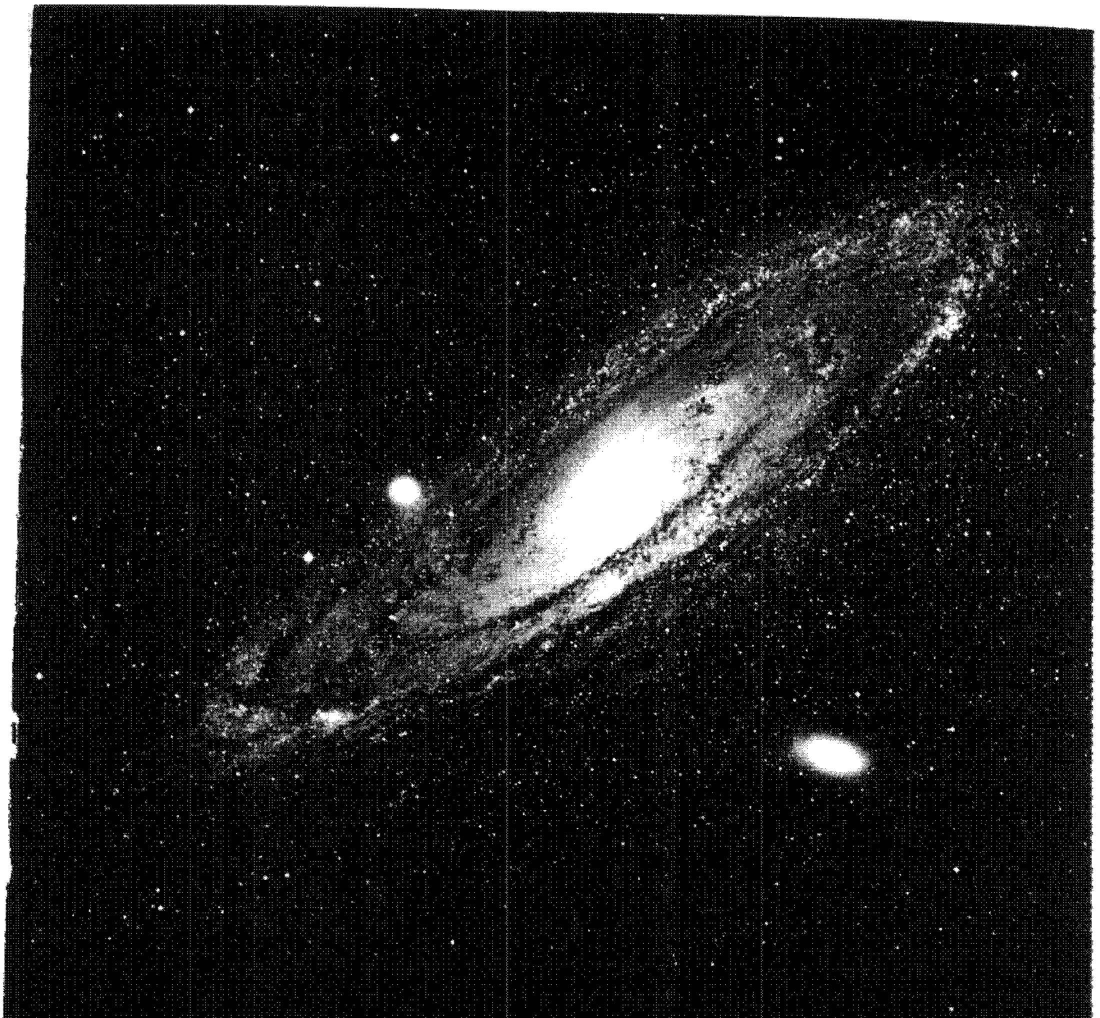

How Galaxies Rotate: Clues to Their Past?

How Galaxies Rotate: Clues to Their Past?

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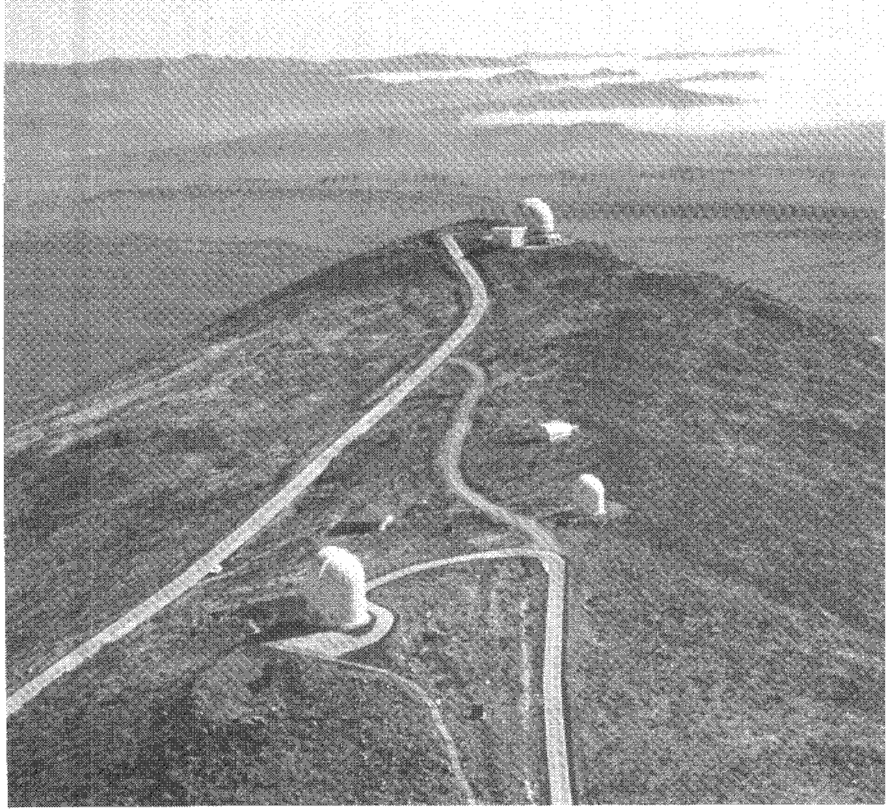
PREFACE

Since the discovery early in this century that beyond our Galaxy lie countless other galaxies, many scientists of many institutions have devoted their careers to studying these dominant units of our Universe. Our story sketches a part of this still-continuing adventure: we will examine the effort to detect and understand the internal motions of galaxies, and to apply such understanding to larger questions.

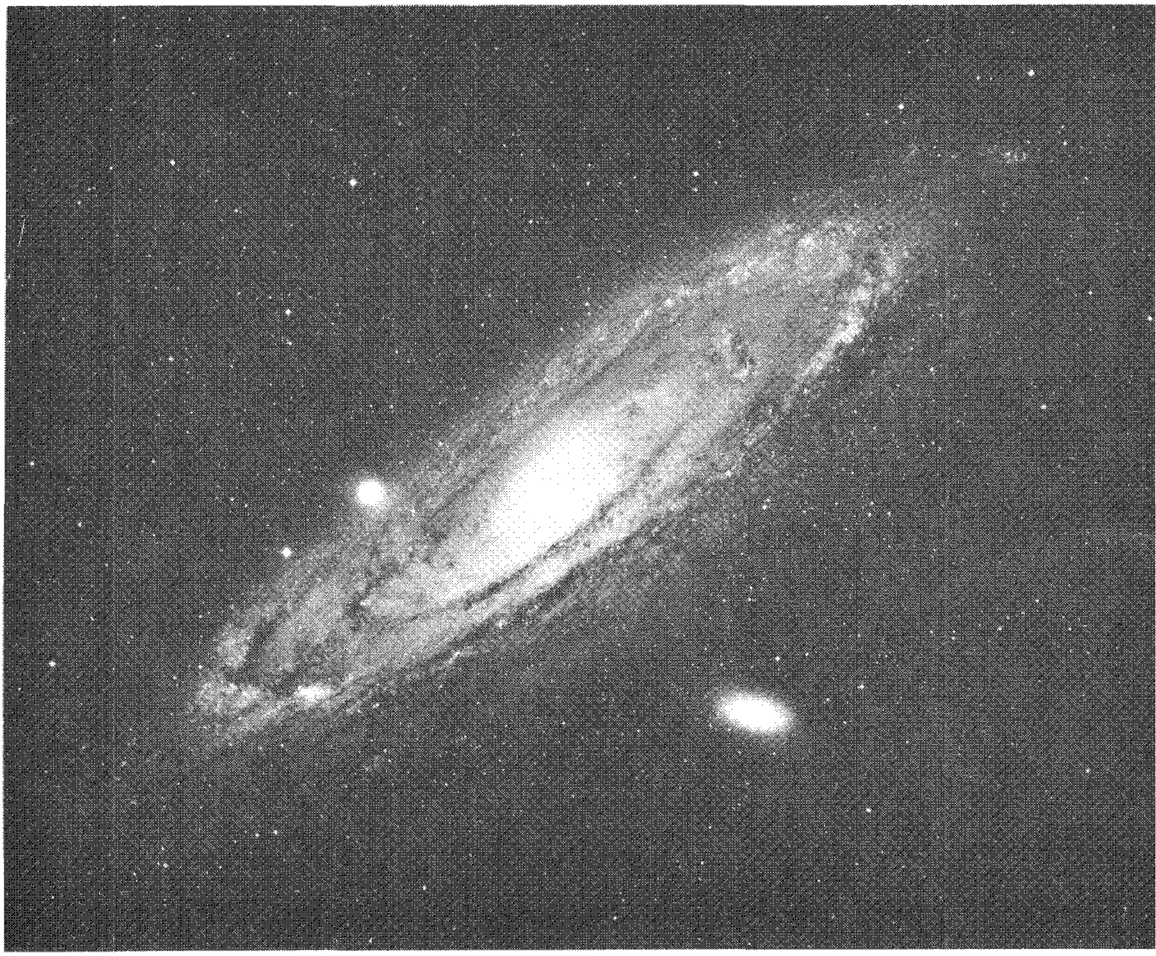
Students may find their acquaintance with the mechanics of Isaac Newton a useful starting point for this essay. Our account reaches beyond the scope of introductory physics textbooks, but the material should not be beyond the understanding of careful readers. Previous knowledge in astronomy is not needed.

It is to these readers—tomorrow's explorers of the Universe—that this series is dedicated.



Carnegie's Las Campanas Observatory, Chile

Contents



M31, the great spiral galaxy in Andromeda. M31 is the closest major galaxy to our own Milky Way Galaxy, which it resembles in form. (The same image appears on the front cover.)

Plato is my friend, Aristotle is my friend, but my better friend is truth. (*Amicus Plato amicus Aristoteles magis amica veritas.*)

Isaac Newton
Undergraduate student
University of Cambridge, 1666

The above words, written on a worn page of a student notebook, revealed that the notebook's owner was indeed an unusual youth. For Cambridge, like most universities of the 17th century, remained steeped in the outlook of the ancient scholars, whose approach to inquiry was largely nonquantitative. The prevailing view yet placed the Earth at the center of the Universe. But although the revolutionary science and mathematics of Kepler, Galileo, and Descartes had only lightly penetrated university thought, the young Isaac Newton, studying independently, had mastered the work of these giants and was prepared to go beyond.

At the age of 25, Newton made the crucial discovery that the force acting on a planet, keeping it from flying off into space, decreases with the square of its distance from the Sun. Later, Newton formulated his law of universal gravitation, which showed that the orbits of planets and moons were governed by the same forces that caused an object at the Earth's surface to fall to the ground. Meanwhile, Newton's three laws of motion—printed in his *Principia* in 1686 and often reprinted in today's physics textbooks—gave birth to the modern science of mechanics.

The same laws that explained the orbits of planets and moons helped astronomers of the early 20th century understand the motions of stars and decipher the structure of our own Milky Way Galaxy. A special problem were the spiral-shaped "nebulae," which looked suspiciously like collections of many stars. Were the nebulae part of our own Galaxy, or were they themselves galaxies beyond our own? The question was settled in 1925 by Edwin Hubble of the Mount Wilson Observatory, California, who confirmed that the spiral nebulae were indeed external galaxies, each an "island universe" like our own.

We shall examine the subsequent quest to understand the galaxies in one important area—the study of their internal motions. As we shall see, the motions of the stars and gas of a galaxy may form a strong, overall pattern of rotation, one rather easily detected by astronomers. But in other galaxies where star orbits are less uniform, orbital motions have been measured only recently, using the newest and most sensitive auxiliary instruments on large telescopes. Such observations, we shall find, are providing critical evidence on the history and basic nature of galaxies, indeed of the Universe itself. Throughout, Newtonian mechanics has remained a fundamental tool.

Much of the leading research on galaxy dynamics has been by scientists of the Carnegie Institution, and our review will look most closely at their work. A fuller account could easily fill a large book. Our examination, however, will show that the community of astronomers is worldwide, and that significant, new understanding about the Universe usually can be traced to contributions by many investigators at many institutions.

GALAXIES AND THE NATURE OF SPIN

A galaxy is a system of billions of stars (and varying amounts of gas, dust, and other largely unseen material), all gravitationally bound. The individual objects and particles generally orbit about the galaxy's center, their paths modified by gravitational interactions among one another. Most galaxies can be seen only by telescope; nearly all the points of light we see in the night sky are nearby stars of our own Galaxy. Traditionally, galaxies have been classified by their visible features under a system perfected by Edwin Hubble.

Among larger galaxies, the most numerous are the *spiral galaxies*—named for the bright spiral arms that often dominate their appearance. Spiral galaxies appear to have the general shape of a flattened disk, though they have a bright, sphere-like bulge, or nucleus, at the center, and are surrounded by a faint outer sphere, or "halo." In the Hubble scheme:

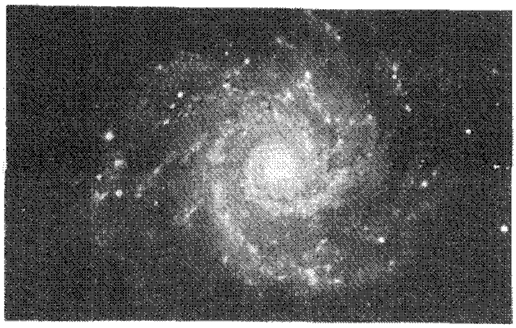
—Sc galaxies have highly developed spiral arms and small central bulges,

—Sb galaxies have less-pronounced spiral arms and medium-sized bulges, and

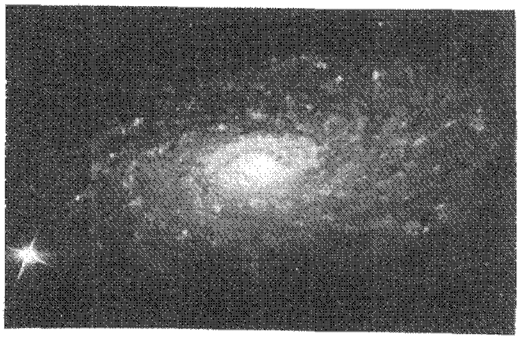
—Sa galaxies have faint spiral arms and very pronounced central bulges.

The pattern continues into the S0 galaxies, where the spiral arms are lacking and the central bulge predominates.

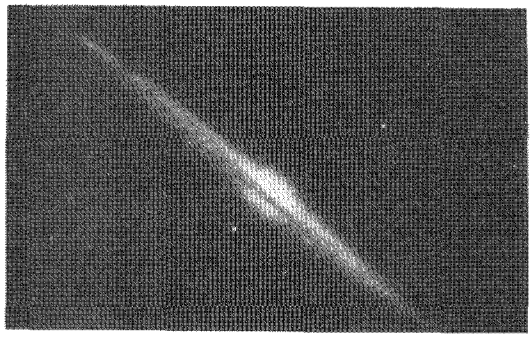
The characteristics of the S0's in turn blend into those of the second major galaxy type—the *elliptical galaxies*. The stars of ellipticals appear to be distributed in the shapes of somewhat-flattened spheres. Ellipticals are subclassified by the apparent extent of flattening.



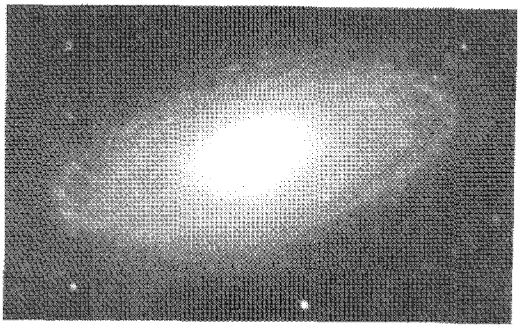
Sc



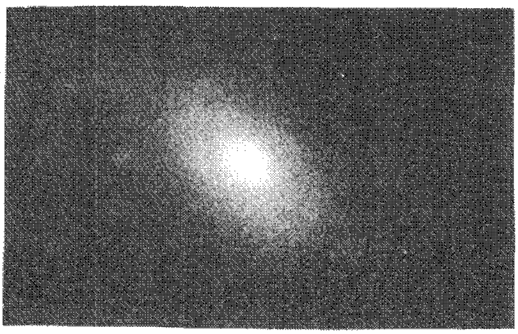
Sb



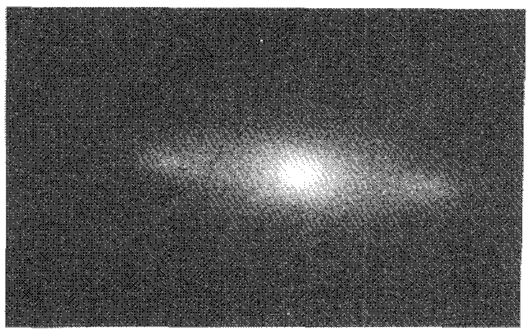
Sb (seen edge-on)



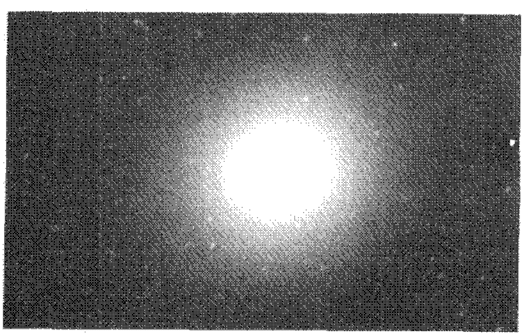
Sa



S0

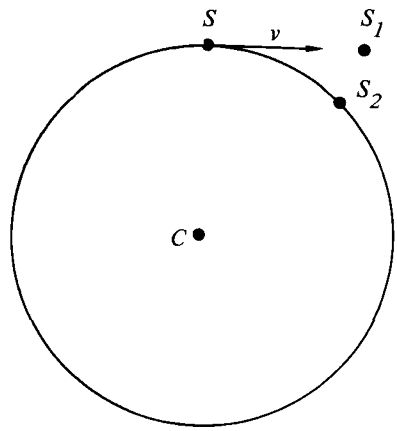


S0 (seen edge-on)



E

The Sc galaxy, at top, is dominated by its spiral arms, while the Sa galaxy's most prominent feature is its central bulge. The Sb is intermediate in this respect. Spiral arms are absent in the S0, which viewed from above resembles the elliptical (E) galaxy. The edge-on views of the Sb and S0 show the flattened shapes characteristic of disk galaxies. The halo regions are too faint to be seen in these pictures.



The instantaneous motion of object at *S* is shown by vector *v*. If the object is unaffected by any forces, it should reach position S_1. But if gravitational force acting inward provides the proper amount of centripetal force, then the object will follow a circular path to reach position S_2. If the gravitational (i.e., the centripetal) force is too large the object will fall inward to lesser radii. If the force is too small it will move outward to greater radii, perhaps to find elliptical orbit or—if the velocity *v* is large enough—to escape from the system.

Early on, astronomers suspected that the progression in galaxy type was evidence that a typical galaxy undergoes gradual change, perhaps evolving from the Sc type toward the elliptical or vice versa. Then for some decades, the notion prevailed that galaxies keep the same type forever. But as we shall see, a different concept is now emerging, in large part from determinations of motions within galaxies.

Galaxy Formation: A Conventional View

If a galaxy is a great collection of matter gravitationally bound, why does gravity not cause its entirety to fall together? Stated differently, how does a galaxy acquire and keep its shape?

The answer lies in the motions of the material composing the galaxy, and in the various masses, forces, and distances related to these motions—i.e., in the Newtonian mechanics. Simplifying, we can envision that a particle attains stable orbit about a galaxy's center of mass when the gravitational force acting on the particle provides the proper amount of centripetal force to keep it from departing into space. (A person exerts centripetal force when swinging an object on a rope; releasing the rope removes the centripetal force, and the object leaves its circular path.) The objects in a galaxy thus orbit the galaxy's center much as planets orbit the center of our solar system, although in galaxies the paths are influenced by interactions among the billions of components.

Most astronomers agree that original galaxies in some way formed by the coming together of highly dispersed gas in a gravitational collapse lasting millions of years. Conventional theory has held that during the inward collapse of a pre-galactic cloud, the speed of rotation increased until eventually the velocities, distances, and masses reached an equilibrium.

The forces became balanced, the rotational motions were preserved in the form of stable orbits, and the collapse ceased (see box below).

The theory explained how spiral galaxies formed. In the very earliest stages, the primitive movements of the material destined to form the galaxy were turbulent and haphazard—in many directions. During the collapse, the haphazard movements tended to be gradually smoothed, resulting in the formation of a rotating disk of gas and dust. Stars that formed in the disk, late in the collapse, thus retained the general rotation. The present rotation of a spiral galaxy's disk, then, is a summation of the original haphazard motions of all the captured particles across the direction of the collapse.

Scientists have found the overall picture inadequate, particularly for explaining the evolution of elliptical and other non-spiral galaxies. But for now, the idealized picture of cloud collapse and spin-up, sketched here, serves to guide our examination of the early explorations of the galaxies.

Gravity and Centripetal Force in Galaxies

An important concept is that of angular momentum, which can be thought of as the magnitude of rotation about a fixed point, in our case the center of a galaxy. The angular momentum of an orbiting object is the product of its mass m, velocity v (perpendicular to the radius), and distance r from the center of the system.

$$\text{Angular momentum} = m\,v\,r.$$

The total angular momentum of a rotating system is the sum of the angular momenta of all its matter. A system's total angular momentum cannot be increased or decreased unless the system is acted on by external forces. This law—Conservation of Angular Momentum—can be seen in the spin of a figure skater, who spins faster by drawing in his or her arms. The angular momentum is redistributed within the skater's rotational system. (The distance r from the skater's central axis is decreased and velocity v is increased, but the total angular momentum mvr is unchanged.) The Conservation of Angular Momentum accounts for the increased spin as the theoretical pre-galactic cloud collapses inward.

A few simple equations involving the m and v of a particle illustrate the physics of a collapsing and spinning cloud. Gravitational force drawing the particle inward is given by Newton's law of universal gravitation:

$$\text{Gravitational force} = \frac{G\,M\,m}{r^2},$$

where G is a gravitational constant and M the total mass of the cloud interior to the radius r of the particle (m is the mass of the particle). Early in the collapse, the gravitational force draws the particle inward.

As the spin-up proceeds, the particle's inward fall continues as long as the centripetal force provided by gravity is sufficient to overcome the "centrifugal" tendencies encouraging the particle to move outward. This amount is given in another equation derived by Newton:

$$\text{Needed centripetal force} = \frac{m\,v^2}{r}.$$

We may modify this equation into an expression of proportionality (omitting m, which is unchanging):

$$\text{Needed centripetal force} \propto \frac{v^2}{r}.$$

Since a particle's velocity v across the direction of collapse increases as radius r decreases (in inverse proportion, from Conservation of Angular Momentum),

$$\text{Needed centripetal force} \propto \frac{1}{r^3}.$$

Then, inasmuch as

$$\text{Gravitational force} \propto \frac{1}{r^2},$$

we see that the centripetal force needed to continue drawing the particle inward increases faster than the available gravitational force. Accordingly, at some radius the particle ceases its inward fall and conceivably enters stable elliptical or near-circular orbit.

In the conventional view, the collapse and orbit of many such particles is probably what produced each spiral galaxy we now see.

THE MILKY WAY AND ANDROMEDA GALAXIES

> There is a way on high, conspicuous in
> the clear heavens, called the Milky
> Way, brilliant with its own brightness.
> By it the gods go to the dwelling of the
> great Thunderer and his royal abode. . . .
>
> Ovid, *Metamorphoses*,
> Book 1, lines 168–176
> c. 8 A.D.

Across the night sky can often be seen that great belt of luminosity known to the ancients as the Milky Way. Today, we understand that when we look at the Milky Way, we are viewing the plane of our own Galaxy's disk, seen from our location inside the disk. Our "Milky Way" Galaxy is a typical spiral galaxy—an Sb or Sc in the Hubble scheme, having most of its luminous matter in a flattened disk. We know that our star and planet reside at the edge of one of the disk's spiral arms, about two-thirds of the way from the center to the apparent edge.

But this picture was not easily reached, for our interior vantage point made the shape and structure of our Galaxy difficult to fathom. Studying our Galaxy is like studying a dense forest from a single location deep inside.

Structure and Rotation of our Milky Way Galaxy

Although the disk-like shape of our Galaxy had been suspected earlier, not until about 1918 was it understood that the Sun is at the fringes, not the center, of the disk. This discovery was made by Harlow Shapley, then a staff member at Mount Wilson, by measuring the locations of the Galaxy's globular clusters. (A globular cluster is a nearly spherical collection of many stars; nearly 200 globulars have been found in our Galaxy.) Shapley developed what was in effect a three-dimensional map of the globular clusters. Reasoning that the center of the globular population should roughly coincide with the center of the Galaxy, he determined with remarkable accuracy the location of Galaxy Center and our location with respect to it. (See Fig. 1.)

How the Galaxy's disk rotated was determined in the 1920's by astronomers Bertil Lindblad in Sweden and Jan Hendrik Oort in the Netherlands, and later by Alfred Joy at Mount Wilson. The problem was not an easy one: the only star motions that are directly observable are motions toward or away from the observer. Further, because of the absorption of light by interstellar dust, the only stars that could be studied were nearby stars, situated in our own region of the Galaxy.

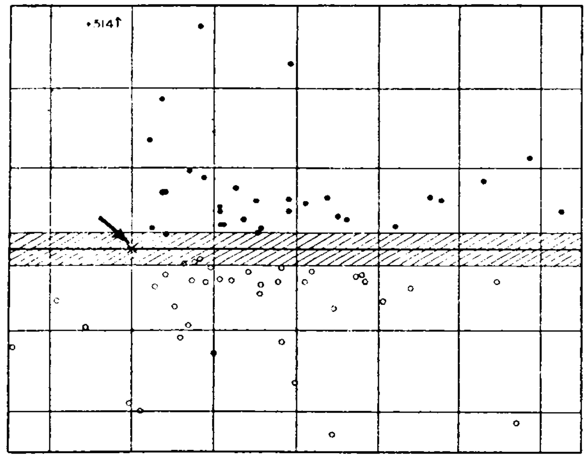


Fig. 1. Harlow Shapley's 1918 *projection of the positions of the* globular clusters of our Milky Way Galaxy, as if viewing the Galaxy from the side. The cross-hatched area represents the Galaxy's disk; the arrow indicates our own position. Most of the globulars lie in the Galaxy's halo, outside the disk. Shapley's map showed that the center of the positions of the globulars (presumably the Galaxy Center) is far removed from our own location. (Each large square is roughly 30,000 light years.)

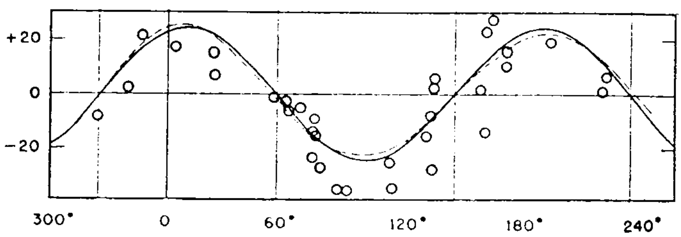


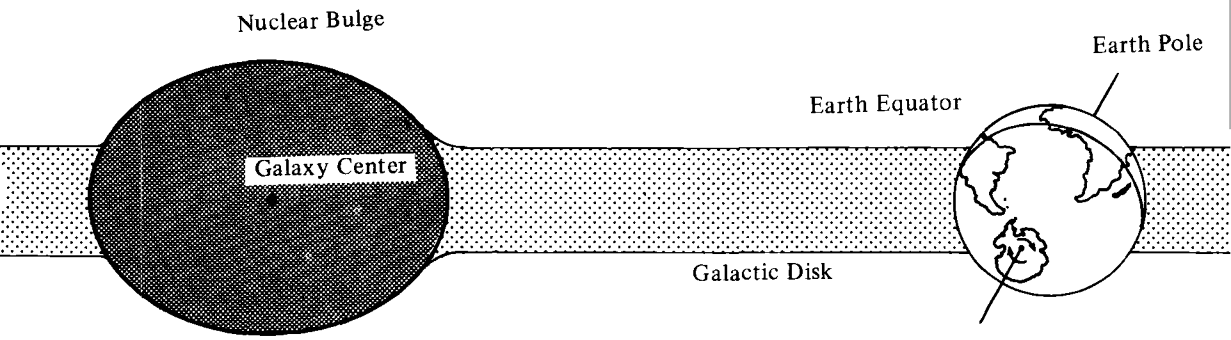
Fig. 2. One of Alfred Joy's curves from his 1939 study of the rotation of our Galaxy. The relative velocity of each star toward or away from us is plotted vs. each star's direction from us. Velocities + are toward the observer; velocities − are away from the observer. Stars seen exactly toward and exactly away from Galaxy Center (325° and 145°, respectively) should have no motion toward or away from us, since their rotational motion is parallel to our own. The motions of stars either side of 325° and 145° plot in opposite senses, confirming the Galaxy's rotation.

Without modern computers, the numerical work of determining the Galaxy's motion from the measurable data was vast, but Lindblad, Oort, and Joy each deduced the general nature of the Galaxy's rotation, as it is still understood. (See Fig. 2.)

The Team of Ford and Rubin

The contributions of Hubble, Joy, and other Carnegie Institution astronomers at Mount Wilson early in the 20th century was owed largely to the completion there of the 60-inch and 100-inch telescopes, each in turn the world's largest. But the principal work in studying spiral galaxy rotation was carried out by another Carnegie group—members of the Institution's Department of Terrestrial Magnetism (DTM), based in Washington, D.C.

The Department's name came from its early work in studying the Earth's magnetic field. After World War II, under its energetic director Merle Tuve, DTM took leadership in developing electronic devices for improving the sensitivity of



Our solar system including planet Earth lies in the disk of our Milky Way Galaxy, about two-thirds from the center to the visible edge. The Earth's spin, however, is severely inclined to the Galaxy's rotation. As the Earth spins, the Galaxy Center is seen directly overhead only at Earth latitude 29 degrees South (as in north-central Chile). In the United States, Galaxy Center lies low in the skies and can be viewed at night only in late summer, when the Sun is in the direction away from Galaxy Center. (The Earth is drawn vastly expanded in scale.)

The early investigators concluded that our Sun and planet rotate about Galaxy Center with a velocity of 200–300 kilometers per second at an orbital radius slightly above 30,000 light years (one rotation in about 200 million years). The approximate accuracy of these values is still generally accepted.

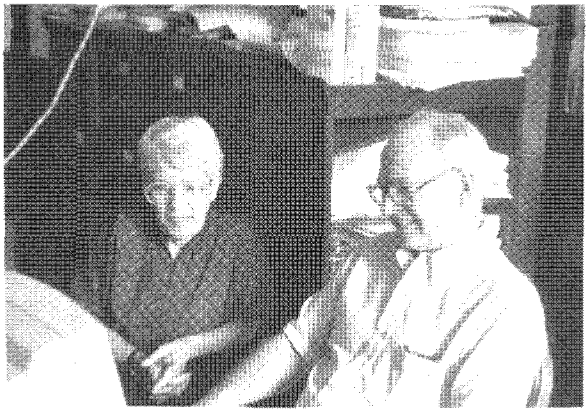
optical telescopes. The Carnegie Image Tubes, built by RCA, came into use at most of the world's major observatories, where they radically reduced the telescope time needed for observing faint objects. The Carnegie tubes were forerunners of today's remarkable family of image-intensifying devices, and some are still used in tandem with newer systems.

Closely identified with the image-tube effort was a talented physicist-astronomer, W. Kent Ford, Jr., who joined the venture while still a graduate student at the University of Virginia. Ford became a full-time staff member at DTM in 1957, and for several years thereafter spent most of his time working on the image-intensifier subsystems and spectrographs used with the tubes.

Joining DTM a few years later was Vera C. Rubin, a faculty member at Georgetown University. Image-tube development had reached a turning point, and director Tuve hoped that the staff would now show the way in using the equipment in actual research. The challenge proved a good match for Rubin's background: she had observed stars in studying the rotation of our Galaxy, and she had assisted in early studies measuring rotation in other galaxies. Now, Rubin and Ford worked together in using the image-tube equipment at several major telescopes.

The team worked well. Rubin later noted:

> Kent builds this exquisite equipment; we both observe and spend a lot of time cracking heads at the telescope; then I measure and reduce the spectra while he goes off to build more equipment.



Astronomers Vera Rubin and Kent Ford.

Rubin and Ford's "spectra" were obtained at the telescope by means of a spectrograph, which separates an object's light into a spectrum of its component colors, or wavelengths.* Readily seen in the spectra of spiral galaxies is the characteristic line of $H\alpha$, which is produced by emissions from excited hydrogen gas in regions of hot, young stars.

The wavelength at which $H\alpha$ is emitted is known. But if the emitting source is moving toward or away from us, we will receive the signal at a somewhat different wavelength. Consider: if a galaxy is moving *away* from us, we receive fewer wavelengths per unit time, and the characteristic wavelengths will appear to be slightly shifted toward the red. In reverse, the light of a body moving *toward* us is shifted toward the blue. The wavelength shifts are the result of the Doppler effect—the same phenomenon that causes the pitch of a train whistle to change as it passes abreast of a listener. By determining the Doppler shift of the received $H\alpha$ signal (or any other recognizable feature in an object's spectrum), astronomers can determine the source's velocity toward or away from us.

The Doppler effect allows astronomers also to measure rotation in spiral galaxies seen nearly edge-on. The rotation causes light from the side of the galaxy turning away from us to be redshifted, while light from the side turning toward us is blueshifted. The faster the rotation, the larger the shifts.

For their first major investigation using the image tubes with Ford's instruments, Ford and Rubin chose to study rotation in a convenient neighbor, M31, our Galaxy's magnificent sister.

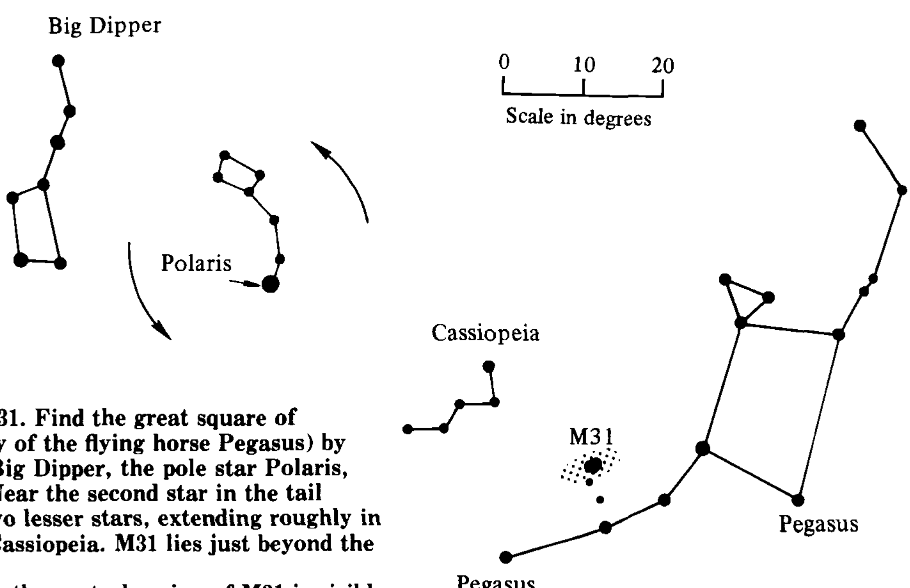
* We can think of light as a wave, which is emitted at a source and which travels at a speed of roughly 300,000 kilometers per second. The light's wavelength is the distance between successive crests. When we look at a rainbow, we see a spectrum of the visible wavelengths of sunlight.

The Andromeda Galaxy, M31

The great galaxy in Andromeda, M31, 2.2 million light years from us, is the closest major spiral to ourselves. Comparable to the Milky Way Galaxy in size and shape, M31 is classed an Sb galaxy, having moderately developed spiral arms. Although only its central region is visible to the unaided eye, because of its closeness its disk viewed by telescope occupies a large arc on the sky—about four degrees. (The diameter of the full Moon is about half a degree.) The disk of M31 is seen inclined about 20 degrees from edge-on. (See Frontispiece, page 4.)

By 1969, Ford and Rubin had obtained spectra from 67 regions in M31. Each observation required long preparations and several hours of telescope time. In Figure 3 are plotted their early measurements of rotational velocity (from wavelength shifts) vs. radial distance from the galaxy's center. The evidence of rotation was clearcut: wavelength shifts on one side of M31 were mirrored by opposite shifts on the other. The peak rotational velocity was more than 200 kilometers per second.

Ford and Rubin found that M31's rotational velocities remained high at large radii. This was a puzzling result, for



How to view M31. Find the great square of Pegasus (the body of the flying horse Pegasus) by referring to the Big Dipper, the pole star Polaris, and Cassiopeia. Near the second star in the tail of Pegasus are two lesser stars, extending roughly in the direction of Cassiopeia. M31 lies just beyond the second.

On dark nights, the central region of M31 is visible by unaided eye. With binoculars, about two degrees of the disk can be seen; with telescope, about four degrees.

(The arrows encircling Polaris indicate the apparent daily rotation of the sky caused by the Earth's spin.)

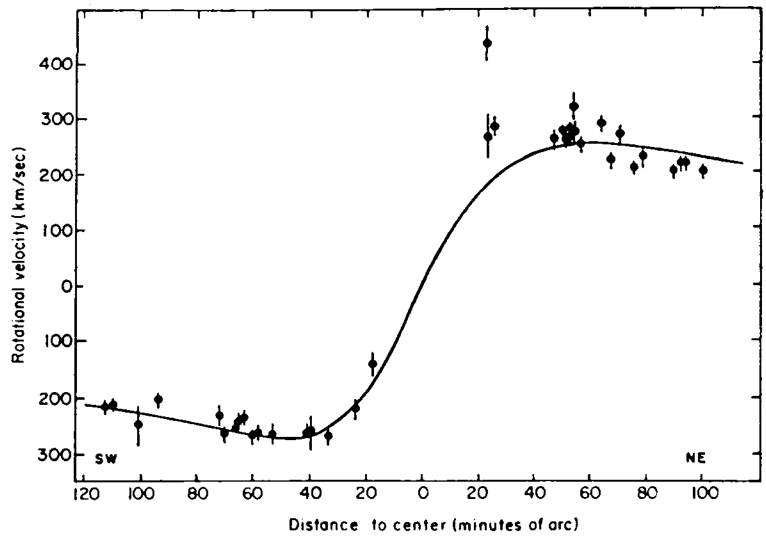


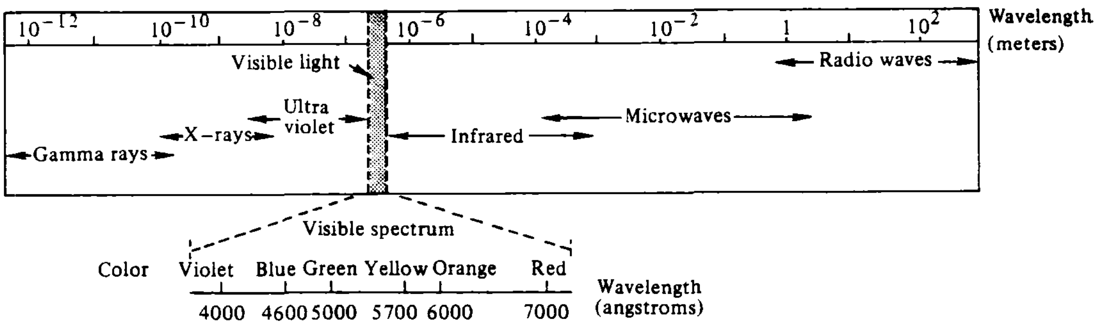
Fig. 3. The plotted points are measurements of rotational velocity in the plane of M31, the Andromeda galaxy, by Ford and Rubin, 1969. The marked change in velocity across the nuclear region is clearly evident. Beyond the central region, rotational velocity decreases only slowly with radius. The Ford-Rubin results in the optical accorded well with earlier results in the radio wavelengths, shown in the solid curve.

the concentration of observable material toward M31's center indicated that the rotational velocities should drop off rapidly. Ford and Rubin would later return to this puzzle in studies of other spiral galaxies; meanwhile, evidence confirming that their M31 results were sound was already at hand, from observations in a very different region of light—the radio wavelengths.

The Early Radio Astronomers

Humans can see light only in the "optical" wavelengths—from the blue-violet (4×10^{-7} m) to the red (7×10^{-7} m). But astronomical bodies emit radiation over a vastly greater range of wavelengths. At wavelengths just shorter than the blue-violet is the region of the ultraviolet, and just longer than the visible red is the region of the infrared. For the most part, our atmosphere blocks ultraviolet and infrared from reaching the Earth's surface. Thus, until a few decades ago, our only view of the Universe was through the narrow window of visible light.

A second window opened in about 1950, when scientists detected radiation at 21 centimeters, beyond the far infrared, emitted by neutral hydrogen atoms in interstellar clouds.



The Electromagnetic Spectrum

Although the resolution of images obtained at the "radio" wavelengths was poor except with grossly large telescopes, it was now possible to study matter never before observed.

Under Tuve, scientists at DTM quickly entered the new field of radio astronomy. Working with a DTM-built receiver at the nation's large radio telescope at Green Bank, West Virginia, DTM investigators studied the 21-cm hydrogen emissions of M31 and several other nearby galaxies. They observed shifts in wavelength similar to those later seen in the optical by Ford and Rubin. Evidently the neutral hydrogen of M31 studied by the radio astronomers and the ionized gas studied in the optical rotated at about the same velocity.

Especially significant results were reached by Harvard radio astronomer Morton Roberts, whose measurements of rotational velocities in M31 extended to radii even greater than those later obtained by Ford and Rubin. Roberts determined that the rotation curve of M31 was clearly flat—i.e., the velocities remained high to extreme radii. But neither Roberts nor Ford and Rubin were yet willing to venture that this phenomenon might characterize spiral galaxies generally.

ROTATION IN A POPULATION OF SPIRALS

Kent Ford continued to work with personnel of RCA to improve the resolution and sensitivity of the image tubes. In the early 1970's, he installed second-generation tubes at the new, 4-meter optical telescopes of the U.S. National Observatories at Kitt Peak, Arizona, and Cerro Tololo, Chile. Then in 1975, having shifted their research to other questions for several years, Ford and Rubin returned to galaxy rotation.

For their new study, they selected sixty isolated spiral galaxies of types Sa, Sb, and Sc; their sample included galaxies of high and low luminosity within each type. They hoped to

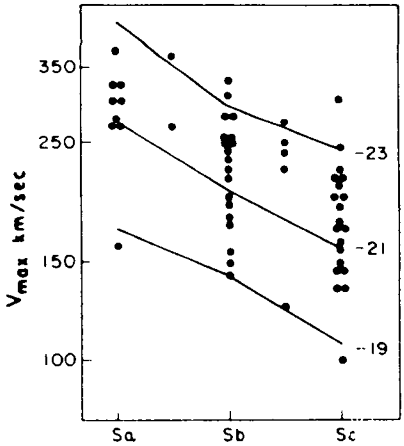


Fig. 4. Peak rotational velocities in galaxies measured by Ford and Rubin, plotted according to galaxy type Sa, Sb, and Sc. Several galaxies of intermediate type Sab and Sbc are also shown. The solid lines represent galaxies of high, medium, and low luminosities. (The larger the negative magnitude, the brighter the galaxy.) Galaxies of high luminosity are seen to be fast rotators. Ford and Rubin's data showed that in determining absolute luminosity from rotational velocity, an allowance must be made for galaxy type. (The absolute blue luminosity of a galaxy rotating at 210 kilometers per second would be about minus 20 if an Sa, minus 21 if an Sb, minus 22 if an Sc.)

study how the rotation varied with various other properties in spiral galaxies.

Their method differed in one respect from that used earlier in studying M31. Because most spirals, unlike nearby M31, occupied only a small arc on the sky, a slit of light from a galaxy's entire visible length could be passed into the spectrograph. Thus a single photographic plate served to record the Hα signal, displaced according to wavelength shift, all along a galaxy's length. A galaxy's rotation could be recorded at all radii in a single observation requiring only about three hours of telescope time.

Each dot on the adjoining Figure 4 represents the peak rotational velocity of one of the galaxies sampled. Generally, the Sa galaxies have high peak velocities, and the Sc's have low peak velocities. The Sb's fall in between. The three solid lines, which represent galaxies of high, medium, and low luminosities, respectively, show that the more luminous (and generally larger) galaxies have higher peak velocities.

Ford and Rubin used their data to test a recently proposed relationship, where peak rotational velocity serves as an indicator of a galaxy's intrinsic, or true, luminosity. (A galaxy's true luminosity if known can be compared with its apparent luminosity as seen by us, thereby indicating its distance from us.) Ford and Rubin's results supported the velocity–intrinsic luminosity relation, but they showed that in applying the relation it was necessary to take into account a galaxy's Hubble type—whether Sa, Sb, or Sc.

But the most interesting revelations in Ford and Rubin's work went back to the puzzling rotation curves found by Roberts and by Ford and Rubin in studying M31. The new observations showed that rotational velocities remained high to large radii not only in M31 but indeed in all spiral galaxies. It was an astonishing result, one that severely challenged the existing understanding of the nature of galaxies and is therefore worthy of our closer examination.

Mass Distribution in Spiral Galaxies

We have noted that a system of orbiting particles and objects attains equilibrium when the gravitational forces acting on the components are exactly sufficient to provide the necessary centripetal force. Borrowing our earlier Newtonian expressions (see box, page 9), we can write the simple relation

gravitational force = needed centripetal force, or

$$\frac{G\,M\,m}{r^2} = \frac{m\,v^2}{r},$$

where m is the mass of an orbiting object, r is the radius of its orbit, M is the total mass inside that radius, and v the rotational velocity (for an assumed spherical mass distribution). G is the gravitational constant. Note that in solving the above, m drops away and the expression is reached

$$M = \frac{v^2\,r}{G}.$$

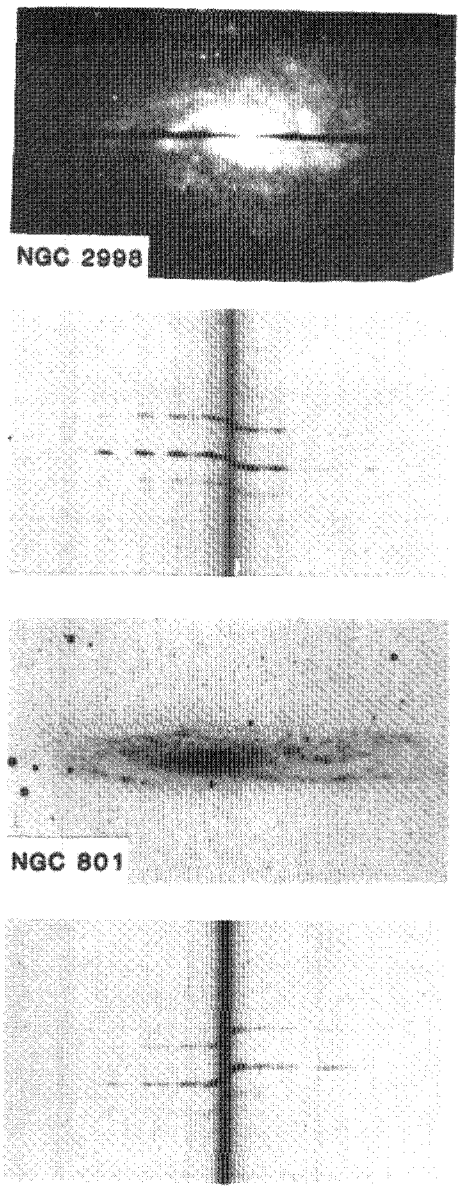
This was the relation used by Ford and Rubin to determine the masses of galaxies from the measured velocities. But also, since velocity at any radius was determinable, the mass interior to any radius could be found (assuming spherical form and the near-circularity of orbits in the disks of spiral galaxies). Thus, the *distribution* of the galaxy's mass could be learned.

It would seem that the mass of a spiral galaxy should be distributed in much the same way as its luminosity. Most of the galaxy's mass should be where the galaxy is brightest (i.e., toward the center), and the distribution of mass should drop off substantially in the disk's fainter outer regions. If so, then rotational velocity would drop off as radius increases, as in the solar system.*

But in the sixty spirals of their sample, Ford and Rubin obtained a different result. In all cases, instead of dropping off rapidly like luminosity, rotational velocity remained high all the way to the galaxy's visible edge. The *density* of mass fell off, to be sure, but at a rate much lower than the decline in luminosity. (See Fig. 5.)

It was difficult to challenge the conclusion that more mass is present in the outer regions of spiral galaxies than can be accounted for by the luminous matter in these regions. It

* In our solar system, essentially all the mass is concentrated within the Sun. The expression M is therefore the same at all orbital distances, so the squares of the velocities of the planets should be in inverse proportion to their radii. This is indeed the case.



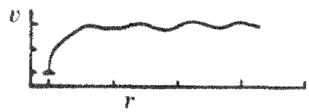
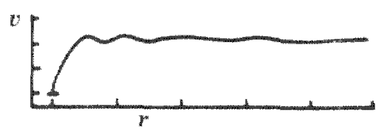


Fig. 5. Photographic images and spectrographic plates of two spiral galaxies. As placed on this page, the centers of the galaxies on the images are directly above the centers of the spectra; either side of center, spectral features correspond to the galaxy regions shown directly above. The displacements of the characteristic spectral lines either side of center are wavelength shifts caused by galaxy rotation. Precise measurement of the plates enables determination of rotational velocity at any radius, as plotted at right.



appeared that large amounts of nonvisible mass must lie beyond the edges—i.e., in the outer halos.

What is the nature of this unseen mass, and what is its full extent? These questions are attracting many scholars, for the answers may have major implications well beyond the nature of galaxies. If, for example, our Universe contains vast quantities of nonluminous material, there may be enough total mass to cause the Universe—known to be expanding—one day to cease its expansion and begin collapsing back upon itself. It is a fundamental uncertainty facing today's cosmologists.

Halo Stars: Keys to How Spirals Formed?

The halo regions were of interest also in studying how spiral galaxies formed. In the conventional view, halo stars were formed early in the collapse of the pre-galactic cloud (or perhaps even before the collapse). That halo stars are generally older than disk stars was confirmed by spectrographic work showing their chemical compositions. Since a star now seen should retain the rotational momentum of the gas and dust at the time of its formation, it seemed that the orbits of halo stars should differ substantially from the systematic rotation seen in the later-forming disks.

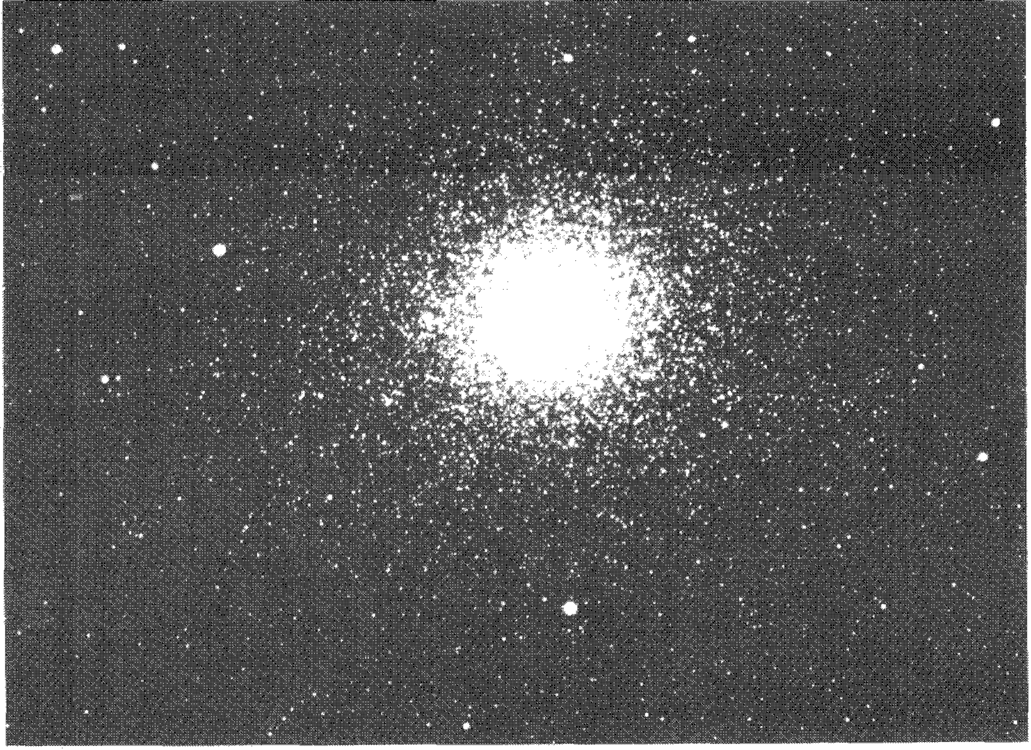
Both in our Galaxy and M31, the globular clusters are most characteristically found in the halo regions. In 1983, several astronomers began a study measuring motions of the globular clusters in M31. The investigators were Stephen Shectman, Leonard Searle, and postdoctoral fellow Peter Stetson, all members of Carnegie's Mount Wilson and Las Campanas Observatories. Using the newest detector produced by the ingenuity of Shectman, and observing at Caltech's 5-meter telescope at Palomar, near San Diego, the investigators were able to pick out individual globulars in M31.

With a sample population of over 100 halo globulars of diverse chemical compositions, the investigators showed that the general rotation of the halo-globular system of M31 is weak, though measurable. The mean rotational velocity of the halo globulars is only 60 kilometers per second—in the same direction as the rotation of the disk but only one-fourth the disk's velocity. The variations in orbital velocity among the individual globulars are very large, however, and nearly a third of them orbit in the reverse direction.

In their analysis, the investigators attempted to correlate two properties: (1) the orbital velocity of a globular cluster and (2) its heavy-element content—i.e., its content in elements heavier than hydrogen and helium. (Stars that formed late in the evolution of a galaxy are believed to be rich in the heavy elements.) Thus if clusters rich in heavy elements (i.e., late-forming clusters) proved to be rapid rotators, this would support the conventional picture where galaxies formed in collapsing, spinning-up clouds.

Shectman, Searle, and Stetson, however, failed to find such a relationship in M31. Could this be evidence, Searle wrote, that the conventional view of galaxy formation is inaccurate? Perhaps, he continued, the globulars were formed in earlier "protogalaxies."

Other investigators have asked similar questions of halo stars in our own Galaxy. One of them is Allan Sandage, who in developing the conventional view of galaxy formation two



The globular cluster Omega Centauri, photographed at the du Pont telescope at Las Campanas. To the unaided eye, a globular cluster is a single point of light, indistinguishable from a single star. Harlow Shapley in 1919 used the globulars of our Galaxy to ascertain the location of Galaxy Center. In recent years, the motions of the globulars of our Galaxy and M31 have been studied for clues to events during galaxy formation.

decades ago relied heavily on evidence from stars of our Galaxy's halo. In 1984, Sandage reported new results from a long-term study of a large sample of nonglobular halo stars, conducted at Mount Wilson. Sandage again found a strong correlation between orbital velocity and heavy-element content. In the same year, Robert Zinn of Yale University (previously a postdoctoral fellow at Pasadena) reported that the late-forming, heavy-element-rich globulars of our Galaxy form a spinning disk, while the older, heavy-element-poor globulars form a spherical cloud having little spin. Thus the new results of both Sandage and Zinn reinforced the view that our Galaxy formed from a collapsing cloud.

How can we account for the velocity-composition relation among halo stars in our Galaxy and its absence in M31? The answer is probably that although M31 and our Galaxy are similar in many respects, they differ in various important properties, perhaps in the details of their formation. The meaning of the present data remains unclear, but the recent M31 results at least call to question any generalized picture of spiral galaxy formation based mainly on studies of our own Galaxy.

Many astronomers nevertheless believe that the weight of evidence supports the conventional picture of spiral galaxy formation. But the situation is quite different for galaxies of other types. Favored by instruments and computing systems of remarkable power, today's astronomers are turning their attention increasingly to the elliptical and S0 galaxies.

THE ELLIPTICAL AND S0 GALAXIES

On shady Santa Barbara Street in Pasadena, beneath the heights of rugged Mount Wilson ten miles away, stands a cluster of white-stucco buildings. It is the headquarters of Carnegie's Mount Wilson and Las Campanas Observatories. It was here that Shapley, Hubble, and Joy did much of their historic work. Here are the offices of Allan Sandage, who as a young man served under Hubble, and the offices of several younger astronomers who are now, like Sandage, working at the forefront in studying the galaxies.

It is a lively group—all colleagues, all rivals, all intensely absorbed in their work. Paul Schechter, who graduated from the Bayside High School, New York, earned the bachelor's degree in physics and mathematics at Cornell, the Ph.D. in physics with a minor in astronomy at Caltech. His mind tends to the unorthodox, the unconventional interpretation, and he believes that this outlook serves to challenge himself and others to explore lines of thought easily overlooked.

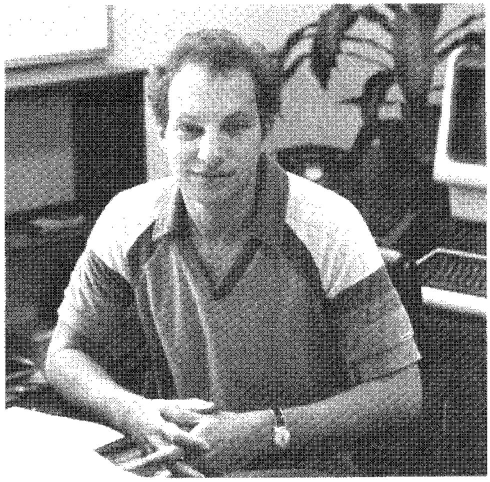
Alan Dressler, too, is a product of the nation's public schools. During boyhood in Cincinnati, fascinated by the night skies, Dressler built several working telescopes. One still detects the enthusiasm that once produced a working observatory on the roof of his parents' home. Dressler obtained the B.A. in physics at Berkeley and later the Ph.D. at the Lick Observatory of the University of California at Santa Cruz. Dressler and Schechter are of the new generation of scientists, who are expected to continue Carnegie Institution's tradition of leadership in astronomy.

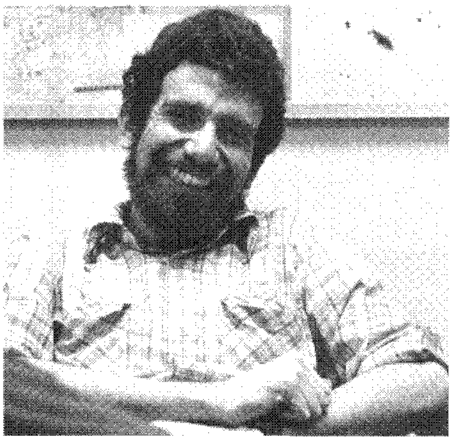
The Carnegie astronomers travel once or twice a year to the desert-and-foothill country of north-central Chile. There, at a ridge called Las Campanas ("the bells"), Carnegie Institution operates its superb 2.5-meter Irénée du Pont telescope. While the historic telescopes at Mount Wilson are today handicapped by the bright lights of Los Angeles, Las Campanas provides a dark-sky observing site of unsurpassed quality.

As our story turns to the elliptical and S0 galaxies, the plot intersects the research of Schechter and Dressler.

Learning About Motions in Ellipticals

An elliptical galaxy contains billions of stars, all gravitationally bound in various orbits about an overall center of mass. Some ellipticals are nearly spherical, but most of them appear to





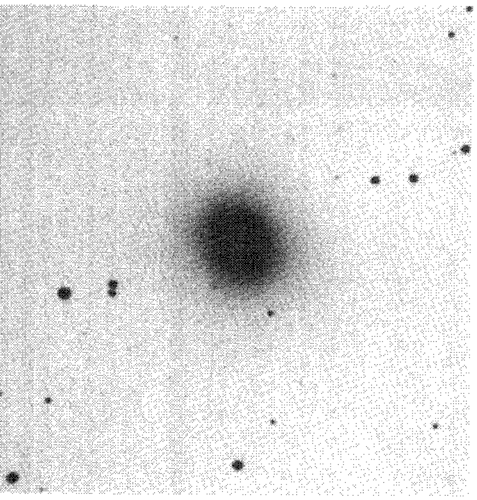
***Top left*: Allan Sandage with DTM astronomers John Graham and Vera Rubin. *Lower left*: Paul Schechter. *Above*: Alan Dressler.**

some degree flattened. Because we see objects on the sky in only two dimensions, we cannot tell the true ellipticity: an elliptical galaxy can be no rounder than it appears, but it can be flatter by any amount.

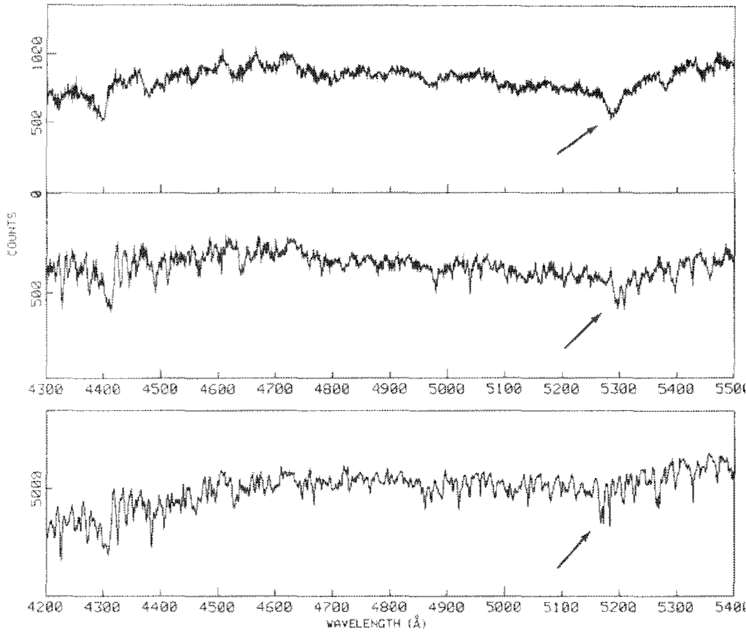
To astronomers two decades ago, the flattening of ellipticals seemed to suggest that they rotated, perhaps somewhat like the disks of spirals. But until recently, rotation was difficult to study in ellipticals, since ellipticals largely lack ionized hydrogen gas—the source of the Hα emission usually used in studying rotation in spirals.

Investigators in Italy in 1975, working from weak stellar absorption lines, became the first to publish a rotation curve for an elliptical galaxy. Their result—that the giant elliptical galaxy under study exhibited very little ordered rotation—came as a suprise to many. But astronomers soon learned that although the rotational tendencies in ellipticals were weak, it was possible (given improvements in the sensitivity and discrimination of detectors) to detect, measure, and analyze such motions.

Among those interested in the motions of ellipticals were the Americans Garth Illingworth (then at Berkeley as a postdoctoral fellow and later at the Kitt Peak National



Elliptical Galaxy IC3370



How velocity dispersion is seen spectrographically. The upper and middle traces are spectra from two elliptical galaxies having different velocity dispersions. The star spectrum at bottom has zero velocity dispersion.

Comparing the three spectra, the various rises, dips, and other features are least clearcut in the upper trace, where a general effect of broadening is evident to the eye. This galaxy therefore has a high velocity dispersion: i.e, the individual orbits of its many components are highly varied. The galaxy of the middle trace has a lower velocity dispersion.

The arrows point to an *Mg* absorption line seen in each spectrum; this absorption region occupies a wider wavelength band and its features are least clearcut in the upper spectrum, indicating high velocity dispersion. In each galaxy spectrum, the Mg line is seen shifted in wavelength because of galaxy recession.

Observatory), Paul Schechter (then of the University of Arizona), and James E. Gunn at Caltech. These investigators often worked with a different measure of orbital motion—the *velocity dispersion*. The velocity dispersion is obtained spectrographically, by analyzing the broadening of a galaxy's characteristic spectral lines. If the line-broadening is great, there are large variations in the orbital velocities among the galaxy's many stars, and the total energy of motion is relatively large. A powerful numerical technique for the analysis was devised by Schechter in 1976 and remains in general use.

Illingworth, Schechter, and Gunn—sometimes working independently, sometimes collaborating—investigated the ratio between ordered velocity (i.e., rotation) and random velocity (indicated by velocity dispersion). The ratio was in effect a measure of the rotational tendency. Although the observational work was very difficult, the investigators found that the ratio tended to correlate statistically with apparent flatness—galaxies with high ratios (i.e., strong rotational tendencies) tended to be flatter, especially among faint

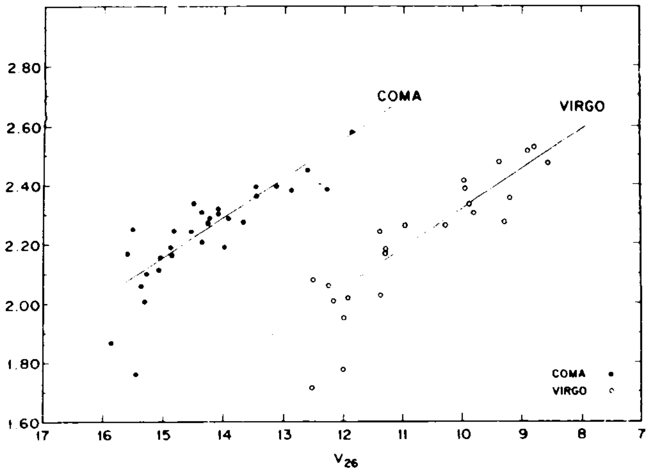


Fig. 6. Dressler's exploration of the Faber-Jackson relation linking velocity dispersion and the luminosity of elliptical galaxies. Shown here is Dressler's plot of velocity dispersion σ (log) vs. the apparent visual luminosity V_{26} of elliptical galaxies in the Coma and Virgo clusters. The velocity dispersion–luminosity relation is evident in each cluster. (Because all galaxies of any cluster are at about the same distance from us, the apparent luminosities shown here are representative of the absolute luminosities.)

ellipticals. The result seemed to suggest a possible method for determining the true shapes of ellipticals. Further, since the nuclear bulges of spiral galaxies behaved similarly, it suggested that ellipticals and spirals might not be as different as they seemed.

Schechter and postdoctoral fellow Robert Jedrzejewski recently initiated another, slightly different approach to the question of elliptical galaxy shape and inclination. They are attempting to measure rotational motions along the apparent minor axes of ellipticals. The velocities are probably small, they note, perhaps only about 20 kilometers per second, but if they can be accurately determined they can be statistically applied against major-axis rotation to indicate the intrinsic shapes and inclinations. An important input must be the precise directions of the apparent minor axes, which are being obtained by measuring the distribution of light in images of the galaxies. The work is still in progress.

Velocity measurements in ellipticals are also helping solve another problem, that of obtaining distances to galaxies. In 1976, astronomers Sandra Faber (once a student assistant and postdoctoral fellow at DTM and now a staff member of the Lick Observatory, California) and her student Robert Jackson showed that the velocity dispersions of ellipticals correlated with their luminosities. This Faber-Jackson relation yields an elliptical's true luminosity, which if compared with apparent luminosity provides an indication of distance.

Alan Dressler, who was once a student of Faber's, has tested the Faber-Jackson relation. In 1983, he reported systematic observations of several dozen ellipticals, all located in the Virgo cluster or the more distant Coma cluster of galaxies. The results are shown in Figure 6, where each galaxy's velocity dispersion is plotted against its apparent luminosity. (Since in each cluster, all galaxies are at essentially the same distance from us, apparent luminosity serves to represent true luminosity.) In Coma and in Virgo, Dressler showed that velocity was directly related to luminosity, and the Faber-Jackson relation seemed confirmed. Indeed, the correlation was tighter in Dressler's data from cluster galaxies than in earlier studies of noncluster galaxies. Dressler noted that his avoidance of adjustments for distance may have accounted for his tighter result.

Do ellipticals, like spirals, have large amounts of nonvisible matter? Evidence on the question is yet fragmentary. Dressler, in studies measuring velocity dispersion in particular regions of ellipticals, detects high dispersion (and therefore substantial energy of motion) well away from the galaxy centers. Furthermore, where rotation has been measured along the radii of ellipticals in other studies, velocity seems to remain high in outer regions. Both results seem to indicate that substantial nonvisible mass is present well away from the centers of elliptical galaxies.

What About S0's?

S0 galaxies appear intermediate in form between Sa spirals and those ellipticals that are highly flattened. Indeed, an S0 whose central bulge blends closely into its outer disk is hard to distinguish from an elliptical. Like ellipticals, S0's generally lack hydrogen gas and exhibit little star-forming activity. Astronomers naturally wondered whether S0's were perhaps transitory forms—spirals evolving into ellipticals, or vice versa.

Alan Dressler and Allan Sandage have investigated such questions by measuring rotational velocity and velocity dispersion in a population of S0's. Their observations—made difficult by the same problems seen in studying ellipticals—were conducted mainly at Palomar and Las Campanas.

In a 1983 paper, Dressler and Sandage reported their observations of 27 S0's. Their data generally seemed to show that the disk regions rotated much like Sa, Sb, and Sc spiral galaxies, and that the central bulges also rotated, indeed more strongly than the ellipticals that they resembled. Their stronger rotation thus seemed to distinguish S0's from ellipticals and suggested that despite the similarities, S0's and ellipticals must have evolved differently. Dressler and Sandage also showed that their S0's loosely behaved like ellipticals in their velocity dispersion–luminosity relation (the Faber-Jackson relation), and like spirals in their rotational velocity–luminosity relation.

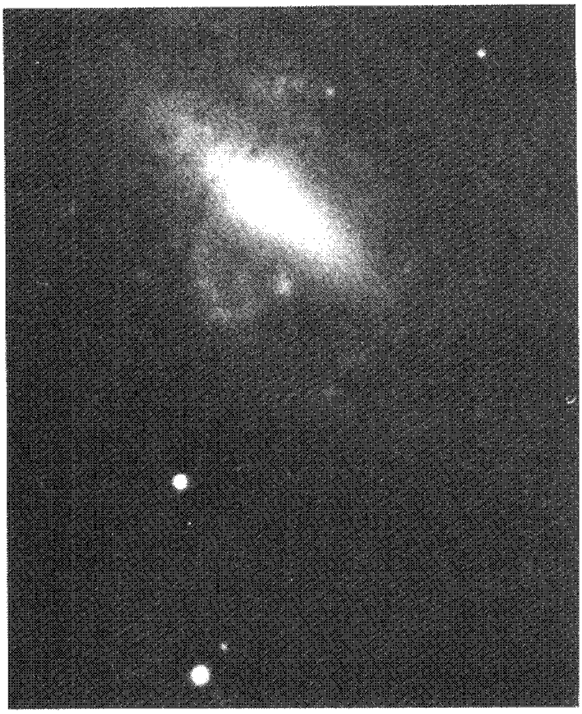
The Dressler-Sandage results do not answer in full the basic nature of S0's, but they provide evidence that must be taken into account in the development of future models.

The Unusual Polar-Ring Galaxies

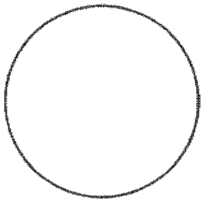
The question of the true shapes of ellipticals was addressed in certain recent mathematical models, which argued that some orbiting systems could be elongated, like a football or a cigar. Thus, there might be a progression in the shape of ellipticals (and S0's)—from the extreme flatness of a pancake all the way to the shape of a cigar. Because sky objects are seen in only two dimensions, anything that looks like a cigar also looks like a pancake viewed edge-on. And a round image can be either a pancake seen from above or a cigar seen from the end. Indeed, an elliptical could be triaxial—of unequal length along all three axes. The Schechter-Jedrzejewski work had been designed to address this question.

As of the mid-1970's, no cigar-shaped galaxy had yet been positively identified. Thus there was great interest in a small class of galaxies that looked suspiciously like cigars.

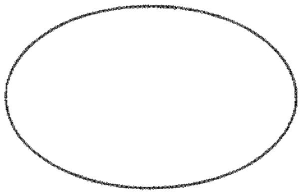
The first-known such galaxy, NGC 2685, had been seen by Hubble and later described in Allan Sandage's 1961 classic, *The Hubble Atlas of Galaxies*. Its image looked much like that of a normal S0 galaxy seen edge-on, except that its long axis was crossed by wisps of faint, apparently encircling material.



The first-known polar-ring galaxy, NGC 2685. The wisp-like rings seemed clearly in rotation about the main component. Was the main component a spinning, cigar-shaped system?



A pancake seen from above, or a cigar end-on?



A pancake seen edge-on, or a cigar from the side?

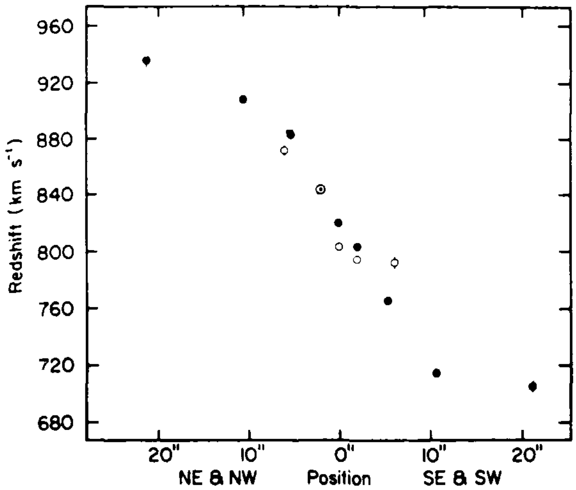


Fig. 7. Schechter and Gunn's data showing star motions along and across the main component of NGC 2685. The solid dots show wavelength shift of light vs. position along the major axis. A characteristic rotation curve is evident, indicating that the main component is rotating and that it must be flattened, like a pancake. The open dots show data obtained along the minor axis; they almost, but did not entirely, allow Schechter and Gunn to rule out the possibility of a spinning cigar.

The appearance of the wisps strongly suggested their rotation about the main image. If so, and if the wisps and the main image had been formed together and were part of a common system of rotation, then the main component must be a spinning cigar, not a flattened pancake. In 1975, Marie-Helene Ulrich of the University of Texas, then a visiting investigator at Kitt Peak, obtained velocity measurements of ionized gas along the minor axis. Her results suggested evidence of spin. It looked as if the first confirmed cigar might be at hand, although Ulrich wrote that without velocity measurements along the long axis and measurements of the star motions, "the dynamics of this galaxy remains unclear."

Schechter and Gunn turned their attention to the question. They obtained spectral shift measurements showing both star and gas velocities at various points both along and across the length of the apparent cigar. Their observations, reported in 1978, showed that the main region rotated, not like a cigar, but like a pancake (Fig. 7). The investigators concluded that almost certainly, the main image is a "run-of-the-mill S0 galaxy."

Several other such galaxies, called polar-ring galaxies, came to attention in the next few years. Each resembled NGC 2685 in exhibiting a cigar-appearing main component and a fainter ring oriented at right angle. In 1980, investigators studying NGC 4650A concluded (incorrectly, we now know) that the true shape of the main component was probably that of a cigar.

The next year, DTM staff members François Schweizer and Vera Rubin with postdoctoral fellow Bradley Whitmore came upon the finest example of the polar-ring class yet discovered, A0136-0801. Wavelength shifts either side of center clearly revealed that the main component is pancake-shaped and that

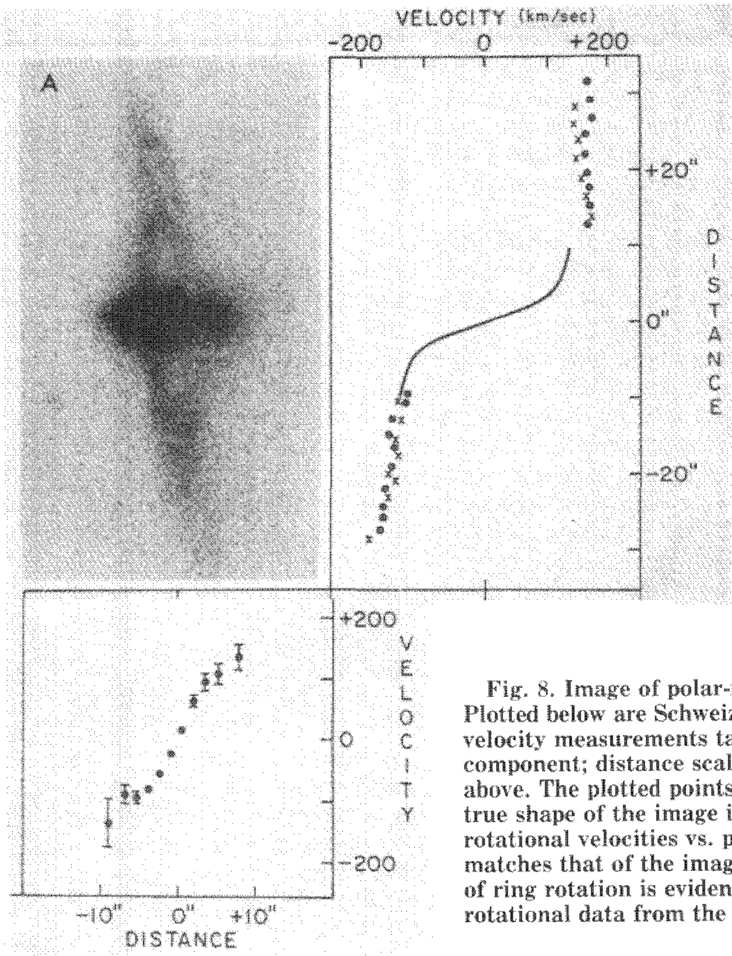


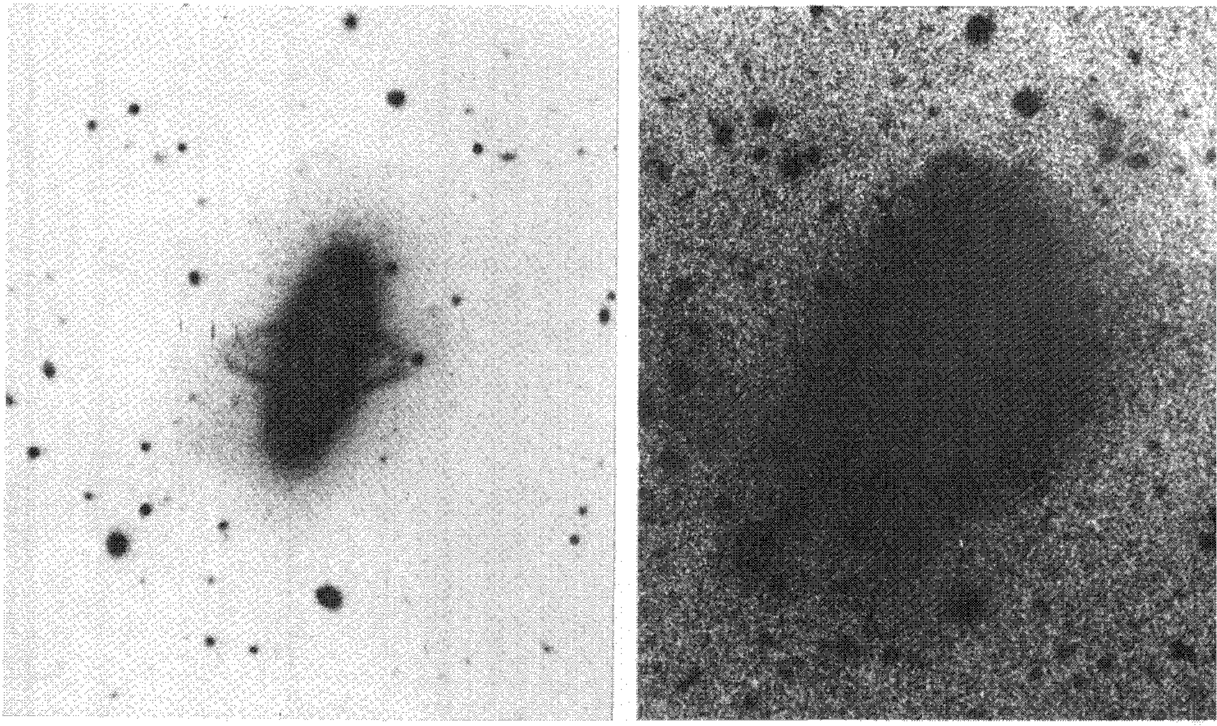
Fig. 8. Image of polar-ring galaxy A0136-0801 at top left. Plotted below are Schweizer, Rubin, and Whitmore's rotational velocity measurements taken along the long axis of the main component; distance scale matches that of the image directly above. The plotted points reveal rotation and show that the true shape of the image is pancake-like. At right are plotted rotational velocities vs. position on the ring; distance scale matches that of the image directly left. The expected pattern of ring rotation is evident. (The solid curve corresponds to rotational data from the major axis of the main component.)

it rotates well in excess of 100 kilometers per second (Fig. 8). There were no rotational velocities along the short axis, no cigarlike spin. Finally, luminosity measurements along the long axis fit the profile expected for a normal disk galaxy.

The DTM investigators also measured shifts in Hα emissions from the polar ring, confirming that the ring rotated as its appearance suggested—its axis at right angle to that of the inner disk.

There seemed no way that the two axes of rotation could be traced to a single episode of galaxy formation. Schweizer and colleagues wrote that most likely, the inner pancake was previously an ordinary spiral or S0 galaxy, which then collided, or merged, with a smaller gas-rich galaxy. The observed rotation of the gas ring was thus a relic of the orbital motions in the smaller galaxy.

Paul Schechter and various colleagues closely examined several other polar-ring systems. Working both in the optical and radio regions, these investigators determined that these



Polar-ring galaxy MCG–5–7–1, imaged at the du Pont telescope at Las Campanas, Chile. The right-hand image, produced at twice the contrast, reveals the presence of extensive material of low luminosity.

systems were likewise composed of an inner disk component and an outer ring rotating at right angles to the inner. Meanwhile, the DTM astronomers from a systematic study of galaxy catalogs, succeeded in identifying 22 polar-ring galaxies; their analysis showed that polar rings occur most often with S0's, especially in regions well populated by other galaxies—a point that seemed consistent with the growing evidence suggesting that the rings were results of mergers. Finally, they noted that the formation of a polar ring does not require a total cannibalization of the smaller parent: "robbing a neighbor may do."

Before returning to the merger hypothesis, we should note that the polar-ring galaxies also gave astronomers a chance to study the question of unseen mass in galaxies. The ability to measure rotation in the ring allowed an opportunity to test whether or not the galaxy's total mass was distributed spherically. The DTM investigators in their study of A0136-0801 showed that at any given distance from the center, material in the ring rotated at about the same velocity as material in the pancake. Thus they showed that the total mass, seen and unseen, was distributed roughly in the shape of a sphere, not in the shape of a disk.

Meanwhile, in 1983 Carnegie's Jerome Kristian and Paul Schechter (who became a staff member at Pasadena in that year) employed the du Pont telescope at Las Campanas to obtain a stunning image of the polar-ring galaxy MCG–5–7–1. By increasing the exposure, the investigators showed the presence of a faint but vast envelope, unseen at lesser contrast, which encircled and extended well beyond the main limit of the galaxy.

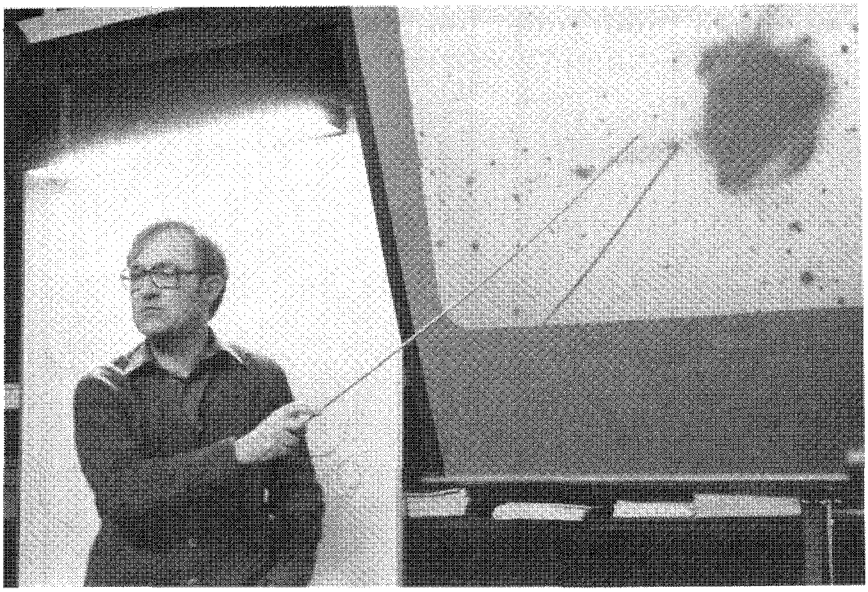
Kristian and Schechter offered thoughts on the possible nature of the formerly unseen material. They suggested that the faint material of the envelope is stellar debris from the lesser galaxy of the earlier merger, while the ring itself consists of gas from the smaller system and new stars formed from the gas.

As we have seen, developments in understanding ellipticals and S0's have been rapid since the first rotational measurements in 1975. The pace of advance has, to a great extent, been determined by improvements in the sensitivity of detectors and in the analytical techniques needed to exploit them. The older views on the origins and nature of the galaxies have come increasingly into question, and it may be that a new synthesis is close at hand. If so, a central point may be that many of the galaxies we now see, perhaps most of them, were not formed primevally but rather as results of interactions and mergers among parent galaxies.

THE QUESTION OF GALAXY INTERACTION

> Things are changing so rapidly in astronomy that the things we thought we knew many years ago, we're not sure we knew. And starting about the 1970's, we thought we knew how the Galaxy formed. We thought that it had collapsed from a fairly spherical gas cloud. . . .
>
> That was the textbook model for the formation of the Galaxy until very recently. And now there are lots of bits and pieces of that model that are being questioned, for a lot of reasons.
>
> Vera C. Rubin
> Astronomer, Carnegie Institution
> July 1985

The case that many of the galaxies now seen were formed from interactions or mergers among earlier galaxies was presented in 1972 by Alar and Juri Toomre of MIT and the Goddard Institute, respectively. They pointed out that galaxies are on average rather close to one another; typical distances between neighbors are only 10–100 times the galaxy diameters. Mergers thus seem rather likely, but they need not involve widespread collisions among stars, for stars physically occupy only a minute fraction of a galaxy's space.



François Schweizer giving a seminar presentation on merging galaxies. Evident on the screen are the tail-like structures of NGC 7252; such features are often observed in merged galaxies.

By means of computer models, the Toomre brothers demonstrated how two closely approaching galaxies induce strong, tidal deformations in each other, disrupting the original orbital motions to produce a variety of forms. Similar forms had been observed in certain peculiar galaxies. The Toomres showed that a merger of two spirals could produce some of the observed forms, eventually to yield a new elliptical galaxy. Could all ellipticals have been the results of mergers?

The ideas of the Toomres interested François Schweizer, a Swiss-born astronomer who had recently earned the Ph.D. at Berkeley and served a two-year fellowship at Mount Wilson. Partly to test these ideas in a detailed study of the Southern Hemisphere galaxy NGC 7252, Schweizer accepted a position as resident astronomer at the U.S. National Observatory at Cerro Tololo, Chile. He and his young family moved to the coastal town of La Serena—site of offices for the several major observatories in Chile. It was scarcely an isolated situation: astronomers from all over the world passed in a steady stream through La Serena, and Schweizer sought every opportunity for talking science with them.

His study of NGC 7252 convinced Schweizer that the Toomres were right. Schweizer observed ripples, tails, and other characteristic features seen in the Toomre models. But the clinching evidence came from Schweizer's spectrographic measurements of rotational motions.

In the innermost regions of NGC 7252, Schweizer found a small, well-defined disk of rotation. Farther out, the rotation was in an entirely different plane. Finally, in the outermost regions, rotation was again oriented to the central plane. Apparently two motion systems were present, which to Schweizer were relics of two original disks whose rotational systems had not yet become fully mixed, as in a fully developed elliptical. NGC 7252, he concluded, is the product of the collision and merger of two spirals about a billion years ago, and is now in the process of becoming an elliptical.

Schweizer moved to Carnegie's DTM in 1981. There, in systematic investigations of many ellipticals, he has discovered ripples in about a fourth of those studied. (Ripples should be detectable when mergers occurred within the past few billion years.) Extrapolating and using stellar-age data, Schweizer calculated that a typical noncluster elliptical may contain the debris of perhaps 4–10 galaxies which have successively merged.

Observations of Interactions in Progress?

Astronomer Kirk Borne came to DTM as a postdoctoral fellow in 1983. Borne's boyhood had been as part of an Air

Jan Hendrik Oort, the Netherlander astronomer who in 1927 determined the rotation of our Milky Way Galaxy, visited the astronomers at Carnegie's DTM in 1985. Seated: Oort and Vera Rubin. Standing: Kirk Borne, Linda Stryker, and François Schweizer. The occasion brought together several generations of students of galaxy dynamics.

Force family, and he attended public schools in several places. He earned the bachelor's degree in physics at LSU and enrolled in a doctoral program at Caltech. There, he became interested in how galaxies interact with one another, and he prepared a dissertation on this subject. Strongly interested in numerical simulations, he modelled a process where spiral galaxies might interact to evolve into ellipticals. Collaborating with an earlier graduate-school colleague, John G. Hoessel, Borne began a series of observations designed to explore theoretical models of interacting galaxies.

In early 1985, Borne and Hoessel reported exciting results from studies of several "binary ellipticals"—galaxies in pairs close enough to interact gravitationally. After picking out the true pairs, where both members were at about the same distance from us, Borne and Hoessel, observing at Kitt Peak, obtained images and spectrographic data. They hoped to study the two-body orbital motion of each pair as well as the rotational motions within each member. They made no attempt to predict the rotational motions; but even so, their results came as a surprise.

In the galaxy-pair K99, the investigators determined that the brighter member, NGC 1587, clearly rotated. (The wavelength shifts revealed motion in opposite directions either side of center.) But in the lesser member, NGC 1588, the wavelength shifts revealed a very different situation: shifts were detectable either side of the galaxy's center, but *the shifts were in the same direction either side.* The rotation curve was U-shaped! The outer stars apparently were not orbiting galaxy center but were instead trailing away, being pulled away from their parent galaxy by the gravitational attraction of the larger companion. It appeared that galaxy robbing, or stripping, was being seen spectrographically for the first time. (See Fig. 9.)

Borne and Hoessel found evidence of U-shaped rotation curves in eight of the nine true galaxy-pairs of their sample. Differences seemed only to suggest that the phenomenon was being seen in different projections or at different stages of evolution. In some cases, as in galaxy-pair K564, U shapes could be seen in both members. (See Fig. 10.)

The young investigators worked with other evidence, including measurements of contours of light intensities. On some of the images, they detected tails characteristic of gravitational interaction. Borne and Hoessel concluded that they were seeing the effects of gravitational forces caused by the nearness of the two galaxies to one another; these tidal forces are tearing apart the previous equilibrium and transferring the rotational momentum of the binary system into new motions of the streaming stars. The images, along with the remarkable spectrographic evidence, were snapshots of galaxy interactions in progress.

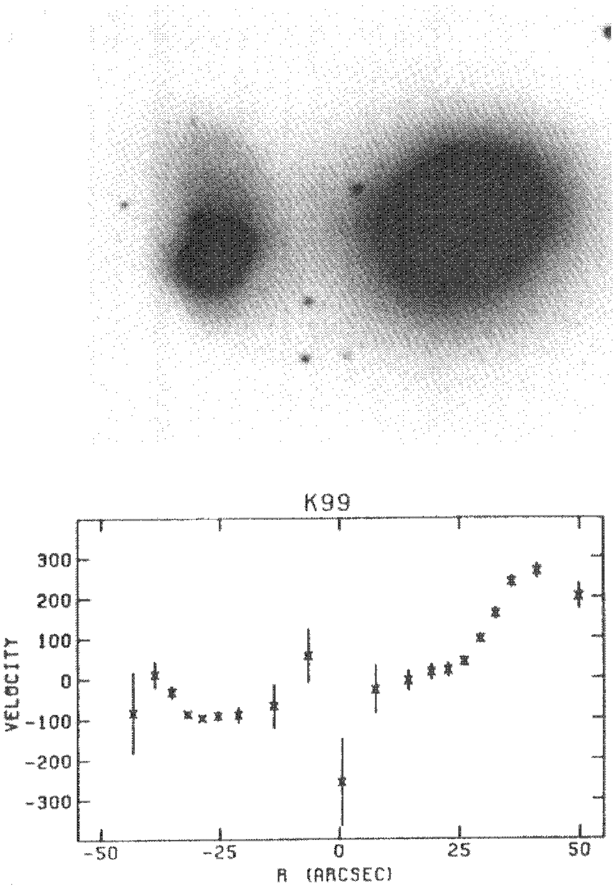


Fig. 9. At top, elliptical galaxy-pair K99; below, a diagram plotting the velocities measured by Borne and Hoessel vs. radius. (Positions on the photo and the diagram are vertically aligned.) The velocity curve of the right-hand galaxy exhibits the shape characteristic of rotation. The curve from the left-hand member is U-shaped, indicating that outer stars are no longer orbiting galaxy center but are being stripped away by the gravitational influence of the larger neighbor.

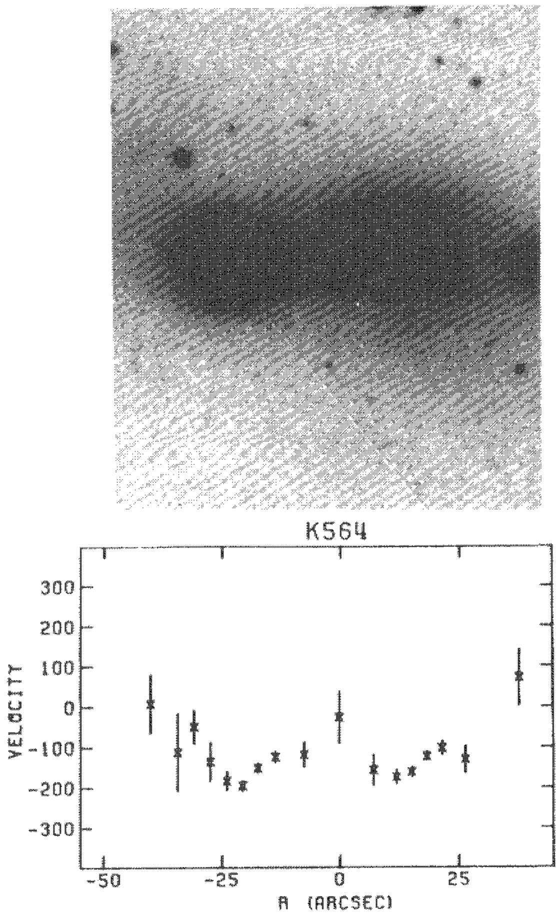


Fig. 10. K564, another galaxy-pair of ellipticals studied by Borne and Hoessel. Evidence of a U shape is seen in the velocity curves of both galaxies. Each galaxy is being strongly influenced by the other.

Borne has finished his fellowship at DTM and now works at the Space Telescope Science Institute in Baltimore. He has started a similar study of spiral binaries, collaborating with two other former DTM fellows. The early results are very similar to those with ellipticals, except that the strong angular momentum in the spirals leads to much greater distortions. Further, the presence of hydrogen gas in the spirals causes the shocks to produce great episodes of star formation and other violent activity.

Relations in Merger Candidates

Recently, Alan Dressler and George Lake (Bell Laboratories, New Jersey) obtained spectra of thirteen highly disturbed galaxies—systems that seemed perhaps in the early and middle stages of evolution into new ellipticals. The outer regions of these systems are quite chaotic; Dressler and Lake, however, calculated that if evolution toward ellipticals is indeed taking place, the stable, final form should occur first in the center. They therefore set out to measure velocity dispersion and luminosity in the central regions, in hopes of testing whether conditions there fit the Faber-Jackson relation known to link velocity and luminosity in elliptical galaxies.

The investigators concluded in 1985 that the central regions do exhibit the Faber-Jackson relation, and that these systems therefore may be evolving toward ellipticals. Dressler and Lake ventured that the galaxies will be recognizable as ellipticals in about a billion years. The result added another piece of evidence supporting the new view of galaxy evolution.

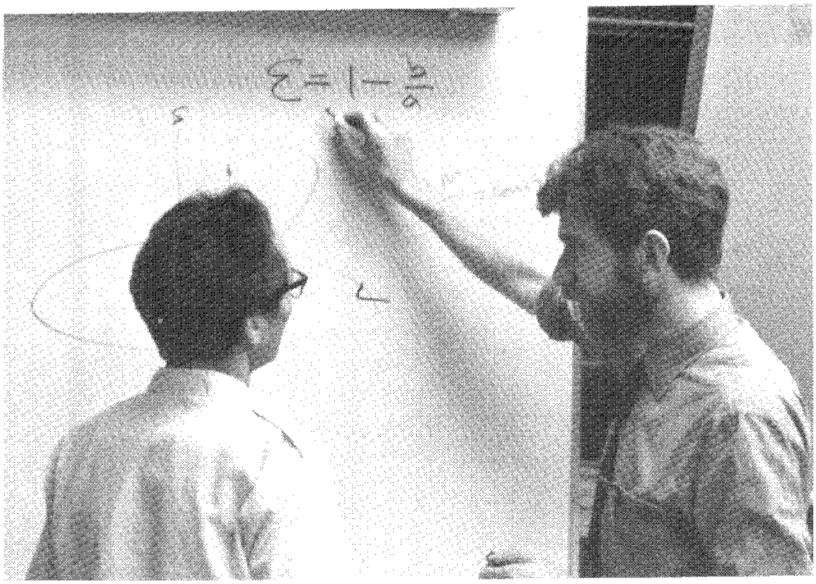
WHERE ARE WE NOW?

> Science is the one human activity that is truly progressive. The body of knowledge is transmitted from generation to generation, and each contributes to the growing structure.
>
> Edwin P. Hubble
> *The Realm of the Nebulae*
> 1936

Our story is far from ended. So basic a question as the rotation of our own Galaxy, for example, remains the object of leading work by Paul Schechter and colleagues. These investigators are observing carbon stars—red giant stars whose features make it possible to measure their velocities at great distances in regions of our Galaxy previously unexplored.

The new techniques for measuring motions in galaxies are being used to address many questions. In one case, Sandra Faber, Alan Dressler, and several collaborators are using velocity dispersion measurements in conjunction with the Faber-Jackson relation to determine distances to certain ellipticals. Their purpose is to study the expansion of the Universe over a large region, and their results early in 1986 stirred wide attention.

The question of large amounts of unseen mass in the Universe remains at the forefront. For several days in 1985, astronomers from many institutions gathered in Princeton to discuss



Paul Schechter (right) and DTM Senior Fellow Gui-zhong Qi of the People's Republic of China.

ramifications of the question. Often, astronomers investigating other topics will include in their reports whatever evidence they may have encountered, however inconclusive, bearing on the possible nature and location of the unseen mass. The matter remains unresolved, indeed little understood.

A technique for determining the true shapes of elliptical galaxies remains elusive. It seems likely that the ultimate method will depend, at least in part, on measurements of rotational velocities. Perhaps the precise measurements of velocity and light distribution by Schechter and Jedrzejewski will lead toward the needed result.

How do astronomers view the growing evidence attesting to the major role of galaxy interactions in galaxy evolution?

François Schweizer and Alan Dressler believe it likely (1) that some ellipticals represent an evolution from earlier systems and (2) that some peculiar galaxies may be transitory forms in this evolution. The case rests partly on computational models, which show that such evolution is a theoretical possibility, and partly on the growing observational evidence. Schweizer writes, however, that although the evidence is strong, it cannot yet be ruled out that some ellipticals may have formed primevally, from gaseous clouds.

Paul Schechter is inclined to go farther. He sees it likely (though not yet proven) that *all*, or nearly all, galaxies now seen were formed from mergers. In this view, large numbers of small galaxies formed in the early Universe; these then interacted with one another in various ways eventually to yield the present galaxy population.

Offices of Carnegie's Mount Wilson and Las Campanas Observatories, on Santa Barbara Street, Pasadena, California.

Tomorrow's Astronomy from Space and Earth

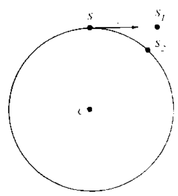
Astronomers look forward to the orbiting of the Edwin P. Hubble Space Telescope. This marvelous instrument should provide vastly improved observing power, both in the optical and in wavelengths previously blocked by the atmosphere. Observations of very faint objects will enable astronomers to study galaxies whose light was emitted perhaps ten billion years ago—more than half-way back to the origin of the Universe. Scientists will be looking backward in time, viewing conditions as they were long ago. Already, most of the astronomers discussed in this essay are preparing proposals for observations with the Hubble telescope.

Does the promise of spaceborne astronomy mean that major ground telescopes are obsolete? Astronomers are convinced that the opposite is true, that superior ground instruments will be needed for conceiving and planning the crucial observations in space, and for carrying out extensive follow-up observations. Believing that the promise of space can only be attained through advanced ground systems, several institutions are moving ahead with plans for large, ground telescopes of new design; the trustees of the Carnegie Institution, for example, recently made a large financial commitment toward the building of a new, 8-meter telescope at Las Campanas.

* * *

The celestial mechanics that governs the motions of astronomical bodies, understood by Sir Isaac Newton long ago, continues to underlie our understanding of forces and motions in galaxies. Today, modern computers apply the classic laws in theoretical models involving thousands of interacting objects—calculations of a magnitude utterly beyond human capacity until recently. Advances in the ability to obtain observational data have been just as spectacular.

But though the new research tools are indeed powerful, discovery remains the product of yet more fundamental matters. In all the pioneering work sketched in this essay—from Sir Isaac to the frontier astronomers of today—commonly present are qualities of intellect of a quite uncommon nature. Among these qualities are a compelling curiosity, a mastery of existing knowledge and technique, and the inclination to turn one's mind in fresh directions. These are the things that drive the process of science.



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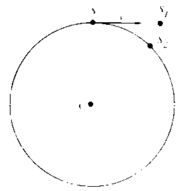

Note to Teachers. Extra copies of this booklet can be obtained by calling or writing to the address given below. In addition, Carnegie Institution has produced a series of radio broadcasts featuring four-minute discussions with scientists whose work is described in this essay. The disks are available free to broadcasters for educational or public service uses. The interviews are also available on cassette tape for use by teachers, without charge. Broadcasters and teachers may request these materials from:

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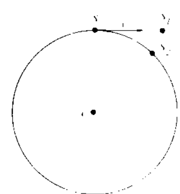

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