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Millennium Essay

One Hundred Years of Rotating Galaxies[1]

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Everything we know about motions within galaxies has been learned in the 20th century. One hundred years ago, galaxies were an enigma. But by 1899, technology made it possible to replace the human eye with the photographic emulsion, so spectroscopes became spectrographs. J. Scheiner, an astronomer at the Potsdam Observatory, obtained the first successful spectrum of a galaxy, M31 (Scheiner 1899), and identified M31 as an assemblage of solar-type stars. However, it was not until Slipher (1914) and Wolf (1914) detected inclined lines in M31 and NGC 4594, the Sombrero galaxy, that astronomers had observational evidence indicating that stars and gas in a galaxy rotate about its center. With heroic effort, Pease (1918) used the Mount Wilson 60 inch telescope to obtain higher resolution spectra of M31 (minor axis, 84 hours exposed 1916 August, September, and October; major axis, 79 hours during 1917 August, September, and October), covering the inner 2% of the major axis. The gradient in the stellar absorption lines on the major axis and the lack of gradient on the minor axis confirmed that the motion was rotation. Astronomers knew that galaxies rotated before they knew what galaxies were.

Observations of M31's rotation (Babcock 1939; Mayall 1951) showed no Keplerian velocity decrease for the outer regions. With startling insight, Mayall compared the M31 rotation curve with the orbital velocities of stars in the solar vicinity and questioned whether the M31 adopted distance was too small. (It was, by a factor of about 3.) Earlier, Opik (1922) had raised a similar concern based on Pease's minimal "rotation curve." Without fanfare, Opik and Mayall had used the new tool of Doppler shift spectroscopy to study galaxy kinematics and galaxy masses.

Most astronomers in the mid-fifties grew up believing that disk galaxies had Keplerian velocities at moderate nuclear distances. Some of this belief may have come from Slipher. More at home with the planets than with galaxies, Slipher used Saturn as a radial velocity standard for his M31 spectra; he characterized the spectrum of the Sombrero galaxy as "planetary." De Vaucouleurs (1959) concluded from the eight available rotation curves, "In all cases the rotation curve consists of a straight inner region ... beyond which the rotational velocity decreases with increasing distance to the center and tends asymptotically toward Kepler's third law." With the 20/20 vision of hindsight, plots of the data reveal only a scatter of points, from which no certain conclusions can be drawn.

I had long been interested in how galaxies "ended" and, with my graduate students at Georgetown, made a study of the velocities of ~ 1000 O and B stars beyond the solar circle (Rubin et al. 1962; see also Rubin 1965) in our Galaxy. Our 1962 conclusion, "For $R > 8.5$ kpc, the stellar curve is flat, and does not decrease as is expected for Keplerian orbits," apparently influenced no one and was ignored even by the senior author when she returned to the problem of galaxy rotation a decade later.

Margaret and Geoffrey Burbidge (1975 and references therein, submitted 1969; following Page 1952) introduced the modern era of kinematic studies of galaxies when they exploited the new red-sensitive photographic plates to observe Hα emission from interstellar gas along the major axes of nearby spirals. But nearby galaxies are large, so only inner parts were observed with the "long slit" of the McDonald 82 inch telescope plus spectrograph. If the Burbidges had placed the spectrograph slit at large nuclear distances, they might have discovered that rotation velocities remain high at large nuclear distances; many galaxies have bright H II regions at large radii. The 1963–1964 academic year I spent in La Jolla working with Margaret and Geoff was an invaluable experience for me, and I happily acknowledge here the lasting importance of their encouragement and support.

During the second half of the 20th century, extragalactic astronomy made enormous strides, due principally to advances in instrumentation: electro-optical devices (initially image tubes; later CCD detectors) for optical telescopes and large radio telescope arrays for observing the 21 cm line of neutral hydrogen. Hundreds of extended rotation curves were acquired in 1978–1988 (Rubin, Ford, & Thonnard 1978; Bosma 1978; Giovanelli & Haynes 1983; Rubin et al. 1985; Sancisi & van Albada 1986; Guhathakurta et al. 1988), and more than 2000 are now available (Mathewson, Ford, & Buchhorn 1992; Prugniel et al. 1998). In general,

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optical data have higher spatial resolution, and H I velocities extend farther.

Few galaxies exhibit the Keplerian velocity fall expected at large nuclear distances for a mass distribution which follows the light distribution within the galaxy. Instead, rotation velocities generally remain high at large nuclear distance; occasionally, rotation velocities decrease slightly at the edge of the optical disk, then flatten. These observations have played a major role in convincing scientists that at least 90% of the total spiral mass, and hence the total mass in the universe, is dominated by nonluminous (i.e., dark) matter. It took 50 years for the discoveries of Zwicky (1933) and Smith (1936), that clusters of galaxies contained unseen matter, to make it to mainstream astronomy.

Yet not all astronomers had been blind to the contradiction posed by the exponentially falling galaxy disk luminosity and the constant rotational velocities. Oort (1940!) wrote of NGC 3115, "It may be concluded that the distribution of mass in the system must be considerably different from the distribution of light ... The strongly condensed luminous system appears embedded in a large more or less homogeneous mass of great density." Freeman (1970: M33, NGC 300) and Shostak (1973: NGC 2405) were similarly impressed by the contradiction; see also Schwarzschild (1954: M31).

We enter the 21st century knowing that galaxy dark halos exist, that they contain an order of magnitude more mass than the visible galaxy, and that they are of great extent. In 15 hours of observation, less that one-tenth the time it took Slipher to obtain the major- and minor-axis spectra of M31, the Sloan Digital Sky Survey (Fischer et al. 2000) detected distortions in over one million background galaxies whose light was gravitationally deflected as it passed through the large dark halo of one of 28,000 foreground galaxies. These two observations, early and late in the 20th century, define the progress that many of us have lived through.

Kinematics of galaxies tell us more than the distribution of mass in spirals; they teach us about galaxy evolution. Twenty-five years ago, we could only dream of obtaining rotation curves for galaxies at distances corresponding to $z \approx 1$, whose diameters subtend only a few arcseconds. Large telescopes and subarcsecond optics now make possible observations of moderately distant spirals, $z \approx 0.2$–0.4 (Bershady 1997; Bershady et al. 1999; Simard & Prichet 1998; Kelson et al. 2000). These have been surpassed with Keck spectrographic observations reaching $z \approx 1$ (Vogt et al. 1996, 1997, 1999; Koo 1999). Regularly rotating spiral disks were in place when the universe was less than half of its present age. The Keck rotation velocities define a Tully-Fisher relation (i.e., the correlation of rotation velocity with blue magnitude) which matches to within ≤ 0.5 mag that for nearby spirals. Spiral galaxy evolution, over the last half of the age of the universe, has not significantly altered the Tully-Fisher correlation.

The significance lies not in these initial details, but in the realization that galaxy kinematics becomes now a viable parameter for cosmological studies. Fifteen years ago, I predicted (Rubin 1986), "Rotation curves can be obtained for galaxies with redshifts as great as $z = 0.05$ and probably even $z = 0.1$. (I hope that some day I will be amused at the conservative nature of this prediction)." I am not only amused, I am delighted. Now we struggle for rotation velocities at $z \approx 5$ and perhaps even higher. These too will come; high-resolution millimeter observations may get there first. If the inferences from the Hubble Deep Field images are correct, spheroidal galaxies were in place at $z = 3$, but well-formed disks were rare. Perhaps the early universe was an inhospitable time and place for large, cold disks.

Studies of even nearby galaxies, especially pathological specimens (Baade's term), also reveal galaxy evolution. Often, their kinematic complexity involves more than one spin axis. For example, polar ring galaxies (Schweizer, Whitmore, & Rubin 1983) permit us to observe mass tracers in two orthogonal planes and offer visible evidence that such objects could not form in a single event. Other equally wonderful galaxies confirm the importance of gravitational acquisitions and mergers in driving galaxy evolution. NGC 4550, an E7/SO disk galaxy near the center of the Virgo galaxy, contains a single disk in which intermingled stars orbit, one-half clockwise, one-half counterclockwise (Rubin, Graham, & Kenney 1992). Stars in NGC 4826 (the Black Eye or Sleeping Beauty) orbit with a single sense, but the gas interior to the outer radius of the prominent dust lane rotates counter to the stars (Braun, Walterbos, & Kennicutt 1992). The bulge in NGC 7331 may (Prada et al. 1996) or may not (Mediavilla et al. 1997) counterrotate with respect to the disk. Water vapor masers observed with milliarcsecond resolution near the center of NGC 4258 define a warped disk in Keplerian rotation about a black hole (Herrnstein et al. 1999). Numerous observations of interacting and merging galaxies, coupled with realistic computer simulations of stars, gas, and dark matter particles, have identified the paths followed by such galaxies. "Pathological" can often be understood as one stage in a merger sequence (Schweizer 1998).

Velocities within elliptical galaxies are harder to observe and more difficult to interpret owing to the uncertain geometry, the lack of gas, and the noncircular orbits within ellipticals. Yet sophisticated reduction techniques (e.g., Cretton 1999) now extract from complex integrated stellar spectral line profiles the full line-of-sight velocity distributions.

Few extended rotation curves for ellipticals exist, yet continuing study will likely confirm the need for dark matter. For NGC 2434, velocity information (Rix et al. 1997) extends to large nuclear distances (3 or $4r_e$, r_e = half-light radius). One-half of the mass within r_e is dark; dark matter dominates beyond. IC 2006 is an elliptical with a large external counterrotating gas ring (Schweizer, van Gorkom, & Seitzer 1989). Interior to the ring, the dark matter exceeds the luminous matter by a factor of 2.

A small nuclear disk of stars and/or gas is not uncommon in studied ellipticals (Jedrzejewski & Schechter 1989; Franx et al. 1989; Bertola, Buson, & Zeilinger 1992). Some disks are skew, some polar, some counterrotating, and hence they offer evidence of a complex evolutionary history. For some, nuclear velocities show evidence of Keplerian rotation about black holes (Kormendy & Richstone 1995).

Like the Tully-Fisher relation for spirals, the three-parameter (half-light radius, surface brightness, and central velocity dispersion) fundamental plane relation offers a tool for studying elliptical galaxy evolution. Keck spectra and *HST* images of 53 galaxies in cluster CL 1358+62 ($z = 0.33$) define a fundamental plane similar to that of nearby ellipticals (Kelson et al. 2000). Ellipticals at $z = 0.33$ are structurally mature; we await data from more distant ellipticals.

Throughout this century, knowledge of galaxies has come from an interesting interplay of what we can discern nearby while living inside a spiral galaxy and what we learn by observing galaxies at a distance. Kinematic studies help. It is likely that this interplay will continue to be a valuable tool. We observe that our Galaxy is capturing a dwarf spheroidal in Sagittarius (Ibata et al. 1997) and that the Carina dwarf is losing stars to the Milky Way (Majewski et al. 1999). Velocity streams in the Milky Way halo and globular cluster motions from earlier captures help convince us that galaxy evolution is a continuous process, not a single event. Rather than the Island Universes evolving in splendid isolation imagined by Hubble (1936), 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, and will be actively forming stars or quiescent depending upon its recent history.

Details of galaxy kinematics are unlikely to be a source of major excitement in the next century (recall that my record for predicting is not good). But discoveries which reveal the composition, distribution, and amount of the dark matter will be exciting. New large telescopes, enormous surveys, Fabry-Perot and integral field spectroscopy, and especially detectors which provide a spectrum at each pixel are already changing the way astronomers observe and analyze data.

Our knowledge of transverse motions of stars, formerly limited to stars in the solar neighborhood, now extends to rapidly orbiting circumnuclear stars (Eckart & Genzel 1996; Ghez et al. 1998) at the Galactic center. For galaxies too, perhaps as far away as Virgo (is this another too conservative prediction?), transverse motions will offer a new parameter with which to study the universe. Astronomers were startled by the discoveries which arose from determining radial velocities; I hope the surprises will be no less from the transverse components.

One hundred years ago, galaxies were an enigma. They still are. It is folly to believe that we know what a galaxy is, while the extent, the density distribution, and the composition of $\geq 90\%$ of its mass are still a dark mystery. Models of enormous complexity exist, which assume that luminous disks form embedded in cold dark matter structures originating early in the universe. In order to make the models fit, adjectives modify cold dark matter models: open, mixed, tilted, Λ. I hope that new observations and new insights will soon impose tighter constraints upon these models, as well as tighter constraints upon the dark matter/bright matter components which produce the observed rotation curves. Some of the current complexity must arise from our ignorance.

Happily, distant observations push back still farther the era of disk formation; I like a very old universe. Surprisingly, we cannot yet rule out a modified gravitational potential, rather than dark matter, as the explanation of our observations. We have learned much about galaxies in the last 100 years. I think that we still have major surprises to uncover. I hope all of our discoveries will be dwarfed by what will be learned in the next century. This century, we have learned about rotating galaxies. But in understanding their role in the evolution of the universe, it may be earlier than we think.

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