope operators at the 84 inch (2.1 m) KPNO telescope would cringe when they saw us coming, for they knew it meant a long night of only two exposures, with the telescope operator sitting on the observing platform as required, with no job to perform after once setting the telescope at the start of the night. Telescope operators even covered the faintly luminous clock face, for we feared red light leaks in the spectrograph during the long exposures.

But there was still more to learn. Brinks' (1984) thesis, a high-resolution study of H I velocities in the inner 60″ of M31, showed additional complexity; along many lines of sight a low-velocity component coexists with the higher rotational velocity. While this component generally is interpreted as outer disk gas warped back into the line of sight, and hence having only a small radial component of velocity, we should be aware that bars or other triaxial motions near nuclei may be responsible (e.g., Merrifield & Kuijken 1995). As in M31, ionized gas with low velocities coexists with the higher rotation velocities in many spirals I observe.

But lest you think that M31 was the first galaxy to define a flat rotation curve, let me refer you to the study by Volders (1959), from H I observations made at Dwingeloo (Fig. 2). For M33, H I velocities, as if drawn with a ruler, slice through a scatter of optical points. The lack of impact on the astronomical community is curious; perhaps the instrumental capability was doubted. Surely a falling rotation curve was expected, based on the rotation curve for our Galaxy predicted by Oort's constants A and B (and Oort was Volder's professor). By 1972 Rogstad & Shostak (1972) could assemble five flat H I velocity curves for Scd galaxies obtained with the Owens Valley two-element interferometer. They conclude their abstract,

> Because of the very flat rotation curves observed for these Scd galaxies, total masses extrapolated to infinite radius are not known. Surface mass-luminosity ratios must reach values of ≈20 at the Holmberg radius.

Before that decade was over, we all knew that rotation curves for Spiral galaxies are flat (e.g., Rubin et al. 1985), and the efforts to determine the distributions and amounts of the mass components are still underway (e.g., Kent 1988). For every galaxy, we can determine only the lower limit to its mass, for a flat rotation curve implies that the mass increases linearly with radius and is not converging to a limiting mass, a distinctly untasteful circumstance in physics. Consequently, M/L increases with radius, as mass M continues to increase where optical luminosity L has already converged to its limiting value. Hence 21 cm studies of spirals with large H I disks are especially valuable for inferring the distributions and amounts of dark matter at large radial distances.

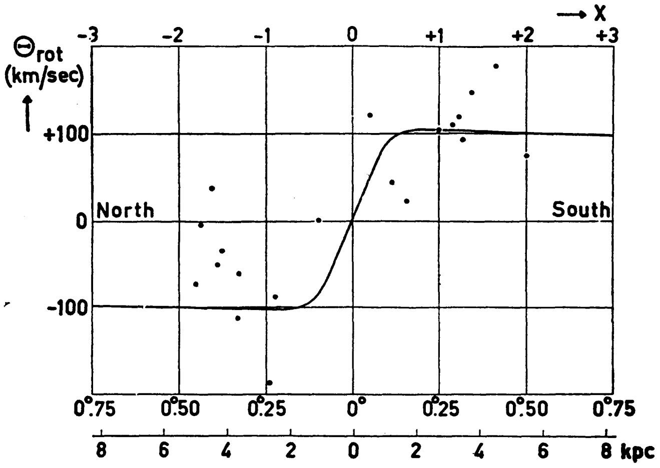

FIG. 2.—Observed velocities (*solid line*) from neutral hydrogen in M33 (Volders 1959), superposed upon the optical velocities (Mayall & Aller 1942) from H II regions (*filled circles*). This early flat rotation curve made surprisingly little impression upon the astronomical community.

Our Galaxy is no exception. The mass interior to the Sun's distance is $10^{11}\ M_\odot$. Mass continues to rise almost linearly with increasing nuclear distance, even beyond the distance of the LMC. This result comes from a study of the space motion of the LMC (Lin, Jones, & Klemola 1995):

> … the Galactic halo has a mass $\approx 5.5 \pm 1 \times 10^{11}\ M_\odot$ within 100 kpc, and a substantial fraction ($\frac{1}{2}$) of this mass is distributed beyond the present Galactic distance of the Magellanic Clouds (≥ 50 kpc). This mass is nearly half that assumed in the previous models, but it is consistent with some recent estimates for the galactic halo. Beyond 100 kpc this mass may continue to increase to $\approx 10^{12}\ M_\odot$ within its tidal radius (≈ 300 kpc).

Other techniques for deriving mass also indicate that the Galaxy mass continues to grow to over $10^{12}\ M_\odot$ at 200 or 300 kpc (Peebles 1990; Kulessa & Lynden-Bell 1992; Zaritski et al. 1993). This distance is getting suspiciously close to the halfway point between our Galaxy and M31. Occasionally I am glad that the matter is dark, or we might find it difficult to be optical astronomers in the brighter universe.

What is the dark matter, especially now that Bahcall et al. (1994) have not detected red dwarfs? Big bang nucleosynthesis (Copi, Schramm, & Turner 1995) tells us that there must be dark baryons, even for a low-density universe; I am optimistic that we will find them. Their detection will occupy astronomers of the next century. But my record for predictions is poor—in 1980 I said we would know what the dark matter is by 1990, from work by particle physicists. Perhaps what I call the Lalande principle will come into play, and knowledge will come from an unexpected direction. In 1779, Lalande said we would not know the solar motion for several hundred years, until the Sun had moved into a new region of stars. Four years later, Herschel determined the solar motion from the proper motions of 12 stars.

Finally, note that the alternative to dark matter, a modification of Newtonian gravitational theory (e.g., Milgrom 1989; Bekenstein & Milgrom 1984) now seems less likely. X-ray observations (Buote & Canizares 1992, 1994) reveal that the geometrical distribution of luminous matter differs from that of dark matter in clusters and in some galaxies. In flattened clusters of galaxies, the dark matter distribution is rounder than the luminous matter distribution. Hence the luminous galaxy distribution traces neither the gravitational potential nor the gravitating matter. Unless dark matter in clusters is distinctly different from dark matter in galaxies, a modified form of Newton's laws which accounts for galaxy rotation curves will not explain the distribution of matter in clusters.

Perhaps the best conclusion to a discussion of dark matter is my favorite Dennis the Menace cartoon, in which Dennis is saying "Lots of things are invisible, but we don't know how many because we can't SEE them."

3. PARTLY PECULIAR GALAXIES

According to Struve, if you pick five stars at random, one of them will be peculiar (Payne-Gaposchkin 1977). Well, if you pick and study one galaxy at random, it will be peculiar. For my random galaxy, I pick M31. An Hα image (Fig. 3) of the central region of M31 (Ciardullo et al. 1988), constructed by Ciardullo from almost 400 individual Hα frames, exhibits an aspect ratio close to face-on, unlike that of the outer M31 disk which is more nearly edge-on. In addition, there is a marked asymmetry between the circularity of the S and N arms. As Figure 3 shows, this morphology is a good match to nuclear gas velocities measured 25 yr ago (Rubin & Ford 1971), which reveal both a nearly circular morphology and a N/S difference. Recently, Stark & Binney (1994) have reproduced the major features, using a triaxial model:

> ... the ionized gas distribution (and to a lesser extent the dust distribution) in the inner few arcminutes of M31 forms a spiral pattern with nearly circular symmetry on the plane of the sky ... this pattern occurs in the transition region where the gas is shocked as it moves from the inner x_1 orbits to the outer x_2 orbits. The spiral looks round because the x_1 orbits are elongated along the line of sight...

Thus the nucleus of M31 offers complexities we only now start to interpret—complexities not only in the gas. Kormendy (1988) observed stars close to the nucleus that have a steep gradient of velocity with radius, and with a large velocity dispersion. This combination is diagnostic of the presence of a supermassive nuclear black hole of mass 10^7 or 10^8 $M_\odot$. And within 0".5 the *HST* detects not one but two nuclei (Lauer et al. 1993; see also Rich et al. 1995); one bright, one fainter. Lauer et al. write

> *V*- and *I*-band *HST* Planetary Camera images of the great spiral galaxy in Andromeda, M31, show that its inner nucleus consists of two components separated by 0".49. The outer isophotes of the nucleus at $1''.4 \leq r \leq 3''.0$ are elongated but are concentric with the M31 bulge. The nuclear component with the lower surface brightness, P2, is also coincident with the bulge photocenter. ... The brighter nuclear component, P1, is well resolved and corresponds to the nuclear core imaged by Stratoscope II.

They suggest that the brighter nuclear region may contain its own black hole, whose presence keeps the knot from being torn apart. The Stratoscope II reference is to the early (Light, Danielson, & Schwarzschild 1974) balloon flight which imaged the core of M31. Understanding the kinematics and the past and future evolution of the nucleus of M31 will offer us much to ponder.

4. MULTISPIN GALAXIES

Only during the past 30 yr have astronomers been able to determine the kinematics of more complex galaxies, the pathological ones. Many of us who had earlier studied spiral galaxies finally had the observational instrumentation, the reduction facilities, and the theoretical framework with which to attack these observationally difficult objects. Just as in medicine, where the study of rare pathological cases often leads to an improved understanding of more normal specimens, the observation of extragalactic systems with tidal distortions, polar rings, and kinematically discrete cores has emphasized the important role that gravitational interactions play in the evolution of all galaxies.

Georgia O'Keefe wrote, "It takes time to see, just as it takes time to make a friend." Arp (1966) was one who took the time to see, and in his beautiful "Atlas of Irregular Galaxies," he arranged a wide variety of pathological types into sequences by morphological appearance. The volume is a monument to the importance of just looking, even before an understanding of process is in place. Only now do we begin to understand the geometry and the kinematics of the interactions which produced the sequences he noted.

NGC 5128 (Cen A), an apparent elliptical with prominent distorted dust lanes across its minor axis, had long been a puzzle to astronomers. In his volume, Galaxies, Shapley (1943) wrote,

> NGC 5128 is a "pathologic specimen"—one of the external galaxies with a peculiar spectrum. Any fully successful theory of structure must take into account such abnormal forms.

Shapley also questioned if NGC 5128 was the result of a merger. Burbidge & Burbidge (1959) heroically observed it (declination = −46°) from McDonald Observatory (latitude = +30°), and detected a rotation in the disk gaseous component. But it was Ulrich's (1975) discovery that the filaments wrapping the minor axis of the Helix galaxy, NGC 2685 (see also Schechter & Gunn 1978), were rotating in a plane parallel to the galaxy minor axis that alerted astronomers and initiated a new direction in galaxy kinematics. Shortly thereafter, Graham (1979) showed that the filaments in NGC 5128 comprise a disk in rotation,

> The present observations reinforce the view that NGC 5128 is a giant elliptical galaxy in which is embedded an inclined and rotating disk composed partly of gas. The disk also contains stars and could be similar to a small galaxy.... The structural peculiarities ... suggest some sort of massive addition of gaseous material to a basically normal elliptical galaxy in the not too distant past.

Within a few years, Schweizer, Whitmore, & Rubin (1983) measured for a polar ring galaxy, A0136 − 0801, the rotation of both the lenticular galaxy and the ring encircling its poles. These curious objects are important because (1) they make it possible to infer the three-dimensional potential of the galaxy and hence to learn about the distribution of dark matter out of the principal plane; and (2) they emphasize the importance of a "second event" in the lives of these galaxies. In each case, the second axis of rotation must have been established by gas collected after the initial rotation axis had been established.

Polar ring galaxies are now understood to be galaxies which acquired cold, infalling gas (e.g., Athanassoula & Bosma 1985), which smears out over several orbital periods into a ring. A ring orthogonal to the principal galaxy is stable over many Hubble times; a ring intermediate between pole and disk precesses to the disk (Tohline et al. 1982; Steiman-Cameron & Durison 1982) and ultimately settles into a stable orbit where it may start forming stars. Both observations and computer simulations reveal that the orbits of this gas may be prograde or retrograde or even skew with respect to the orbits of the preexisting stars.

The knowledge of polar ring galaxies and their derivatives lessened somewhat the surprise of finding significant numbers of elliptical and S0 galaxies with small disks of cold gas. These

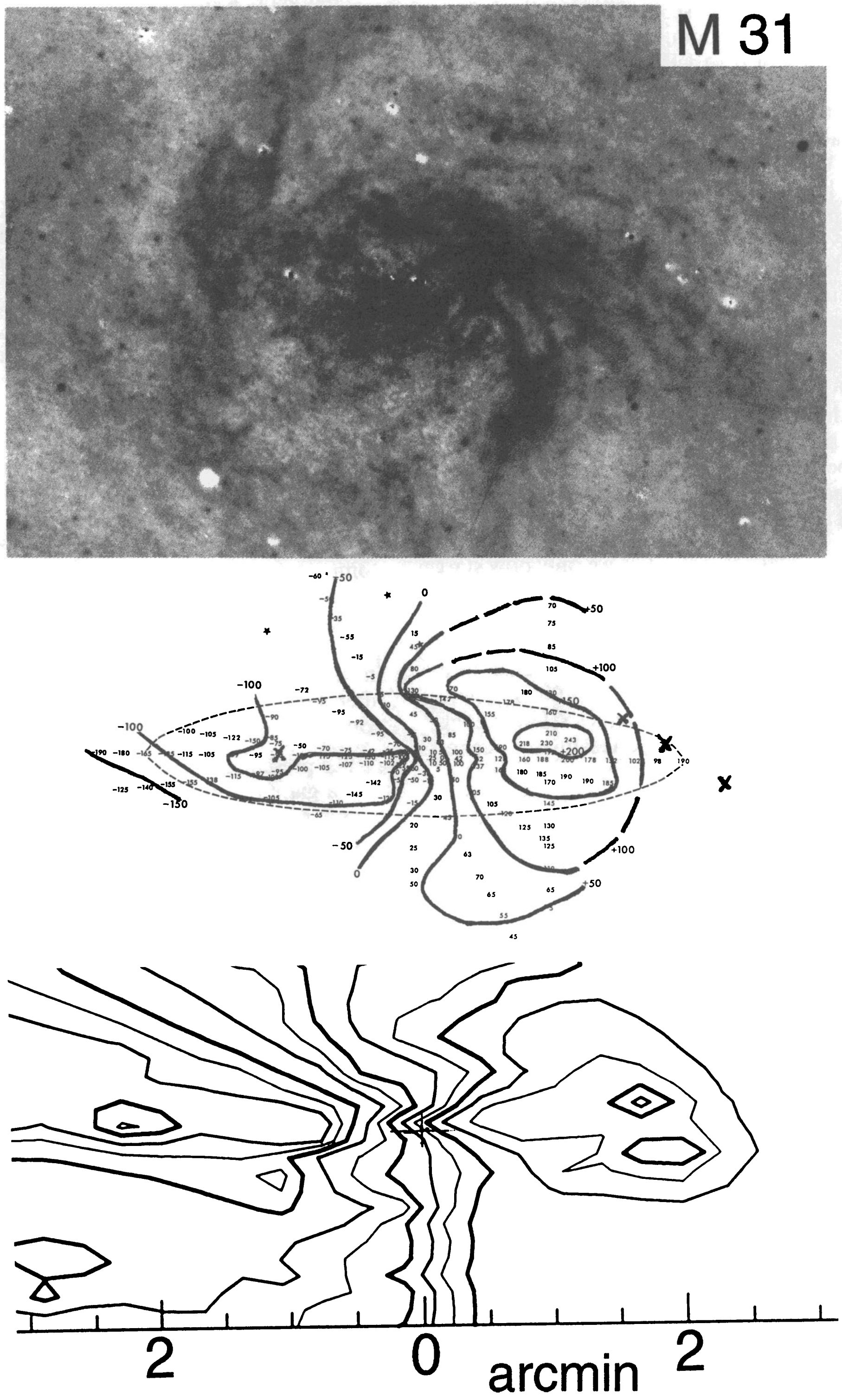

FIG. 3.—(*Top*) Hα plus [N II] image (Ciardullo et al. 1988) of inner region of M31. Note the many fine threads of emission curving outward, which produces an overall appearance more face-on than the optical disk, and also note the N/S asymmetry. (*Middle*) Line-of-sight velocities from the ionized gas in M31 (Rubin & Ford 1971). Ellipse represents the extent of a thin disk of 400 pc (2′), viewed at an angle of 77°. Contour intervals are 50 km s^{-1}. (*Bottom*) Isovelocity contours from the triaxial model of Stark & Binney (1994). Contour intervals are 30 km s^{-1}. Note the general agreement with the velocities above. Position angle 128° is up, and 218° to the left. The lower scale applies to all images. Two minutes of arc is only 2% of the M31 radius.

disks, with higher angular momentum than could arise from gas shed by evolving stars, are presumably of external origin, perhaps even infallen tidal debris. Their kinematics, generally decoupled from the larger galaxy, are complex and sometimes triaxial; their location is generally in the core but sometimes more extended. A compendium of E and S0 galaxies with nuclear gas disks (Bertola, Buson, & Zeilinger 1992) counted nine with counterrotating gas, three with skew rotation, and 13 with corotating gas and stars.

In some cases, the nuclear gas disks have aged and formed stars. Nuclear stellar disks too may orbit prograde, retrograde, or skew to an existing stellar disk (Jedrzejewski & Schechter 1989; Franx, Illingworth, & Hickman 1990). And in yet other cases, the cold gas is external to the E galaxy, as in IC 2006. Here, an H I ring rotates counter to the rotation of the elliptical (Schweizer, van Gorkom, & Seitzer 1989), offering the opportunity to determine the shape of the potential in the plane (circular: Franx, van Gorkom, & de Zeeuw 1994), and the mass beyond the optical galaxy (continuing to rise, with mass-to-luminosity ratio increasing by a factor of ~ 4).

And, in an even more novel development, radial velocities of planetary nebulae, at large radial distances, are now used to study the kinematics of complex objects. For NGC 5128, velocities of over 400 planetaries show rotation in two coordinates along the dust lane and perpendicular to it, i.e., along the major axis of the elliptical (Hui 1993; Hui et al. 1993). The mass-to-light ratio increases with nuclear distance, from 3 at origin to 10 at 20 kpc, offering evidence for dark matter. H I too has now been detected (Schiminovich et al. 1994) in the outer region, some perhaps related to the blue knots detected optically (Graham 1994).

So a surprise of the 1980s was that we could learn about motions within ellipticals, once thought to be gas free, by study of their gas components and even of their planetaries. Thirty years earlier, Osterbrock (1960) had studied ionized gas in a few ellipticals, but the field could not flourish until sophisticated observing techniques were widely available. For spheroidal galaxies, a rotating disk in equilibrium with the overall gravitational potential presently offers the best opportunity for determining the mass distribution.

Some observers of nuclear disks sit not at a telescope but at a computer. Fifteen years of computer simulations of two merging disks of "stars" developed ultimately to simulations which included also "gas" particles (Hernquist & Barnes 1991; Barnes & Hernquist 1991) and demonstrate the important phenomena which occur when even a small amount of gas is included. Calculations show that when two disks merge, tidal torques cause the interacting gas to lose angular momentum, to be funneled efficiently to the center where the resulting angular momentum of the gas disk is unrelated to the initial angular momentum. Statistics of merging disks containing gas (Barnes 1995) show that the inclusion of as little as 1.5% gas makes the remnant rounder, less triaxial, and hence more in keeping with the observations than with theoretical predictions of extreme triaxiality.

Thus, computer models successfully approximate some of the properties of spheroidals with gas disks. Observers too have now initiated attempts to date ancient mergers. Schweizer and Seitzer (1992) have shown that the residuals in the broad-band color-magnitude relation correlate with morphological evidence of the merger: ripples, tidal tails, and isophotal peculiarities. Both morphology and spectroscopy reflect the age since the merger. A more comprehensive summary of these multispin galaxies is given elsewhere (Rubin 1994b). A more artistic summary is given in the 1963 painting of Remedios Varo, "Phenomenon of Weightlessness" (Kaplan 1988). Here, the professor stands amazed, each foot in a different sense of gravity, as a dark mass outside the window pulls an astronomical model into the second frame. This painting offers a moving, artistic view of galaxies with two senses of rotation.

So the end of the Eighties' decade left us confident: theory, observations, and computer simulations could explain much of the curious kinematics that our improved instrumentation and techniques could uncover. We did not predict the larger surprises that were shortly to come.

5. THE DECADE OF THE NINETIES: SEEING THE FUTURE

With the decade of the 1990s only half gone, we already glimpse some future directions of galaxy spectroscopy, and I offer four examples. Other features, not yet imaginable, must await the future.

NGC 4826.—While multiple axes of rotation could be understood for hot spheroidals, it was not expected that colder spirals would show equivalent complexity. But early in the decade, Braun, Walterbos, & Kennicutt (1992; Braun et al. 1994) uncovered a surprise. Neutral hydrogen in the outer disk of the Sab galaxy NGC 4826 (the Sleeping Beauty galaxy, nee the Black Eye) was counterrotating. From earlier optical spectroscopy (Rubin et al. 1965), the sense of rotation of the inner excited gas was known: from early radio observations, it had gone unnoticed that the outer H I was counterrotating. Recent optical observations (Rubin 1994a; Walterbos, Braun, & Kennicutt 1994) detail motions in the inner region, including the prominent dusty lane, where the stars and gas orbit in concert and in the transition region beyond where the gas undergoes an orderly, rapid fall from 180 km s^{-1} prograde to 200 km s^{-1} retrograde, along with an infall of 100 km s^{-1}. However, the stars continue their prograde rotation.

NGC 4826 can be understood as the equatorial counterpart of a polar ring galaxy, in which gas, captured in an oblique angle and smeared into a ring, precesses to the plane where its sense of rotation is counter to that of stars and gas in the preexisting disk. However, because the acquisition of only a few percent of the galaxy mass is expected to heat up and destroy the disk (Toth & Ostriker 1992), it is still unclear how Nature manages this delicate feat of maintaining the disk.

NGC 4550.—NGC 4550 (E7/S0) remains the only galaxy known with two coincident, coplanar extended stellar disks, one disk rotating prograde, one retrograde. A gas disk is coincident with one of the stellar disks. Details of its discovery and its kinematics are published elsewhere (Rubin, Graham, & Kenney 1992; Rix et al. 1992; Rubin 1993). Although such a configuration has a distinguished mathematical history (e.g., Lynden-Bell 1960; Toomre 1982), it had been assumed to be unrealistic, for no mechanism for its formation could be imagined. Toomre's first sentence, "The galaxy models about to be displayed here belong perhaps only in the category of elegant curiosities" is no longer true. Like NGC 4826 and other multi-spin galaxies, these forms spring from the merger of a stellar disk and a counterrotating gas mass which ultimately settles to the disk and forms stars. We may someday know how galaxy evolution with retrograde capture differs from galaxy evolution which involves prograde capture.

Located near the center of the Virgo cluster, NGC 4550 is undistinguished by its morphology. Recent *HST* nuclear images (Fig. 4) show arcs of absorbing material extending into the center, in one location obscuring a bit of the small ($\approx 1''$) central disk, prominent in the $V-I$ image. Bryan Miller, Brad Whitmore, and I are now starting to examine these high spatial resolution images.

NGC 4550 and NGC 4826 have taught us that not only elliptical galaxies, but spirals too, encompass a wider range of kinematical complexity than had been previously imagined or believed realistic. Such galaxies cause us to enlarge the domain of "what is possible." They also force us to enlarge the reduction procedures for measuring gas and stellar velocities. The usual computer reduction programs which pick the peak of a Gaussian line profile are not capable of revealing that spectral lines in NGC 4550 consist of two separate components. New reduction techniques (Gerhard 1993; Rix & White 1992; Merrifield & Kuijken 1994; van der Marel & Franx 1993) determine, for example, the detailed velocity pattern of the stars from the integrated line of sight velocity distribution at each radial distance. Using such a procedure, Merrifield & Kuijken (1994) have established that 30% of the stars in NGC 7217 form a distinct component which orbits retrograde.

M87.—We had long anticipated faint object spectroscopy (FOS) from the repaired *Hubble Space Telescope*, and our expectations were rewarded with a view of the kinematics near the nucleus of M87, the peculiar elliptical near the center of the Virgo cluster. Harms et al. (1994) write,

> Radial velocities of the ionized gas in the two positions 0".25 on either side of the nucleus are measured to be $\approx \pm 500$ km s^{-1} relative to the M87 systemic velocity. These velocities plus emission-line spectra obtained at two additional locations near the nucleus show the ionized gas to be in Keplerian rotation about a mass $M = (2.4 \pm 0.7) \times 10^9 M_\odot$ within the inner 0".25 of M87.

The broad emission wings on the nuclear spectrum suggest even more rapid rotation within 0".25 (18pc); by the time this paper is published, spectra obtained with the 0".09 aperture may have yielded even tighter limits on the volume encompassing the central black hole.

NGC 4258.—As anticipated, *HST* has obtained spectra of galaxy nuclei at significantly higher resolution than possible from the ground. But suddenly, on a very special object, ground-bound astronomers have observed the nucleus of a galaxy at a resolution several orders of magnitude higher than that of *HST*. The object is NGC 4258, the technique is VLBA, and the sources are water vapor masers (Miyoshi et al. 1995; Greenhill et al. 1995). These authors observe numerous water

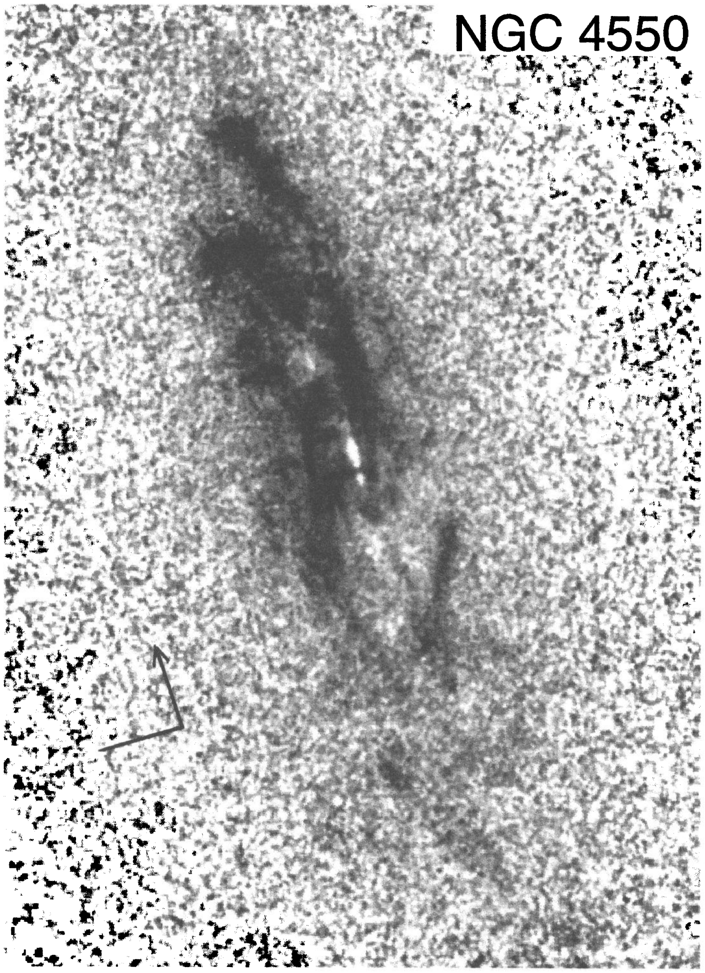

FIG. 4.—*Hubble Space Telescope* WFPC2 ($V-I$)-band image of NGC 4550, the 2" arrow marks North. Original scale 0".046 pixel^{-1}. The bluest (lightest) feature here is a central edge-on disk, diameter $\approx 1''$. Note the asymmetrical, chaotic dust lanes.

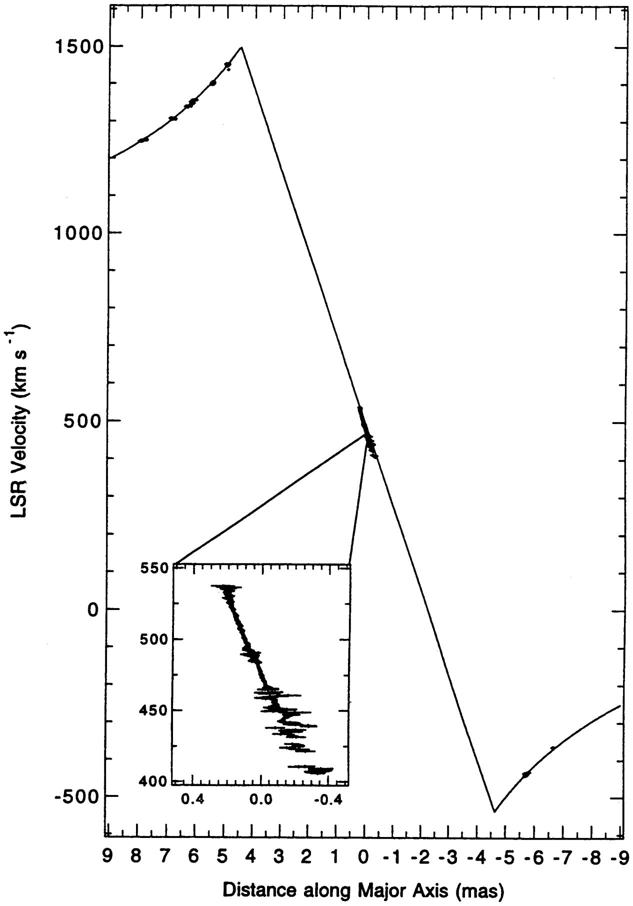

FIG. 5.—Velocities of water vapor masers in the nuclear ring of NGC 4258 (Miyoshi et al. 1995). At the distance of NGC 4258, 4 mas = 0.13 pc = 27,000 AU. The solid line shows linearly rising velocities, followed by a Keplerian ($r^{-1/2}$) fall. A mass of 3.6×10^7 $M_\odot$ is interior to 0.13 pc.

vapor masers situated in a ring, orbiting the nucleus. Inner and outer dimensions are 4 and 8 mas (4 mas = 0.13 pc). The velocities imply a steep rise to 1000 km s^{-1} and then a fall in an exact Keplerian pattern (Fig. 5). Note that velocities near 500 km s^{-1} come from masers distributed along the inner edge of the ring, all approximately equidistant from the center. The observed gradient arises from the varying projection along the line of sight. A mass of 3.6×10^7 $M_\odot$ in a region less than 0.13 pc (27,000 AU) is implied. The mass density, $\geq 4 \times 10^9$ $M_\odot$ pc^{-3}, exceeds by a factor of 40 that for any previous black hole candidate and is thus compelling evidence for a massive central black hole.

6. CONCLUDING RANDOM THOUGHTS

Virtually all of the research programs attacked by spectroscopic observations of galaxies during the past century are in need of additional study. These include the amount, distribution, and composition of dark matter; the rate of the expansion of the universe; the character of the distribution of galaxies; the amount, cause, and significance of large-scale motions; the ages and evolution of galaxies, the structure and motions at very small nuclear distances; and the prevalence of supermassive nuclear black holes.

This impressive list offers much for observers to pursue. Yet surely the role of observers is to confound the theorists. Thus, when the *New York Times* (Wilford 1991) headline read "New Surveys of the Universe Confound Theorists," describing the wedge velocity plot (de Lapparent, Geller, & Huchra 1986) of thousands of galaxies, I felt pretty smug. As an observer, I was not confounded, and I was pleased that the theorists were. However, when I displayed the printed page at Durham, England, Carlos Frenk pointed out the headline of an adjacent, unrelated article, "The Brain May See What Eyes Cannot." Touché, Carlos. The combination of brain and eye will resolve these outstanding questions.

As an extragalactic observer, my livelihood has been based upon the existence of the Doppler shift. I hope other extragalactic observers too recognize the Doppler shift as a gift of Nature, especially because its magnitude does not diminish with increasing distance. But it has occasionally concerned me that we live in a radially expanding universe, when radial motions are the only component that we can measure. So I wonder if there will be surprises in the transverse components, once we can measure sufficient transverse velocities at large distances.

Finally I stress once again my belief that many deep mysteries of the universe are yet to be discovered. In a spiral galaxy, the ratio of dark-to-light matter is about a factor of 10. That's probably a good number for the ratio of our ignorance-to-knowledge. We're out of kindergarten, but only in about the third grade. A good third grade summary might be the Monty Python song, "The Galaxy Song." We have learned a lot. We will have much joy in discovering some of the rest.

I thank the many colleagues and postdoctoral fellows who have contributed so actively to my understanding of the history and practice of galaxy kinematics. They have been a continued source of information, ideas, and encouragement, especially Drs. R. J. Rubin, W. K. Ford, Jr., E. M. Burbidge, G. R. Burbidge, R. Ciardullo, S. D'Odorico, J. A. Graham, D. A. Hunter, J. P. D. Kenney, B. Miller, C. J. Peterson, M. S. Roberts, F. Schweizer, N. Thonnard, and B. C. Whitmore. I thank D. E. Osterbrock for his careful and cheerful comments on the manuscript. I am grateful to many observatories for making telescope time available: Cerro Tololo, Kitt Peak, Las Campanas, Lowell, and Palomar Observatories. I also happily acknowledge the active support from the Carnegie Institution of Washington.

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