24 June 1983, Volume 220, Number 4604 SCIENCE

The Rotation of Spiral Galaxies

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Historians of astronomy may some day call the mid-20th century the era of galaxies. During those years, astronomers made significant progress in understanding the structure, formation, and evolution of galaxies. In this article, I will discuss a few selected early steps in determining the internal dynamics of galaxies, as well as current research concerning the rotation and mass distribution within galaxies. These studies contribute to the present view that much of the mass of the universe is dark.

Summary. There is accumulating evidence that as much as 90 percent of the mass of the universe is nonluminous and is clumped, halo-like, around individual galaxies. The gravitational force of this dark matter is presumed to be responsible for the high rotational velocities of stars and gas in the disks of spiral galaxies. At present, the form of the dark matter is unknown. Possible candidates span a range in mass of 10^{70}, from non-zero-mass neutrinos to massive black holes.

In 1845, Lord Rosse (*1*) constructed a mammoth 72-inch reflecting telescope, which remained the largest telescope in the world until the construction of the "modern" 100-inch telescope on Mount Wilson in 1917. Unfortunately, the Rosse telescope did not automatically compensate for the rotation of the earth, so an object set in the field of the telescope would race across the field. Nevertheless, Lord Rosse made the major discovery that some nebulous objects show a spiral structure (*2*).

Insight into the nature of these enigmatic objects was slow in coming, but by 1899 the combination of good tracking telescopes and photographic recording made it possible for Scheiner (*3*) to obtain at the Potsdam Observatory a spectrum of the nucleus of the giant spiral in Andromeda, M31. From the prominence of the *H* and *K* absorption lines of calcium, Scheiner correctly concluded that the nucleus of M31 was a stellar system composed of stars like the sun, rather than a gaseous object.

Even earlier, Lord and Lady Huggins (*4*) had attempted at their private observatory to obtain a spectrum of M31, but their labors were fraught with disaster. Exposure times were so long that each fall when M31 was overhead they would expose consecutively on one plate during the early evening hours, until they could build up the requisite exposure (perhaps 100 hours). They would then superpose a solar spectrum adjacent to the galaxy spectrum to calibrate the wavelength scale. Year after year, their single exposure was a failure, sometimes showing no galaxy spectrum, sometimes contaminated by the solar spectrum; once the plate was accidentally placed emulsion side down, where it dried stuck to the laboratory table. A copy of their 1888 failure is published along with their remarkable stellar spectra (*4*).

Slipher (*5*), working with the 24-inch reflector at Lowell Observatory, initiated in 1912 systematic spectral observations of the bright inner regions of the nearest galaxies. For NGC 4594, the Sombrero galaxy, he detected inclined lines [(*6*); see also (*7*)], which he correctly attributed to stars collectively orbiting about the center of that galaxy. On the side of the nucleus where the rotation of the galaxy carries the stars toward the observer, spectral lines are shifted toward the blue region of the spectrum with respect to the central velocity. On the opposite side, where rotation carries the stars away from the observer, lines are shifted toward the red spectral region.

Several years later, Pease (*8*) convincingly illustrated that rotation *was* responsible for the inclined lines. Using the 60-inch telescope on Mount Wilson during the months of August, September, and October 1917, he patiently acquired a 79-hour exposure of the spectrum of the nuclear region of M31 with the slit aligned along the apparent major axis of the galaxy. Inclined lines appeared. A second exposure made during these 3 months in 1918, with the slit placed perpendicular to the major axis along the apparent minor axis, showed no inclination of the lines. Along the minor axis, stars move at right angles to the line-of-sight of the observer, so no Doppler shift appears. The rotation of galaxies was established even before astronomers understood what a galaxy was.

By the mid-1920's, astronomers knew that we lived in a Galaxy composed of billions of stars distributed principally in a disk, all rotating about a distant center. Each spiral viewed in a telescope, located at an enormous distance beyond our Galaxy, is itself a gigantic gravitationally bound system of billions of stars all orbiting in concert about a common center. This knowledge came from a variety of observational discoveries: Henrietta Leavitt's (*9*) discovery of Cepheid variables, stars whose periods of light fluctuation reveal their true brightnesses and hence distances; Shapley's (*10*) demonstration that the globular clusters surround our own Galaxy like a halo, with a geometric center located not at the sun but at a great distance in the dense star clouds of Sagittarius; and Hubble's (*11*) discovery of Cepheids in M31 and M33.

In a brilliant study, Öpik (*12*) used the rotational velocities in M31 to estimate its distance. His result, 450,000 parsecs

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(1 pc = 3 × 10^{13} km), comes closer to the distance in use today, 750,000 pc, than the distance of 230,000 pc which Hubble derived from the Cepheids and which he was still using in 1950 (*13*). Öpik's distance was based on the procedure used currently to determine the masses of galaxies, and I will discuss it in some detail. For a particle of mass m moving in a circular orbit with velocity V about a spherical distribution of mass M at distance r from the center, the equality of gravitational and centrifugal forces gives

$$\frac{GM(r)m}{r^2} = \frac{mV^2(r)}{r} \quad (1)$$

where G is the constant of gravitation and $M(r)$ is the total mass contained out to a distance r from the center. It follows that the mass interior to r is given by

$$M(r) = rV^2(r)/G \quad (2)$$

or

$$V(r) = [GM(r)/r]^{1/2} \quad (3)$$

Today we adopt a distance to a galaxy (generally from its Hubble velocity), determine the rotational velocity V at each r, and then calculate the variation of M with r. Öpik assumed that the ratio of mass to luminosity was the same for M31 as for our Galaxy, and used M and V to determine r. Both the dynamics and the astrophysics were sound, and the result convinced many astronomers that spiral galaxies were external to our own Milky Way system.

Modern Optical Observations of Spiral Galaxy Rotation

Several observational procedures are available today to study the rotation (that is, orbiting) of stars and gas in a spiral galaxy. A spectrograph with a long slit will record the light arising from all of the stars in the galaxy along each line-of-sight. The resulting spectrum will be composite, the sum of individual stellar spectra. A stellar motion toward the observer will displace each spectral line toward the blue region of the spectrum; a motion away from the observer will displace each line toward the red. Measurement of the successive displacements along a spectral line will give the mean velocity of the stars corresponding to that location in the galaxy. The shape and width of the line contain information concerning the random motions along the line-of-sight.

Starlight from external galaxies is generally too faint to permit a dense spectral exposure on which accurate positional measurements may be made from stellar absorption lines. One way around this difficulty is to measure velocities from the emission lines arising in the ionized gas clouds surrounding the hot young blue stars which delineate the spiral structure. Because the light from these clouds is emitted principally in a few lines of abundant elements (hydrogen, ionized oxygen, ionized nitrogen, and ionized sulfur), a measurable exposure is obtained in a fraction of the time required for the stellar exposure. This is the method we employ in our optical observations. A third procedure is to observe in the radio spectral region, at the wavelength of 21 cm emitted by the hydrogen atom. Hydrogen gas, a major constituent of the prominent dust lanes seen in spiral galaxies and hence opaque for an optical astronomer, becomes the object of observation for the radio astronomer.

Following the pioneering work discussed above, observations of the rotation of galaxies proceeded very slowly. A major addition to our knowledge came from the extensive work of Margaret and Geoffrey Burbidge (*14*). Due to the long observing times, velocities were obtained only for the brightest inner regions. Only for a few of the nearest galaxies was it possible to observe individual regions and map the rotation to large nuclear distance (*15*). Until recently, radio observations had limited spatial resolution and hence poor velocity accuracy. Astronomers attempting to examine the dynamical properties of galaxies (*16*) had few measured velocities well beyond the bright nuclear regions.

For the past several years, W. K. Ford, Jr., N. Thonnard, D. Burstein, B. Whitmore, and I (*17–19*) have been using modern detectors to study the dynamical properties of isolated spiral galaxies. We attempt to measure the rotational velocities across the entire optical galaxy. We have observed galaxies of Hubble types Sa (disk galaxies with large central bulges, and tightly wound weak arms with few emission regions), Sb, and Sc (disk galaxies with small central bulges, and open arms with prominent emission regions), emphasizing galaxies of high and low luminosity within each class. Our aim is to learn how rotational properties vary along the Hubble sequence of galaxies, and within a Hubble class, and to relate the dynamical properties to other galaxy parameters.

For 60 Sa, Sb, and Sc program galaxies, we have obtained spectra with the 4-m telescopes at Kitt Peak National Observatory (near Tucson, Arizona) and Cerro Tololo Inter-American Observatory (near La Serena, Chile). A few spectra come from the 2.5-m du Pont Telescope of the Carnegie Institution of Washington at Las Campanas (also near La Serena). Optical observations are made with spectrographs which incorporate an RCA C33063 image tube (*20*). The image is photographed from the final phosphor of this tube. Use of this electronic enhancement device makes it possible to obtain spectra at a high spatial scale and of high velocity accuracy with exposure times of about 3 hours, on Kodak IIIa-J plates which have been baked in forming gas and preflashed to enhance their speed.

We choose galaxies that are relatively isolated, that are not strongly barred, that subtend an angular size at the telescope which approximately matches the length of the spectrograph slit, and that are viewed at relatively high inclination to minimize uncertainties in transforming line-of-sight velocities to orbital velocities in the galaxy. Distances are calculated from velocities arising from the cosmological expansion, adopting a Hubble constant of 50 km sec^{-1} Mpc^{-1}.

A sample of Sc program galaxies and spectra is shown in Fig. 1; the spectra were taken with the spectrograph slit aligned along the galaxy major axis. The galaxies are arranged by increasing luminosity. Velocities are determined by measuring the displacement of the emission lines with respect to the night sky lines to an accuracy of 1 μm. We measure with a microscope which moves in two dimensions, a rather old-fashioned but still very accurate technique. Many astronomers now trace plates with a microdensitometer or obtain digital data directly at the telescope. From the measured velocities on each side of the nucleus a mean curve is formed. It describes the circular velocity in the plane of the galaxy as a function of distance from the nucleus, as shown on the right in Fig. 1.

Within a Hubble type, rotation curves vary systematically with luminosity. For a low-luminosity galaxy (NGC 2742), velocities rise gradually from the nucleus and reach a low maximum velocity only in the outer regions. For a high-luminosity galaxy (UGC 2885), rotational velocities rise steeply from the nucleus and reach a "nearly flat" portion in a small fraction of the galaxy radius. An Sc of low luminosity (6 × 10^9 solar luminosities) has a maximum rotational velocity V_{max} near 100 km sec^{-1}, compared with V_{max} near 225 km sec^{-1} for an Sc of high luminosity (2 × 10^{11} solar luminosities). Dynamical variations from one Hubble class to another are equally systematic.

What differentiates Sa and Sc galaxies of equal luminosity are the amplitudes of their rotational velocities. At equal luminosity, an Sa has a higher rotational velocity than an Sb, which in turn has a higher velocity than that of an Sc. A low luminosity Sa has V_{max} = 175 km sec^{-1}, a high-luminosity Sa has V_{max} = 375 km sec^{-1}. Each value is higher than that of the corresponding Sc galaxy.

Mass Distribution Within Spiral Galaxies

What do these flat rotation curves tell us about the mass distribution within a disk galaxy? Unfortunately, we cannot determine a unique mass distribution from an observed rotation curve; only the mass distribution for an assumed model can be deduced. In practice, a spheroidal or disk model is adopted, and an integral equation is solved for the density distribution as a function of r (*21*).

In several cases of special interest, the velocity or mass distribution follows directly from Eq. 2 or Eq. 3, for a simple spheroidal model. These cases are now briefly discussed.

1) *Central mass*. In the solar system, where essentially all of the mass is in the

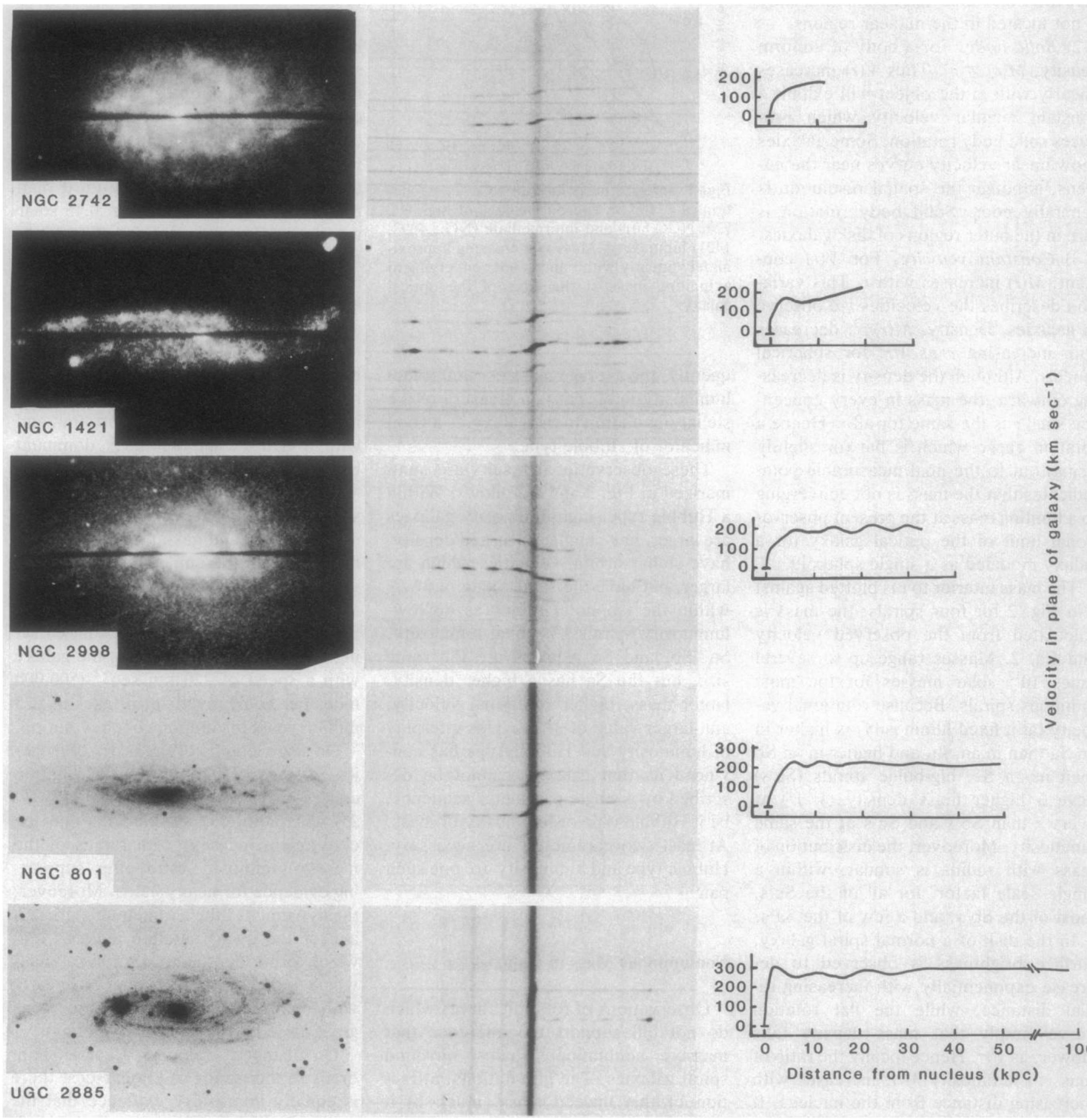

Fig. 1. Spectra and rotation curves for five Sc galaxies, arranged according to increasing luminosity. Photographs for NGC 2742, 1421, and 2998 are copies of the television screen which displays the image reflected off the spectrograph slit jaws. The dark line crossing the galaxy is the spectrograph slit. NGC 801 and UGC 2885 are reproduced from plates taken at the prime focus of the 4-m telescope at Kitt Peak National Observatory by B. Carney. The corresponding spectra are arranged with wavelength increasing from the bottom to the top. The strongest step-shaped line in each spectrum is from hydrogen in the galaxy, and is flanked by weaker lines of forbidden ionized nitrogen. The strong vertical line in each spectrum is the continuum emission from stars in the nucleus. The undistorted horizontal lines are emission from the earth's atmosphere, principally OH. The curves at the right show the rotational velocities as a function of nuclear distance, measured from the emission lines in the spectra.

sun, $M(r)$ is constant for all distances beyond the sun. Velocities of all planets decrease as $r^{-1/2}$, that is, a Keplerian decrease, with increasing distance from the sun (Eq. 3). Mercury (solar distance = 0.39 of the earth's distance) orbits with a velocity of 47.9 km sec^{-1}. Pluto, 100 times farther (39 earth distances), moves with a velocity one-tenth that of Mercury, V = 4.7 km sec^{-1}. For galaxies, the lack of a Keplerian falloff in velocities indicates that most of the mass is not located in the nuclear regions.

2) *Solid body*. For a body of uniform density, $M(r) \propto r^3$. Thus $V(r)$ increases linearly with r; the object will exhibit a constant angular velocity which produces solid body rotation. Some galaxies show linear velocity curves near the nucleus, although the spatial resolution is generally poor. Solid body rotation is rare in the outer regions of disk galaxies.

3) *Constant velocity*. For $V(r)$ constant, $M(r)$ increases with r. This variation describes the velocities we observe in galaxies. Density, $M(r)/r^3$, decreases with increasing r as $1/r^2$ for spherical models. Although the density is decreasing outward, the mass in every concentric shell r is the same for all r. Hence a rotation curve which is flat (or slightly rising) out to the final measurable point indicates that the mass is not converging to a limiting mass at the present observational limit of the optical galaxy for a galaxy modeled as a single spheroid.

The mass interior to r is plotted against r in Fig. 2 for four spirals; the mass is calculated from the observed velocity and Eq. 2. Masses range up to several times 10^{12} solar masses for the most luminous spirals. Because rotational velocity (at a fixed luminosity) is higher in an Sa than in an Sb, and higher in an Sb than in an Sc, big-bulge spirals (Sa's) have a higher mass density (V^2/r^2) at every r than Sb's and Sc's of the same luminosity. Moreover, the distribution of mass with radius is similar, within a single scale factor, for all of the Sc's, most of the Sb's, and a few of the Sa's.

In the disk of a normal spiral galaxy, surface brightness is observed to decrease exponentially with increasing radial distance, while the flat rotation curves imply that mass density falls slower, as $1/r^2$. Hence locally the ratio of mass to luminosity M/L increases with increasing distance from the nucleus. If we average the mass and the luminosity across the entire visible galaxy, then the ratio of mass to luminosity is a function of Hubble type, but is independent of luminosity within a type. This statement holds for observed ranges of (blue) luminosity L_B up to a factor of 100. Consequently, the average mass per unit (blue) luminosity in a galaxy, a measure of the stellar population in the galaxy, is a good indicator of Hubble type.

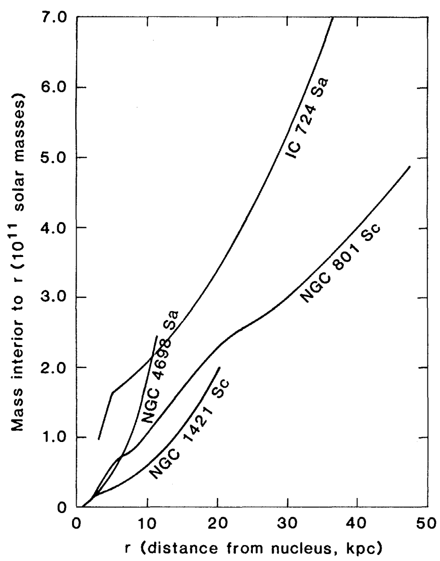

Fig. 2. Integral mass interior to r, as a function of r, for Sc and Sa galaxies of high (IC 724, NGC 801) and intermediate (NGC 4698, 1421) luminosity. Mass is increasing approximately linearly with r and is not converging to a limiting mass at the edge of the optical galaxy.

These observational results are summarized in Fig. 3 and as follows. Within a Hubble type, high-luminosity galaxies are larger, have higher mass and density, have stellar orbital velocities which are larger, but have the same value of M/L_B within the isophotal radius as do low-luminosity spirals. At equal luminosity, Sa, Sb, and Sc galaxies are the same size, but the Sa has a higher density, larger mass, higher rotational velocity, and larger value of M/L_B. This interplay of luminosity and Hubble type has convinced us that galaxies cannot be described by a single parameter sequence, be it Hubble type or luminosity or mass. At least two parameters are necessary; Hubble type and luminosity are one such pair.

Nonluminous Mass in Galaxies

Observations of rotation curves which do not fall support the inference that massive nonluminous halos surround spiral galaxies. The gravitational attraction of this unseen mass, much of it located beyond the optical image, keeps the rotational velocities from falling. The increase in M/L_B with nuclear distance indicates that this nonluminous mass is much less concentrated toward the center of the galaxy than are the visible stars and gas. Even at large nuclear distances, the average density of the nonluminous matter is several orders of magnitude greater than the mean density of mass in the universe. Hence it is clumped around galaxies and is not just an extension of the overall background density.

During the past decade, there has been growing acceptance of the idea that perhaps 90 percent of the mass in the universe is nonluminous (*22*). The requirements for such mass come from a variety of observations on a variety of distance scales. In our own Galaxy, we can calculate the disk mass at the position of the sun by observing the attraction of the disk on stars high out of the plane, and comparing this mass with that which we can enumerate in stars and gas. Oort (*23*) first showed that the counted density at the sun is less by about one-third than that implied by the dynamics, 0.15 solar mass per parsec cubed. But self-gravitating disks of stars are unstable against formation of barlike distortions. Hence it is appealing to place the unseen matter in a halo, rather than a disk, and solve both the problem of the Oort limit and that of the stability of spiral disks. Moreover, a halo of low density at the solar position is consistent both with the Oort limit and with a halo which becomes dominant beyond the optical galaxy.

Additional evidence for a massive halo surrounding our Galaxy comes from individual stars and gas at greater nuclear distance than the sun, whose rotational velocities continue to rise (*24*). The galaxy rotational velocity is high, befitting the enormous distances. The sun, carrying the planets with it, orbits the galaxy with a speed of 220 km sec^{-1} (500,000 miles per hour); even so, it takes us 225 million years to complete one revolution.

On scale lengths of the order of galaxies, $20 < R < 100$ kpc, the flat rotation curves observed at both optical (*17, 19, 25*) and radio (*26*) wavelengths and the consequent increase with radius of the mass-to-luminosity ratio offer supporting evidence for heavy halos. Moreover, the dynamics of the globular clusters (*27*) and of the dwarf satellite galaxies (*28*) which orbit our Galaxy imply a mass which increases approximately linearly with increasing radius, to distances as great as 75 or 100 kpc.

On distance scales as great as hundreds to thousands of kiloparsecs, there is equally impressive evidence that the gravitational mass far exceeds the luminous mass. The evidence comes from the orbits of binary galaxies (*29*) (our Galaxy and the Andromeda galaxy form one such pair), random motions of galaxies in clusters (*30*), and the distribution of hot gas in clusters of galaxies (*31*) as observed by the x-ray emission. Such observations compose a body of evidence which lends support to the concept of heavy halos clumped around individual galaxies.

Increased interest in rotation curves has led astronomers to related studies. Radio astronomers have determined rotational velocities beyond the optical image for a few galaxies in which the neutral hydrogen distribution extends farther than the optical galaxy. Sancisi (*32*) suggests that rotation curves do fall beyond the optical galaxy, perhaps by 10 percent in velocity over a small radial distance, but then level off once again. Casertano (*33*), Bahcall and collaborators (*34*), and Caldwell and Ostriker (*35*) have constructed multicomponent mass distributions, consisting of central point masses, disks (sometimes truncated), bulges, and halos, which can reproduce the observed rotational properties of spiral galaxies.

Observations in a variety of spectral ranges have been unable to detect the dark matter. Massive halos do not appear to radiate significantly in the ultraviolet, visible, infrared, or x-ray regions; they are not composed of gas or of normal low-luminosity stars. Other possible forms include fragments of matter which never became luminous (Jupiter-like planets, black holes, neutrinos, gravitinos, or monopoles) (*36*). The enormity of our ignorance can be measured by noting that there is a range in mass of 10^{70} between non-zero-mass neutrinos and massive black holes. Not until we learn the characteristics and the spatial distribution of the dark matter can we predict whether the universe is of high density, so that the expansion will ultimately be halted and the universe will start to contract, or of low density, and so that the expansion will go on forever.

Theoretical models of the formation and evolution of galaxies currently attempt to take into account the environmental effects of enormous quantities of nonluminous matter surrounding newborn and evolving galaxies. Most likely, the formation processes for galaxies and for the nonluminous matter were distinct; one attractive idea is that much of the mass of the universe was arranged in its nongaseous dark guise before the galaxies began to form. Recent reviews by Rees (*36*), Silk (*37*), and White (*38*) enumerate the various interesting possibilities. An especially pleasing model by Gunn (*39*) suggests that disks of spirals form from relatively slowly infalling material. Regardless of which evolutionary scheme ultimately explains the current phases of galaxies and of the universe, we have learned that galaxies are not the isolated "island universes" imagined by Hubble (*40*), but that environmental effects play a prominent role in directing their evolution.

For nonbelievers in heavy halos and invisible mass, an alternative explanation (*41*) modifies the $1/r^2$ dependence (Eq. 1) in Newton's law of gravitation for large r. Under this circumstance, the distribution of mass follows the distribution of light, but the velocities resulting from the mass distribution remain high due to a modified law of gravitation. For the present, this possibility must remain as a last resort.

Why Was It Thought That Rotational Velocities Decreased?

Most present-day astronomers grew up believing that disk galaxies had Keplerian velocities at moderate distances. The reasons for this belief are easy to identify. In the early 1900's, astronomers were more at home with the planets than with the galaxies. Slipher's early observations concerned the study of the planets, Percival Lowell's major interest. Galaxies were studied only to learn whether these nebulous disks in the sky were the stuff from which planets were formed. Slipher used Saturn as a radial velocity standard for his M31 spectra; he characterized the spectrum of the Sombrero galaxy as "planetary." Astronomers were predisposed to draw an analogy between the distribution of luminosity in a galaxy and the distribution of mass in the solar system.

Early spectral observations of galaxies generally did not extend beyond the bright nuclear bulges. Measured velocities usually increased with increasing nuclear distances and mass distributions were in the solid body domain. By 1950, only a handful of rotation curves had been determined, and astronomers were acting on their expectations when they "saw" a region of Keplerian falling velocities. Mayall (*42*) described his newly determined velocities in M33 as follows: "As in the Andromeda nebula, the results suggested more or less constant angular velocity . . . for the main body of the spiral. Beyond the main body these outer parts rotate more slowly . . . as in a planetary system where

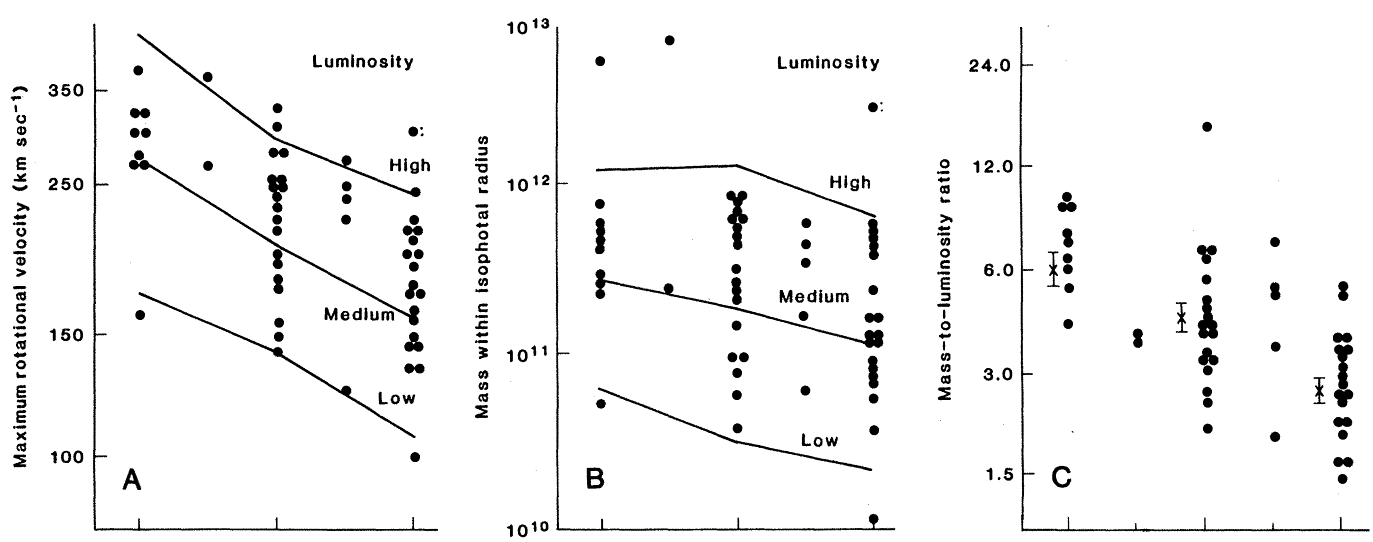

Fig. 3. (A) Maximum rotational velocity as a function of Hubble type for the galaxies studied. Lines show the increase in V_{max} with earlier Hubble type for galaxies of low, intermediate, and high luminosity. (B) Mass (solar masses) within the optical galaxy as a function of Hubble type. Within a Hubble type, higher velocity and higher mass indicate higher luminosity. (C) Mass-to-blue luminosity ratio (solar units) as a function of Hubble type. The mean value and the 1σ range are indicated. Within a Hubble type, there is no correlation of the mass-to-luminosity ratio with luminosity.

most of the mass lies inside the orbit concerned." De Vaucouleurs (*43*) reviewed the eight available rotation curves in 1959 and concluded, "In all cases the rotation curve consists of a straight inner part in the region of constant angular velocity up to a maximum at $R = R_m$ beyond which the rotational velocity decreases with increasing distance to the center and tends asymptotically toward Kepler's third law (Figure 27)." But with the 20/20 vision of hindsight, plots of the data reveal only a scatter of points, from which no certain conclusion can be drawn.

Yet not all astronomers were blind to the contradication posed by rapidly falling light distributions and nonfalling rotational velocities. In a classic paper discussing the structure and dynamics of NGC 3115, an almost featureless disk S0 galaxy, the ever-wise Oort (*44*) wrote, "It may be concluded that the distribution of mass in the system must be considerably different from the distribution of light." And he concluded, "The strongly condensed luminous system appears imbedded in a large and more or less homogeneous mass of great density." Schwarzschild (*45*), too, looked at the rotation curve of M31 and noted that "Contrary to earlier indication, the five normal points in Figure 1 do not suggest solid body rotation. . . . Rather, they suggest fairly constant circular velocity over the whole interval from 25′ to 115′ (5–25 kpc with the current distance)."

Indeed, the literature is replete with isolated comments stressing the same point. When in 1962 Rubin *et al.* (*46*) examined the kinematics of 888 early type stars in our Galaxy, they concluded that beyond the sun "the rotation curve is approximately flat. The decrease in rotational velocity expected for Keplerian orbits is not found." Shostak (*47*) noted that "the overwhelming characteristic of the velocity field of NGC 2403 is the practically constant circular rotation seen over much of the object."

Now that systematic studies indicate that virtually all spiral galaxies have rotational velocities which remain high to the limits of the optical galaxy, we can recognize the circuitous route which brought us to this knowledge. Astronomers can approach their tasks with some amusement, recognizing that they study only the 5 or 10 percent of the universe which is luminous. Future astronomers will have to be clever in devising detectors which can map and study this ubiquitous matter which does not reveal itself to us by its light.

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48. More complete references are contained in the literature cited. I thank my colleagues Kent Ford and Norbert Thonnard for their continued assistance and support in all the phases of this work and Drs. Robert J. Rubin, Robert Herman, Francois Schweizer, and W. Kent Ford, Jr., for wise comments on the manuscript.