Stars, Galaxies, Cosmos: The Past Decade, the Next Decade

Vera C. Rubin

Discoveries in astronomy during the past 20 years have challenged our perception of the universe. Attempts to understand these discoveries should direct the course of astronomy for years to come. Rarely in the history of science has there been an equivalent period in which the boundaries of our understanding have been enlarged so dramatically.

Until the middle of this century, astronomical knowledge came from observations made in the optical region of the electromagnetic spectrum, that region transmitted by the earth's atmosphere and detected with the eye. This radiation has a frequency of 10^{15} cycles per second and a wavelength of 10^{-7} meter, and is characteristic of thermal radiation from stars like our sun with surface temperatures near 6000 K. The universe that astronomers knew in the middle of this century was a majestic, slowly evolving stellar universe. But advancing technology has now produced instruments which detect radiation from the radio and infrared spectral regions, which are beyond the visible red end of the spectrum but are transmitted by the earth's atmosphere. In addition, advanced detectors fly above the earth's atmosphere and observe in the x-ray, γ-ray, ultraviolet, and far-infrared spectral regions, where the atmosphere is opaque. The observable spectrum has been enlarged to cover the wavelength range from 10^{-14} to 100 meters. Astronomers now know that we live in a veritable zoo, where x-rays are emitted by objects as diverse as quasars, diffuse intergalactic gas, coronae about cool stars, matter accreting onto compact objects (perhaps black holes), and pulsating stellar remnants from supernova explosions; where γ-rays are a direct probe of cosmic nuclear processes and are produced from the interaction of cosmic rays with the interstellar matter and in supernovae, the sun, and compact galactic objects, sometimes in transient events lasting no more than 10 seconds; where nuclei of galaxies and some quasars radiate more in the infrared than they do in the visible; where sites of newly born stars are marked by infrared emission from dense molecular clouds; and where the vast regions between the stars in our galaxy contain complex organic chemical compounds, compounds that are fundamental constituents of living things on the earth. An exotic menu of astronomical sources is now routinely available for study, and the universe is known to be immeasurably richer, more varied, and more violent than would have been dreamed even 20 years ago. Glimpses of this variety are described below, and a few obvious paths for astronomical investigation in the 1980's are identified.

Summary. Our perception of the universe has been altered by recent discoveries in astronomy, discoveries of new objects and of new phenomena, coming from a wide range of observing techniques. By 1990 astronomers expect to know more about the distribution of mass in the universe, the physics of energetic sources, and the intricate interconnections of astrophysical processes on a variety of spatial and temporal scales.

The author is a staff member of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C. 20015.

Cosmology

At its broadest, astronomy is the study of the universe. By observations made here and now, astronomers attempt to deduce the early history of the universe and uncover factors that have directed its evolution to the present. Most astronomers accept as a model a universe which has expanded and cooled from an initial hot, dense state. The primeval fireball radiation arose from the Big Bang, the inception of the expansion. This radiation has been expanding and cooling during 10 to 20 billion years since the Big Bang; its present temperature is 3 K. After George Gamow's cosmological studies, the existence of this background microwave radiation was predicted in the late 1940's by Alpher and Herman (*1*), but it was not detected until 1965 by Penzias and Wilson (*2*). Current research in cosmology is dominated by the impact of this discovery.

Thermal radiation of 3 K (blackbody radiation to the physicist) has a characteristic spectrum with its peak radiation at a wavelength of 1 millimeter in the microwave spectral region, a region in which the earth's atmosphere is radiating with a temperature near 300 K. Hence accurate measurements of the spectral energy distribution of the background radiation can only be made above the earth's atmosphere. An outstanding achievement during the 1970's was the verification of the blackbody nature of the microwave radiation from instrumentation flown in a balloon (*3*). However, tantalizing small departures from blackbody radiation may have been detected (*4*). Such deviations are important because they make it possible for us to differentiate between events arising during the early thermal history of the universe and more recent effects, such as the radiation of warm dust from intervening galaxies along the line of sight.

The degree to which the radiation is isotropic—that is, the same in all directions—is a test of Big Bang cosmology; is a measure of the initial shear, rotation, and inhomogeneities of the early universe; and acts as a speedometer for the motion of our galaxy. We are immersed in a sea of photons, photons which outnumber nucleons by a factor of 10^8, photons with energies equivalent to a temperature of 3 K. As our galaxy moves through this field of photons, we will see a hotter temperature in the direction of our motion and a correspondingly cooler temperature in the direction from which we have come. Within the past few years, a surprisingly large anisotropy in the background radiation has apparently been detected (*5*). With respect to the background radiation, the galaxy and the local group of galaxies have a velocity of about 400 kilometers per second toward the Virgo supercluster of galaxies. If confirmed, this motion would imply that the combined mass of galaxies in the Virgo supercluster is sufficient to slow slightly the expansion of the universe in our vicinity.

Because the microwave background

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radiation is presently our most accessible probe of the early universe, crucial experiments during the 1980's will be designed to improve the accuracy of the measured spectrum and to place more stringent limits on the large-scale and small-scale isotropy. Only such observations can establish for certain that the radiation is a relic of the Big Bang rather than the superposition of numerous point sources. Such measurements will be made by COBE, the Cosmic Background Explorer, an orbiting NASA instrument which will fly during the 1980's to observe the background radiation in the millimeter and submillimeter range. We should enter the decade of the 1990's more knowledgeable about the details of this fossil radiation.

Efforts to map the expansion of the universe in the vicinity of our galaxy have proved to be unexpectedly difficult. Knowledge of the distances and velocities is required for a large number of galaxies; distance determinations especially are fraught with complex selection and systematic effects. Despite heroic efforts on the parts of numerous astronomers, the value of the velocity of expansion, the Hubble constant H, is probably uncertain by a factor of 2 (*6*). The value of H is a scale factor in cosmology. It affects calculated luminosities, sizes, and densities of extragalactic objects and measures the age of the universe in the simplest cosmologies. Observations which can produce a value of H accurate to 10 or 20 percent are required if we are to know the age and the scale of our universe; such observations will continue as a major observational effort during the 1980's.

With the launch of the Space Telescope in the 1980's, astronomers will have a large, high-resolution optical telescope outside of the earth's atmosphere. With this superb instrument it will be possible to observe individual stars, clusters, novas, and ionized gas clouds in external galaxies to greater distances than ever before possible. All of these objects serve as standard candles for determining distances to individual galaxies. Observations made with the Space Telescope, coupled with detailed ground-based studies carried out with the use of both classical and novel techniques, should resolve the present controversy concerning the value of H.

Is the universe open or closed? Is the mean mass density low enough so that the universe will continue to expand forever, or is the density sufficiently high that gravity can slow the expansion and ultimately halt it so that it reverses into a contraction? Although presently available evidence favors continued expansion, we really do not now have a convincing answer (*7*). We do understand that tests devised earlier to tell if the universe is open or closed often tell instead about galaxy evolution. Some galaxies may have been brighter in the past, a past which included more active star formation (*8*). Large galaxies in clusters may have been fainter in the past, before they brightened by cannibalizing stars in the outlying regions of neighboring galaxies or by merging completely with their smaller neighbors (*9*). Until we understand the luminosity history of galaxies, we cannot map distances in the early universe by measuring luminosities. Alternative approaches which attempt to enumerate directly the mass of the universe fail. The curious reasons for this failure are discussed below.

Quasars

The discovery of quasi-stellar objects (quasars) in the early 1960's had implications far beyond the astronomy and physics of these particular objects. Astronomers learned that a major constituent of the universe had until then been undiscovered; there is little doubt that other major components within our universe remain unknown today.

Quasars were identified initially by their intense radio emission (*10*). Optical studies showed pointlike stellar sources whose spectra indicated enormous red shifts of strong emission lines (*11*). In an expanding universe, spectral lines shifted redward arise from a velocity of recession; quasars with $z = 3.5$ (that is, wavelengths of lines shifted from the laboratory positions by a factor of 3.5) are the most distant objects known in the universe. Today, most astronomers agree that quasars are abnormal nuclei of very distant galaxies, radiating with enormously high luminosities. Some quasars have been found to reside in faint clusters of normal galaxies; the quasar and the cluster galaxies have the same red shift and hence are at the same distance. Some quasars have faint surrounding material, identified as the normal galaxy disk (*12*).

In one extraordinary case, two quasars extremely close together on the sky have virtually identical optical spectra and red shifts (*13*); this finding may mean

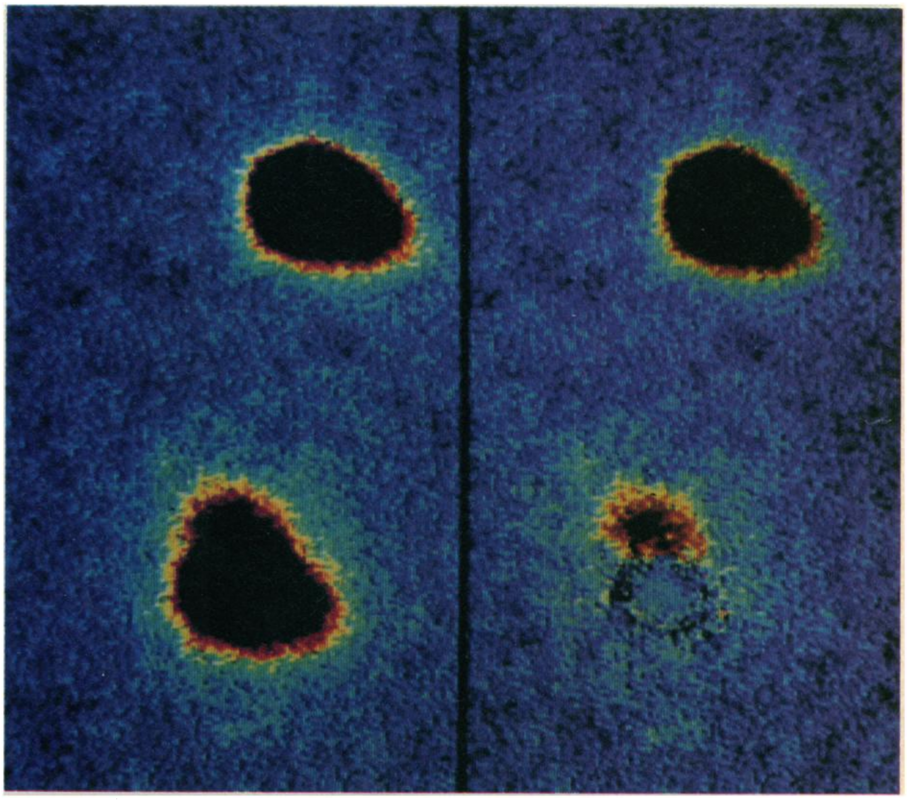

Fig. 1. The double quasar, observed during exceptionally good seeing conditions, with an image tube and the Hawaii 2.2-meter telescope. The left panel shows the digital addition of five 1-minute exposures. The fuzz at the top of the lower image is a faint superposed galaxy, which is assumed to be acting as a gravitational lens and forming two images of the single background quasar. The right panel shows the result of scaling the top image to the bottom image and subtracting, thereby showing the intervening galaxy. [Courtesy the Institute for Astronomy and Planetary Sciences and Data Processing Facility, University of Hawaii, and A. Stockton]

that we are observing two images of a single object (Fig. 1). An intervening galaxy along the line of sight deflects the radiation from the background quasar, thereby acting as a gravitational lens and forming two (or perhaps three) images. If this model is correct, a long-predicted phenomenon will have been discovered. Moreover, there will be decisive evidence that the quasar is more distant than the intervening galaxy.

Quasars are observed to vary in brightness on incredibly short time scales (*14*). At optical and infrared wavelengths, some magnitudes vary on a time scale of a day; some polarizations vary on a time scale of hours. The enormous x-ray intensity of quasars (10^{14} solar luminosities per second) can change on a time scale of hours. The short light times involved indicate that the central energy source is tiny, having only solar-system dimensions! From the plethora of models for quasars and active galaxy nuclei, accretion onto massive black holes of between 10^6 and 10^{10} solar masses now appears most satisfactory. Stars approaching near the black hole are torn apart and swallowed, releasing enormous amounts of gravitational energy. Regardless of whether this specific model proves to be correct, most astronomers agree that there are no compelling reasons to doubt that the observed red shifts indicate enormous distances or to believe that "new physics" is required to understand quasars. Still, the puzzle posed by their energetics is one of the most challenging in contemporary astronomy.

A continuing enigma has come from the observations of quasars which are double radio sources. For some of these, it appears that the radio sources are separating with superluminal (that is, faster than the speed of light) velocities, if the quasars are placed at the cosmological distances inferred from their red shifts. At the present time, such observations are not interpreted as a threat to the current understanding of quasars. Rather, the radio signals are assumed to be generated or scattered or reflected in a stationary medium surrounding the active central object (*15*). Such sources must be related to the jets seen on optical photographs of some radio galaxies. Continued interferometric observations during the 1980's should delineate their properties still further.

The numerous absorption lines seen in the spectra of quasars apparently have a variety of origins (*16*). Some arise in the quasar, some in the surrounding galaxy, some in intervening galaxies, and some in intergalactic clouds along the line of sight. Such clouds will provide a unique probe of gas densities and abundances at earlier epochs in the universe. It is hoped that studies of these ubiquitous clouds will tell us the chemical and evolutionary history of both the clouds and the primeval galaxies which formed from them.

Quasars were more numerous and more luminous in the past (*17*). The numbers of detected quasars decline at $z = 3$, and the most distant quasar has $z = 3.5$. Quasars thus are useful as a tool for identifying distant galaxies with z up to 3.5. What should we look for to identify still more distant galaxies, galaxies with z near 10? Will they be diffuse, very extended, have very low surface brightness regions, be red from their large red shifts, or will they be abnormally blue, signaling an enormous rate of star formation in those early days? And what characteristics identify the epoch of galaxy formation after the Big Bang? These are questions which astronomers are now trying to answer, often with the use of novel observing techniques, and which will receive critical study in the 1980's.

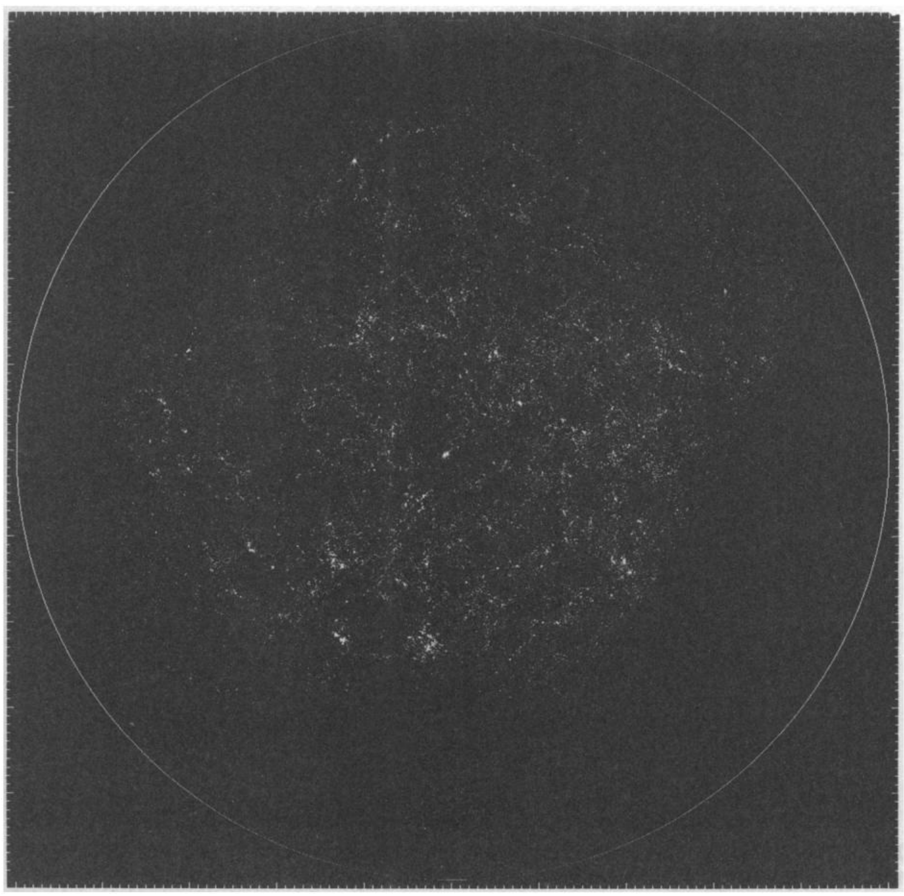

Fig. 2. The million brightest galaxies as they appear on the northern sky, from counts by Shane and Wirtanen at Lick Observatory (*46*), newly reduced (*18*). The north galactic pole is at the center, the galactic equator is at the edge, and galactic latitude is a linear function of radius. Note the striking lacework pattern and the conspicuous voids. [Courtesy of P. J. E. Peebles]

Distribution of Mass in the Universe

The distribution of visible matter in the universe is hierarchical, progressing from galaxies to clusters of galaxies to clusters of clusters. Counts of the million brightest galaxies (Fig. 2) reveal a lacy network of extended linear arrangements and great voids, with a surprising lack of isolated field galaxies (*18*). Most galaxies reside in small groups or clusters (Fig. 3), which in turn clump to form superclusters. It was during the past decade that astronomers realized that galaxies, after formation, are not the isolated island universes which Hubble envisioned earlier. Rather, they interact with their environment and with each other in complex ways. Elliptical galaxies are preferentially found in the higher density regions of clusters; spiral galaxies are most often found in the low-density outer cluster regions or in isolation (*19*). Within clusters, central galaxies grow massive at the expense of halo stars from near neighbors. Galaxies in collision or galaxies tidally distorting each other produce the pathological forms often observed on the sky (*20*). The galaxy environment appears fundamental in determining the morphology of the galaxy.

Additional factors which cause a galaxy to evolve as a spiral or as an elliptical remain unknown, although the local mass density and the local gas content must both be important. The gas content particularly is significant in directing the evolution of a galaxy, for from it new stars are formed. We do not yet know if galaxies preferentially accrete gas or lose gas to the intercluster spaces during their lifetimes; perhaps they do each at a different stage in their evolution. For massive galaxies at rest in the centers of large clusters, there is observational evidence of infalling hydrogen clouds. For galaxies moving at large velocities through the intercluster medium, it is expected that gas will be stripped from the galaxy as a result of the ram pressure of the intercluster gas. Within galaxies, high-velocity stellar winds, stirring by supernova explosions, shedding of cocoons by newly formed stars, and evaporation by a hot intergalactic medium will alter the balance between gas, dust, and stars. The delicate interplay of these processes will establish the presence or absence of a significant gaseous component (*21*).

Stars within galaxies evolve; galaxies within clusters evolve; and clusters of galaxies evolve. The present epoch may be called the epoch of cluster evolution. A cluster such as the Virgo supercluster (of which our galaxy is a suburban member) is in an early evolutionary stage, with an irregular shape, a large fraction of spirals, small random motions among the galaxies, low intercluster gas temperature, and low x-ray luminosity clumped around individual galaxies (Fig. 4). As clusters evolve, the cluster shape becomes more regular, the spread in velocities among the galaxies increases, the central gas density increases (perhaps as a result of the stripping of gas from galaxies which pass through the core of the cluster), the central gravitational potential grows, and a supergiant elliptical galaxy may form at the center (*22*). Astronomers were startled to learn that the hot intracluster gas, identified by its x-ray emission, is not the pristine hydrogen and helium formed shortly after the Big Bang and left over after galaxy formation but is rich in heavy elements such as iron (*23*). This is a certain sign that this gas has been synthesized in stellar interiors and returned by way of supernova explosions to the intergalactic spaces. Programs for the 1980's will attempt to learn how the evolution of galaxies within clusters has affected the evolution of clusters, and vice versa. Astronomy in the last 50 years has enlarged from the study of stars to the study of galaxies; the 1980's should be a time devoted to the study of clusters of galaxies.

Only during the last decade have astronomers acknowledged that much of the mass of the universe must be invisible, although the controversial evidence had been accumulating for a long time. Almost 50 years ago, Smith (*24*) and Zwicky (*25*) made an amazing observation; individual motions of galaxies in a cluster are so large that the gravitational attraction of all the cluster galaxies is not sufficient to bind the cluster. Galaxy clusters should thus be dissolving, although they apparently are not. This suggests that an unseen component of matter is present to bind the clusters. Very recent work has strengthened this conclusion; the dynamics of individual galaxies, double galaxies, groups, and clusters all point to this unobserved but ubiquitous mass component (*26*). As much as 90 percent of the mass of the universe may be presently unseen. Its luminosity per unit mass must be considerably below that of the usual stellar matter. Astronomers are fond of saying that such mass could be in the form of bricks, or baseballs, or Jupiters, or comets, or mini-black holes. At present, its signature is known only by its gravitational interaction, but continued studies in all regions of the electromagnetic spectrum should help delineate its properties. The presence of such mass in quantities sufficient to bind the clusters could still be insufficient to close the universe.

At least some fraction of the nonluminous matter in the universe is located in the outer parts of individual spiral galaxies. Astronomers have long known that the stars and gas in a spiral galaxy are orbiting about the center of the galaxy. It was anticipated that the orbital velocities of stars would decrease with increasing distance from the center of the galaxy, just as the velocities of planets in the solar system decrease with increasing distance from the sun. Decreasing velocities arise as the gravitational response to a massive central body, that is, the sun in the case of the solar system. However, recent spectroscopic studies of spiral galaxies (*27*) show without doubt that the velocities of gas and stars remain high at large distances from the center (Fig. 5). This signifies that the mass in a galaxy is not as centrally condensed as it is in a solar system. In ordinary spirals, mass must be distributed far beyond the optical image, probably in massive dark halos.

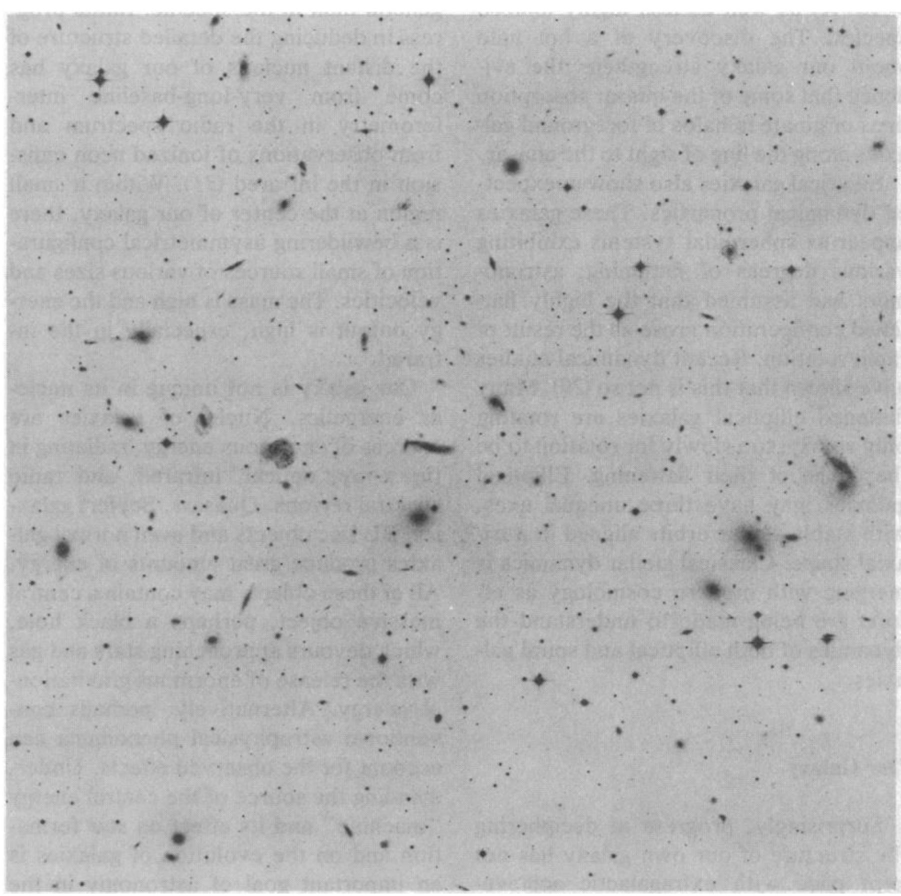

Fig. 3. The Hercules cluster of galaxies, photographed with the du Pont 2.5-meter telescope at Las Campanas, Chile. Note the incredible variety of forms of galaxies contained within the cluster. [Courtesy of A. Dressler, Hale Observatories]

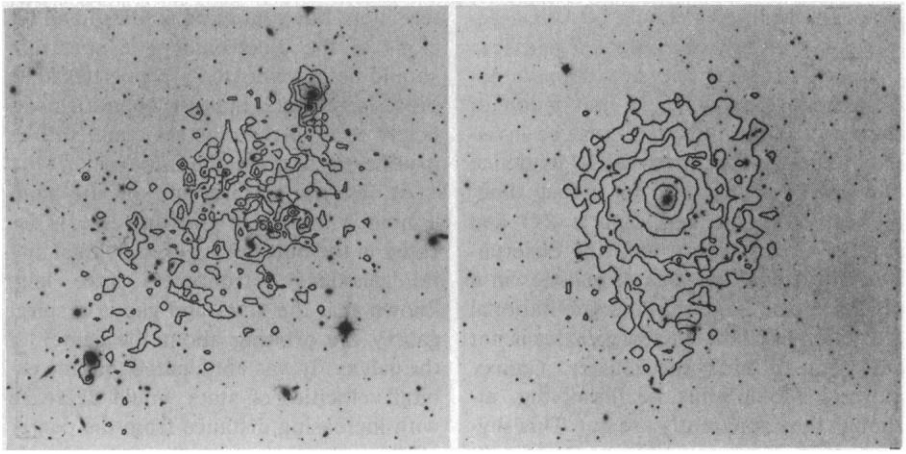

Fig. 4. Contours of equal x-ray emission shown superposed on Palomar Sky Survey fields for two clusters of galaxies, Abell 1367 (left) and Abell 85 (right). A cluster like A1367 is assumed to be in an early evolutionary stage, with the x-ray-emitting gas clumped about individual galaxies. In an evolved cluster like A85, the x-ray-emitting gas has been blown away from the individual galaxies and is sharply peaked about the dominant central giant elliptical galaxy. The x-ray observations by Jones *et al.* (*22*) were made with the Einstein Observatory. [Courtesy of C. Jones]

A hot gaseous corona surrounding our galaxy may recently have been detected (*28*) on the basis of its characteristic ultraviolet lines seen in spectra obtained by the orbiting International Ultraviolet Explorer. Preliminary analysis indicates a halo of highly ionized atoms of carbon and silicon (suggesting a temperature of $\sim 10^5$ K) as well as less highly ionized species. The discovery of a hot halo about our galaxy strengthens the evidence that some of the quasar absorption lines originate in halos of foreground galaxies along the line of sight to the quasar.

Elliptical galaxies also show unexpected dynamical properties. These galaxies appear as spheroidal systems exhibiting various degrees of flattening; astronomers had assumed that the highly flattened configuration arose as the result of rapid rotation. Recent dynamical studies have shown that this is not so (*29*). Many flattened elliptical galaxies are rotating only slowly, too slowly for rotation to be the cause of their flattening. Elliptical galaxies may have three unequal axes, with stable stellar orbits aligned in a triaxial shape. Classical stellar dynamics is merging with modern cosmology as efforts are being made to understand the dynamics of both elliptical and spiral galaxies.

Our Galaxy

Surprisingly, progress in deciphering the structure of our own galaxy has not kept pace with extragalactic achievements. We know that we live in a spiral galaxy (see page 63), although its detailed morphology and dimensions remain a mystery. We do not know how far our sun is from the center, nor do we know our rotational velocity about the center with an accuracy sufficient to determine the galactic scale to within 20 percent. Astronomers now understand spiral arms as a wave phenomenon (*30*), but the theory is more successful in the general than in the specific. Initial progress in deducing the detailed structure of the distant nucleus of our galaxy has come from very-long-baseline interferometry in the radio spectrum and from observations of ionized neon emission in the infrared (*31*). Within a small region at the center of our galaxy, there is a bewildering asymmetrical configuration of small sources of various sizes and velocities. The mass is high and the energy output is high, especially in the infrared.

Our galaxy is not unique in its nuclear energetics. Nuclei of galaxies are sources of enormous energy, radiating in the x-ray, optical, infrared, and radio spectral regions. Quasars, Seyfert galaxies, BL Lac objects and even normal galaxies produce great amounts of energy. All of these objects may contain a central massive object, perhaps a black hole, which devours approaching stars and gas with the release of enormous gravitational energy. Alternatively, perhaps conventional astrophysical phenomena can account for the observed effects. Understanding the source of the central energy "machine" and its effect on star formation and on the evolution of galaxies is an important goal of astronomy in the 1980's.

During the coming decade, the variety of approaches available for the detailed study of our galaxy should produce a more coherent picture of the stellar system in which we live. From the Space Telescope, studies of faint halo stars, distant globular clusters, and outlying satellite galaxies should delineate the extent of the system and its chemical evolution as a function of age and of position; it is hoped that radio and millimeter observations of molecular clouds will identify regions of star formation and help us to learn their dynamics. Sophisticated theoretical models will address the stability of disk systems. From these investigations astronomers should learn what role warps in the outer disk play in this stability. Perhaps the Magellanic Stream (*32*), that extensive band of neutral hydrogen reaching from our galaxy to the nearest satellite neighbors, will be understood in this context. From x-ray observations of nearby galaxies, we should learn about energetic nuclear events. Our nearest spiral neighbor, M31, now has 17 sources of x-ray radiation identified (*33*) in its nucleus (Fig. 6); their nature is not yet understood. We may ultimately be able to piece together a detailed picture of our own galaxy from studies both internal and external.

Stellar Evolution

Crucial to our understanding of star formation is a knowledge of the interstellar gas and dust between the stars, from which new generations of stars are born. During the 1970's, astronomers learned that the interstellar medium in our galaxy has both hot and cold components (*34*). Some gas is at a temperature of 1,000,000 K, some gas is in the form of dense molecular clouds with temperatures near 10 K. New instruments in the millimeter and infrared spectral regions have permitted astronomers to probe the cold molecular clouds, the birthplaces of stars. The cocoons of gas and dust contract under their own self-gravity, warming as they collapse, until their core temperatures become high enough to initiate nuclear fission; a protostar or cluster of protostars is born.

There is some evidence that supernova explosions from dying stars compress the clouds (*35*), initiating a new generation of star births. Both spatially and temporally, star formation appears sequential (*36*), with new generations arising at the outer edges of older associations. The roles played by magnetic fields, rotation, and turbulence and the factors that control single or multiple births are not known. Like the sun, some stars retain a disk or a complex pattern of debris after their formation. Such stars are candidates for associated solar systems.

Most of a star's lifetime is spent in a stable phase, during which the star draws upon its nuclear energy sources to maintain its energy supply; details of its evolution depend, among other factors, upon its mass and composition. It has become increasingly clear, however, that stars of almost all masses lose significant amounts of mass during their evolution, either in active winds or explosive events (*37*). From observations in the ultraviolet, optical, and infrared, a crude picture of the processes involved has been drawn. Interestingly, it now appears likely that the interstellar dust originates in the stellar ejecta. Knowledge of stellar interiors, stellar mixing, and ejection mechanisms will have to precede an understanding of the cycling, nucleosynthesis, and recycling of gas through stars.

Fig. 6. Einstein Observatory exposure of the central region of M31, the Andromeda Galaxy, showing the numerous x-ray sources located there. The natures of many of these sources are presently unknown. The bright source identified by the arrow is very close to the center of M31 and may arise from gas clouds accreting onto a massive object. The x-ray luminosity of this source is 1000 times stronger than any steady point source located at the center of our galaxy. [Courtesy of L. Van Speybroeck]

An energy crisis occurs during the late stages of stellar evolution, when a star has exhausted its nuclear fuel or when further heating by contraction is not possible. We can now identify white dwarfs, neutron stars, and probably black holes as the end products of stellar evolution. Observations of Sirius B established the existence of white dwarfs, and the identification of the pulsar in the Crab Nebula established the existence of neutron stars. Unfortunately, there is as yet no corresponding conclusive evidence for the existence of black holes, although candidates continue to emerge. One clue as to their existence is the x-rays emitted by matter accreting onto massive compact objects. Exotic objects recently identified, x-ray bursters and γ-ray bursters, are both related to such circumstances, although little is yet certain about the mechanisms involved. In view of the intense observations and theoretical studies concerning the reality of black holes, it is interesting to recall the discovery of the first white dwarf, Sirius B. In 1844, Bessel noted the irregular motion of Sirius and concluded that it was a double star. In 1862, the firm of Alvan Clark, the American telescope maker, completed an 18-inch lens ordered by the University of Mississippi. (Because of the Civil War, the lens was never delivered and ultimately ended up at the Dearborn Observatory of Northwestern University.) In testing the lens apart from a telescope, Alvan Clark, Jr., detected the faint companion (*38*). However, not until 50 years later was a spectrum obtained, and not until 10 years after that was the astrophysical significance of a small but massive star recognized. The pace of science is faster today, and we hope that it will not be 80 years until direct evidence for black holes is established.

Neutron stars have masses like that of the sun, but radii 10^5 smaller and densities 10^{14} larger. The first neutron star was discovered (*39*) as a radio pulsar; the pulsed radiation signature arises from the presence of an intense magnetic field. Presently about 300 pulsars within our galaxy are known. Some of these are in close double systems; x-ray emission in these systems is understood as the accretion of mass onto the neutron star.

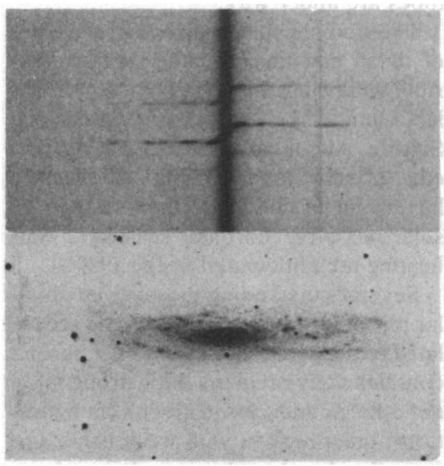

Fig. 5. (bottom) NGC 801, a spiral galaxy seen close to edge on, from a Kitt Peak National Observatory plate taken with the 4-meter telescope. (top) Emission lines along the major axis of NGC 801 arising from the excited gas in the galactic disk (horizontal); the stronger is due to hydrogen. The strong (vertical) continuum arises from stars in the nucleus. As a result of the rotation of NGC 801, gas on the southeast (left) is approaching the observer, and so the emission lines here are shifted to short wavelength; gas on the northwest (right) is receding from the observer, and the emission lines are shifted to longer wavelength (up on print). The strong velocity gradient near the nucleus produces the highly inclined lines seen there. The gravitational influence of low-luminosity mass at large nuclear distances produces constant rotational velocities observed at large nuclear distances. [Photo courtesy of B. Carney; spectrum from V. C. Rubin and W. K. Ford, Jr.]

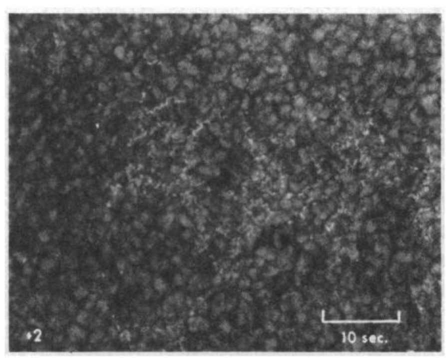

Fig. 7. The solar "filigree," observed at the Tower Telescope, Sacramento Peak Observatory, New Mexico. These sub-arc-second structures, discovered by R. B. Dunn, are shown as they appear in the wings of Hα, at 2 angstroms from the line center. The underlying granulation of the solar image is also seen. Filigree appears in areas of strong magnetic field, but the field may not be confined to the filigree. The nature of this phenomenon is still uncertain. [Photo copyright Association of Universities for Research in Astronomy, Inc., Sacramento Peak Observatory]

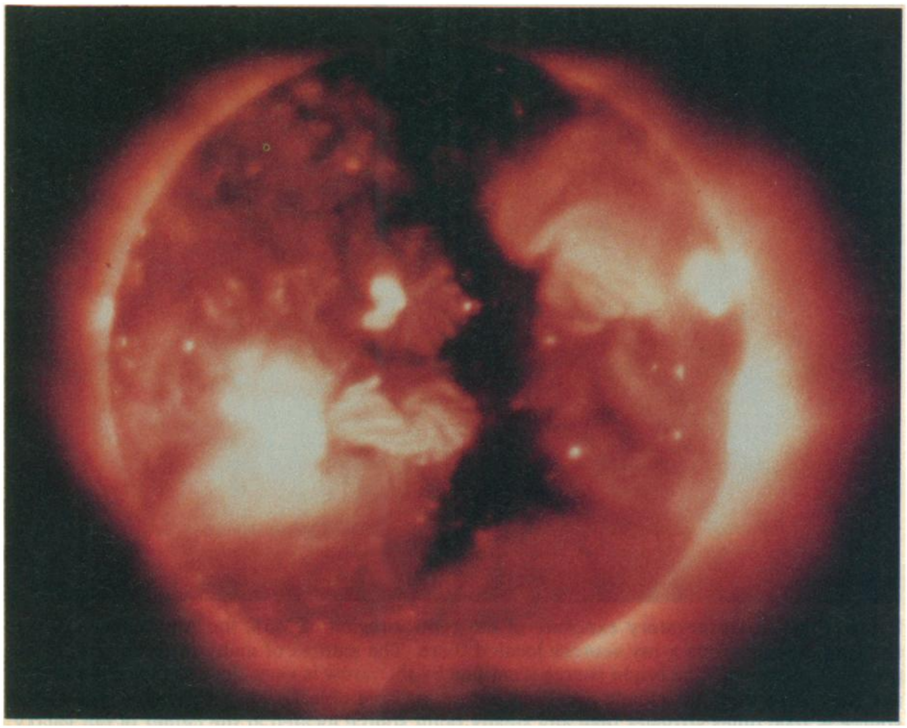

Fig. 8. The solar image, made on 1 June 1973 with the x-ray telescope of the American Science and Engineering, Inc., aboard the first NASA Skylab mission. The prominent dark region is a coronal hole, a region where the temperature and density of the corona are reduced. The coronal hole is larger than 750,000 kilometers. The small white spots are x-ray bright points, regions of intense emission. [Courtesy of American Science and Engineering, Inc.]

Changes in the observed period of pulsation give insights into exceedingly complex physical conditions. With their solid lattice surfaces and superfluid cores, pulsars are laboratories for physical conditions not attainable on the earth.

A binary pulsar whose orbital period has been monitored for 5 years (*40*) has produced the first convincing indirect evidence of the existence of gravitational waves, long predicted as a result of the general theory of relativity. The small but continual shortening of the orbital motion of the two objects is attributed to the energy dissipated by the radiation of gravitational waves. Experiments to detect directly the gravitational radiation from more intense sources (collapsing cores of supernovae, for example) are extremely difficult but presently under way (*41*).

The Sun

Solar physics during the 1970's has been evolving from an intensive study of our closest star to a broader inquiry into the behavior of ionized gas in gravitational and electromagnetic fields in stars. The sun acts as an almost "hands on" laboratory which can provide insight into phenomena such as mass loss, hot coronae, activity cycles, and heating. All of these processes are known to occur in a wide variety of stars.

The discovery of an unexpectedly low neutrino flux from the sun has forced a broad reevaluation of ideas concerning the structure and dynamics of the solar interior. The probable detection of neutrinos (*42*) at the level of 2.2 ± 0.4 solar neutrino units still remains too low a value by several times in comparison with the value predicted on the basis of recent laboratory and theoretical results. A reexamination of stellar models, abundances, and nuclear parameters, and of questions such as whether the sun has a rapidly rotating core or whether the interior undergoes episodes of mixing, will be imperative if we are to understand the solar interior. We are forced to conclude that the rate of burning in the solar interior is not as well understood as was once thought.

Understanding the nature of both large- and small-scale structures on the sun and their circulation is essential. Such motions are intimately connected with solar activity and possibly with long-term fluctuations of the sun, both of which may have direct consequences on terrestrial climate. The surprising discovery that the solar atmosphere has radial wave motions with a 5-minute period (*43*) has led to major theoretical studies of the generation, propagation, and damping of sound, gravity, and magnetic waves. The 5-minute oscillations are now being used to probe part of the solar interior in a manner analogous to seismological probing of the core structure of the earth.

George Hale's early investigations of solar magnetic fields made it possible to distinguish between strong magnetic fields in sunspots and a weak, 1-gauss general magnetic field of the sun. During the last decade, sophisticated observing techniques have revolutionized our concept of the solar magnetic field structure (*44*). In regions where a solar magnetic field occurs, its strength is very high (1500 gauss). The 1-gauss general magnetic field observed earlier was the result of the small size of these high-field magnetic elements, which were averaged over by the low-resolution magnetometers. Observationally, their true size is unknown; they are too small for resolution by even the best ground-based magnetograms. They may have the size of solar "filigree" (Fig. 7), the smallest structures that have been seen on the sun (< 0.3 arcsec), which appear to be cospatial with the magnetic elements. Theoretical attempts to explain the origin and stabilities of these magnetic flux tubes are under way.

The study of solar magnetism at a level of detail and quality never before possible will be a prime objective of the Solar Optical Telescope on the Space Shuttle. Major advances in our knowledge of solar (and, by implication, stellar) magnetic fields and their relation to solar activity, coronal structure, and heating are anticipated in the 1980's.

Several outstanding discoveries of solar physics during the past decade are related to the corona (*45*). The solar corona contains active regions with strong magnetic fields and closed (loop) configurations; quiet regions with weak fields, apparently closed on large scales; and coronal holes (Fig. 8) associated with weak magnetic fields having a diverging open configuration. Coronal bright points are small regions of intense x-ray and extreme ultraviolet emission associated with newly emerging magnetic flux into the corona. Coronal holes are the source of recurrent high-speed solar wind streams (1000 kilometers per second). Coronal transients are frequent mass-ejection events of large energy, important in restructuring the outer corona and in the flare process. All of these phenomena must be understood if we are to build a meaningful foundation for stellar wind theory. During the 1980's, satellites carrying x-ray telescopes and magnetographs with high-resolution imaging capability should provide data needed by theoreticians to address these problems not only for the sun but also for their astrophysical and geophysical implications.

Although the study of the stars and the sun leads ultimately to the study of the origin of the solar system, at present only a handful of astronomers and geophysicists are at work on these problems. Studies of abundances in meteorites, the debris from the formation of the planets, of planets and small particles in the solar system, of nuclear chronology, of stars just forming and stars with associated disks, all should increase our understanding of what it takes to make a solar system. Searches for planets about other stars, carried out with a variety of techniques including imaging them directly or noting their effect on the motions of the parent star, are likely to be undertaken during the 1980's. If we can detect other solar systems, then we may be able ultimately to detect other civilizations. And the detection and eventual communication with others in the universe is truly a goal for the future.

Conclusions

We live in a fascinatingly beautiful universe. For thousands of years, people have been looking at the sky and enumerating the objects; for hundreds of years astronomers have been using telescopes to discover fainter components. Only during the last 30 years have astronomers and physicists been able to look at the sky in wavelength bands other than that of visible light. Such views have shown us entirely new classes of objects and phenomena never imagined.

But astronomers during the past few decades have done more than discover and catalog. Fundamental insights into the complex interplay of all facets of the universe have emerged. Stars form from primordial gas, synthesize heavy elements, and return the enriched gas to the interstellar spaces as material for new generations of stars. The dynamics of spiral structure affect the star formation process in the galactic disk; the rates of star formation influence galaxy morphology. The particular cluster environment influences the morphology of galaxies, whether spiral or elliptical; cluster characteristics reflect galaxy evolution. The molecules in our bodies are formed from atoms synthesized in some star and deposited, probably explosively, into the primitive solar nebula. In the coming decades, it seems likely that astronomers will discover still more bizarre objects and will study their properties with innovative instrumentation on the ground and in space. During the 1980's, the inaugural flight of the Space Telescope is expected to show us wonders we can now only dimly perceive. From all of these studies we should be able to determine more about how the universe works. In *My First Summer in the Sierra*, John Muir wrote (*47*), "When we try to pick out anything by itself, we find it hitched to everything else in the universe." The thrust of astronomical investigation in the next decade will be to elucidate some of these connections.

References and Notes

1. R. A. Alpher and R. Herman, *Nature (London)* **162**, 774 (1948).
2. A. A. Penzias and R. W. Wilson, *Astrophys. J.* **142**, 419 (1965).
3. D. P. Woody, J. C. Mather, N. S. Nishioka, P. L. Richards, *Phys. Rev. Lett.* **34**, 1036 (1975).
4. D. P. Woody and P. L. Richards, *ibid.* **42**, 925 (1979).
5. G. F. Smoot, M. V. Gorenstein, R. A. Muller, *ibid.* **39**, 898 (1977); E. S. Cheng, P. R. Saulson, D. T. Wilkinson, B. E. Corey, *Astrophys. J. Lett.* **232**, L139 (1979).
6. A. Sandage and G. A. Tammann, *Astrophys. J.* **210**, 7 (1976); G. de Vaucouleurs and G. Bollinger, *ibid.* **233**, 433 (1979); P. J. E. Peebles, *Comments Astrophys.* **6**, 197 (1978); R. B. Tully and J. R. Fisher, *Astron. Astrophys.* **54**, 661 (1977); M. Aaronson, J. Huchra, J. Mould, *Astrophys. J.* **229**, 1 (1979).
7. J. R. Gott III, J. E. Gunn, D. N. Schramm, B. M. Tinsley, *Sci. Am.* **234**, 62 (March 1976).
8. B. M. Tinsley, *Astrophys. J. Lett.* **173**, L93 (1973).
9. J. P. Ostriker and S. D. Tremaine, *ibid.* **202**, L113 (1975); A. Toomre, in *The Evolution of Galaxies and Stellar Populations*, B. M. Tinsley and R. B. Larson, Eds. (Yale University Observatory, New Haven, Conn., 1977), p. 401.
10. D. O. Edge, J. R. Shakeshaft, W. B. McAdam, J. E. Baldwin, S. Archer, *Mem. R. Astron. Soc.* **68**, 37 (1960); C. Hazard, M. B. Mackey, A. J. Shimmins, *Nature (London)* **197**, 1037 (1963).
11. T. A. Matthews and A. R. Sandage, *Astrophys. J.* **138**, 30 (1963); M. Schmidt, *Nature (London)* **197**, 1040 (1963).
12. A. Stockton, *Nature (London)* **274**, 342 (1978); J. Kristian, *Astrophys. J. Lett.* **179**, L61 (1973); E. J. Wampler, L. B. Robinson, E. M. Burbidge, J. A. Baldwin, *ibid.* **198**, L49 (1975).
13. D. Walsh, R. F. Carswell, R. J. Weymann, *Nature (London)* **279**, 381 (1979); D. H. Roberts, P. E. Greenfield, B. F. Burke, *Science* **205**, 894 (1979).
14. H. Smith and D. Hoffleit, *Publ. Astron. Soc. Pac.* **73**, 292 (1961); M. Schmidt, *Annu. Rev. Astron. Astrophys.* **7**, 527 (1969); H. Tananbaum *et al.*, *Astrophys. J. Lett.* **234**, L9 (1979).
15. G. A. Seielstad, M. H. Cohen, R. P. Linfield, A. T. Moffet, J. D. Romrey, R. T. Schilizzi, D. B. Shafer, *Astrophys. J.* **229**, 53 (1979).
16. J. N. Bahcall and L. Spitzer, *Astrophys. J. Lett.* **156**, L63 (1969); A. F. Davidsen, G. F. Hartig, W. G. Fastie, *Nature (London)* **269**, 203 (1977); P. A. Strittmatter and R. E. Williams, *Annu. Rev. Astron. Astrophys.* **14**, 307 (1976).
17. R. F. Green and M. Schmidt, *Astrophys. J. Lett.* **220**, L1 (1978).
18. M. Seldner, B. Siebers, E. J. Groth, P. J. E. Peebles, *Astron. J.* **82**, 249 (1977).
19. A. Dressler, *Astrophys. J.*, in press.
20. A. Toomre and J. Toomre, *ibid.* **178**, 623 (1972).
21. W. G. Mathews and J. C. Baker, *ibid.* **170**, 241 (1971); S. M. Faber and J. S. Gallagher, *ibid.* **204**, 365 (1976).
22. C. Jones, F. Mandel, J. Schwarz, W. Forman, S. S. Murray, F. R. Harnden, Jr., *Astrophys. J. Lett.* **234**, L21 (1979); J. P. Ostriker, in *The Evolution of Galaxies and Stellar Populations*, B. M. Tinsley and R. B. Larson, Eds. (Yale University Observatory, New Haven, Conn., 1977), p. 369.
23. P. J. Serlemitsos, E. A. Boldt, S. S. Holt, R. Ramaty, A. F. Brisken, *Astrophys. J. Lett.* **184**, L1 (1973).
24. S. Smith, *Astrophys. J.* **83**, 23 (1936).
25. F. Zwicky, *ibid.* **86**, 217 (1937).
26. S. M. Faber and J. S. Gallagher, *Annu. Rev. Astron. Astrophys.* **17**, 135 (1979).
27. M. S. Roberts and A. H. Rots, *Astron. Astrophys.* **26**, 483 (1973); A. Bosma, thesis, Rijksuniversiteit te Groningen (1978); V. C. Rubin, W. K. Ford, Jr., N. Thonnard, *Astrophys. J. Lett.* **225**, L107 (1978).
28. B. D. Savage and K. S. de Boer, *Astrophys. J. Lett.* **230**, L77 (1979).
29. F. Bertola and M. Capaccioli, *Astrophys. J.* **200**, 439 (1975); G. Illingworth, *Astrophys. J. Lett.* **218**, L43 (1977).
30. C. C. Lin, *J. Soc. Ind. Appl. Math.* **14**, 876 (1966); _____ and F. H. Shu, *Astrophys. J.* **140**, 646 (1964); W. W. Roberts, Jr., M. S. Roberts, F. H. Shu, *ibid.* **196**, 381 (1975); E. B. Jensen, K. M. Strom, S. E. Strom, *ibid.* **209**, 748 (1976).
31. K. Y. Lo, R. T. Schilizzi, M. H. Cohen, H. N. Ross, *Astrophys. J. Lett.* **202**, L63 (1975), E. R. Wollman, T. R. Geballe, J. H. Lacy, C. H. Townes, D. M. Rank, *ibid.* **218**, L103 (1977).
32. D. S. Mathewson and M. N. Cleary, *Astrophys. J.* **190**, 291 (1974).
33. L. Van Speybroeck, A. Epstein, W. Forman, R. Giacconi, C. Jones, W. Liller, L. Smarr, *Astrophys. J. Lett.* **234**, L45 (1979).
34. G. Field, in *Confrontation of Cosmological Theories with Observational Data*, M. S. Longair, Ed. (International Astronomical Union Symposium 63, Reidel, Dordrecht, Netherlands, 1974), p. 13; P. Thaddeus, in *Star Formation*, T. de Jong and A. Maeder, Eds. (Reidel, Dordrecht, Netherlands, 1974), p. 37.
35. W. Herbst and G. E. Assousa, *Astrophys. J.* **213**, 473 (1977).
36. B. G. Elmegreen and C. J. Lada, *ibid.* **214**, 725 (1977).
37. J. P. Cassinelli, *Annu. Rev. Astron. Astrophys.* **17**, 275 (1979).
38. A. M. Clerke, *A Popular History of Astronomy During the Nineteenth Century* (A. and C. Black, Edinburgh, 1885), p. 52.
39. A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, S. A. Collins, *Nature (London)* **217**, 709 (1968).
40. J. H. Taylor, L. A. Fowler, P. M. McCulloch, *ibid.* **277**, 437 (1979).
41. J. Weber, *Sci. Am.* **224**, 22 (May 1971).
42. J. N. Bahcall and R. Davis, Jr., *Science* **191**, 264 (1976).
43. R. B. Leighton, R. W. Noyes, G. W. Simon, *Astrophys. J.* **135**, 474 (1962); R. F. Stein and J. Leibacher, *Annu. Rev. Astron. Astrophys.* **12**, 407 (1974).
44. E. N. Parker, *Sci. Am.* **233**, 42 (September 1975); *Cosmical Magnetic Fields* (Oxford Univ. Press, London, 1979).
45. G. L. Withbroe and R. W. Noyes, *Annu. Rev. Astron. Astrophys.* **15**, 363 (1977); G. S. Vaiana and R. Rosner, *ibid.* **16**, 393 (1978).
46. C. D. Shane and C. A. Wirtanen, *Publ. Lick Obs. 22* (part 1) (1967).
47. J. Muir, *My First Summer in the Sierra* (Houghton Mifflin, Boston, 1916, reprinted in 1979), page 157.

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