The Evolution of Galaxies

The evolution of galaxies, which involves large parts of nuclear physics, relativity, radio astronomy, spectroscopy, celestial mechanics, plasma physics, and even philosophy, received a good deal of attention at the 12th congress of the International Astronomical Union, held in Hamburg, Germany, 26 August to 4 September 1964 (*1*). Strongly linked with the more complete theories of stellar evolution, this topic cuts across studies of our Milky Way galaxy and its interstellar medium, stellar interiors, and stellar motions, as well as external radio sources of all kinds, the other galaxies, and cosmology; it was discussed by at least 12 of the 40 specialized commissions through which the Union organizes its activities. A large part of this discussion was stimulated by the discovery at Palomar in 1963 of the Quasi-Stellar Objects (popularly known as QSO's or "quasars"). These small, distant, and extremely luminous objects, of which only a dozen are known, possibly contain giant stars about a million times more massive than the sun, and may be in the process of gravitational collapse (*2*) to densities higher than any previously considered; however, they seem to represent a very minor fraction of the thousands of normal galaxies studied by astronomers, or of the millions counted in surveys of the sky.

The special discussion of evolution by Commission 28 (Galaxies) of the IAU was focused on three broad concepts which are expected to account for the observed variety among galaxies. (Little credence is now given to the idea that differences in age alone can account for the various types, which range from open spirals to smooth ellipticals.)

1) The initial conditions in a large gas cloud of low density determine its later evolution by contraction into a galaxy—or group or cluster of galaxies—observed today, 10^9 or 10^{10} years later. The steady-state cosmology of Bondi, Hoyle, *et al.* virtually requires this model because it postulates the condensation of stars from matter created uniformly throughout space; but McCrea proposed a modification of this theory, in which the rate of creation would depend on the previously existing local density of matter. In more conventional relativistic cosmologies that match the observed Hubble Law (that recession of galaxies is proportional to distance), the initial density would presumably depend on the epoch of formation (age) of a galaxy, but most of the studies of collapse start with densities from 10^{-29} to 10^{-31} g/cm^3.

2) There may be a low-density intergalactic medium from which galaxies accrue mass by gravitational attraction throughout their life history. This implies an increase with time in the mass of each galaxy and dependence of the evolution of the galaxy on external conditions, including collisions and captures. Radio observations of gas clouds falling into our own galaxy (the Milky Way) were reported by Oort, von Woerden, and others at Leiden.

3) The nuclei of galaxies, possibly formed by gravitational collapse, may release vast amounts of energy during relatively short periods, thus ejecting matter from a galaxy and thereby modifying the structure of the galaxy, or splitting it into separate galaxies in a group or cluster. This concept, originated by V. A. Ambartsumian at Erevan, Armenia, was the subject of a special conference (*3*) at the last IAU Congress in 1961. It is partly supported by recent radio observations of the nucleus and spiral arms of the Milky Way.

The Milky Way Galaxy

Of course, these three concepts are not entirely independent of and distinct from one another. The first, which can be said to include the other two, involves a statistical theory of star formation first developed by Salpeter for the Milky Way. Maarten Schmidt (California Institute of Technology) finds that the stars and interstellar material observed in the vicinity of the sun, together with the dynamics of the Milky Way, are consistent with a rate of star formation proportional to $\sigma_g{}^n$, with $n = 1 + q \log M_s$, where q is between 0 and 2, M_s is the mass of the star formed (in solar masses), and σ_g is the projected gas density. Schmidt uses the dynamical model of the galaxy, which is based on the latest radio observations of interstellar hydrogen and places the sun at $R_0 = 10$ kiloparsecs from the center, where the circular velocity is 250 km/sec, the escape velocity 380 km/sec, the Oort constant $A = 15$ km/sec kparsec, and the density projected on the galactic plane $\sigma = 75$ solar masses/parsec^2. (Note that 1 kparsec $= 10^3$ parsec $= 3.00 \times 10^{21}$ cm; 1 solar mass $= 2 \times 10^{33}$ g; 1 km/sec $= 1$ parsec/10^6 yr; 1 solar mass/parsec^2 $= 21 \times 10^{-5}$ g/cm^2; and since the thickness of the galaxy near the sun is about 1000 parsec, the local total density is $\rho = 10^{-23}$ g/cm^3 $= 6$ H atoms per cubic centimeter). The mass density in the plane varies with distance from the center (nucleus) of the galaxy: $\rho = 3.93/(R - 0.025R)$ for $R < R_0$, $\rho = 1450/R^4$ for $R > R_0$, according to Perek (Prague), the mass being distributed in spheroidal shells of eccentricity 0.99, 0.82×10^{11} suns' mass within R_0 and 0.93×10^{11} outside R_0 plus 0.07×10^{11} in the nuclear bulge, making a total mass of 1.82×10^{11} suns.

Schmidt takes the present projected gas density to be 15 suns/parsec^2 and matches the present distribution of stellar types by distributing the masses of new stars formed in 10^9 years in a square-parsec column through the galaxy where $\sigma_g = 15$ (constant) as follows: 0.001 supergiant (10^4 suns' luminosity); 0.04 giant (10^2 suns' luminosity); 0.08 solar type (1 sun's luminosity); 0.8 dwarf (10^{-2} sun luminosity). This involves more than one solar mass of gas ejected from supernovae per square parsec in 10^9 years and 110 to 230 solar masses of gas condensed to stars. It implies that an average atom in the interstellar gas has been in several previous stars and that this material is mixed over volumes of several million cubic parsecs. It has a bearing on the abundances of the chemical elements and may be extended to explain observed differences among the stars in different parts of the galaxy.

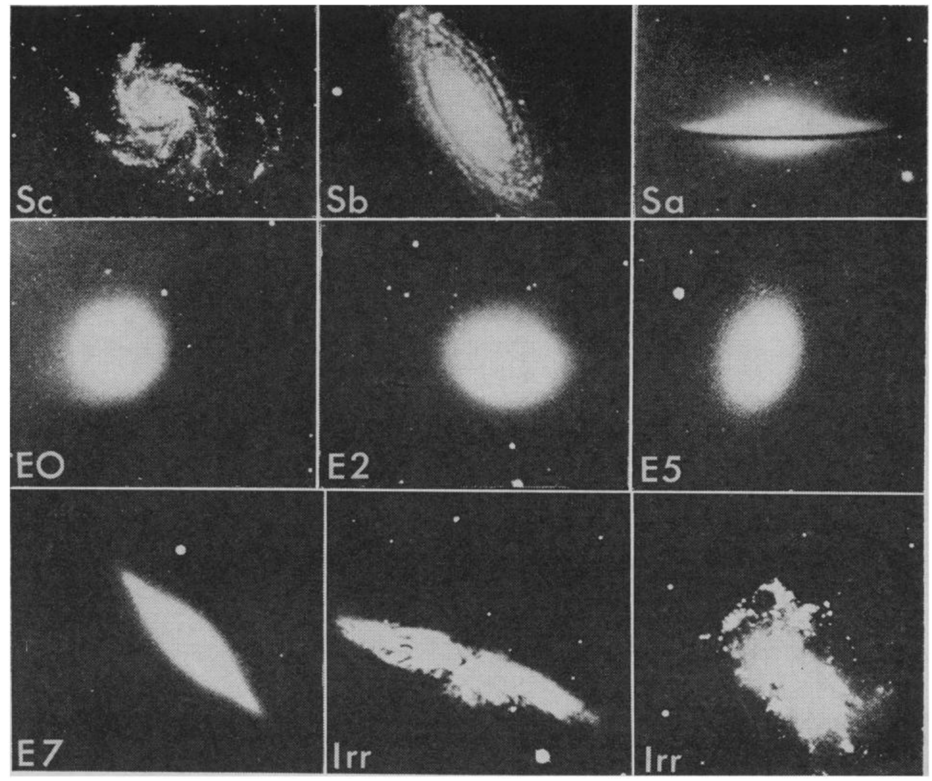
Other discussion—some of it in meetings of other commissions—cast doubt on three basic aspects of Schmidt's calculations:

1) In a special lecture, Oort emphasized that mass density probably was

not constant in time and may have changed by factors of 1000 or more in our galaxy and in most other galaxies over times of 10^9 or 10^{10} years.

2) Herbig (Lick Observatory) has shown that new stars of the T-Tauri type are distributed as if their rate of formation depended on the square of the density of interstellar *dust*, rather than gas. Some of the evidence indicates that the ratio of gas to dust varies widely, but Schmidt-Kaler (Germany) reported that reddening by interstellar dust corresponds closely to the interstellar hydrogen density.

3) Reddish (Edinburgh) has derived a different distribution of masses among newly formed stars with an assumed cut-off at 100 suns (the largest stars formed) and numbers increasing proportional to $M_s^{-2.3}$ to dwarfs as small as 0.02 suns. Fowler (Caltech), Hoyle (Cambridge), Chandrasekhar (Yerkes Observatory), and others have shown that much more massive stars can be stable and that some of these super-supergiants are probably formed in a large condensing gas cloud. However, the physics of ordinary star formation is imperfectly understood.



Types of spiral (Sc-Sa), elliptical (E0-E7), and irregular (Irr) galaxies. [Yerkes Observatory]

The rate of star formation is generally believed to be high in the arms of spiral galaxies, including those observed nearby in the Milky Way. The general rotary motion (observed primarily from measured Doppler shifts in the radio and optical spectra of gas clouds and in the optical spectra of stars) can be interpreted in terms of circular planetary motion in the plane of each galaxy, usually plotted as a smoothed function of distance from the center. The center of mass is generally assumed to be at the center of luminosity in an external galaxy. In the early analysis of nearly neutral-hydrogen (H-I) gas clouds from radio spectra, it was necessary to assume that the gas shared the general rotary motion of the stars in our galaxy in order to identify clouds at various distances from us, and the resulting plots of 21-cm radio emissivity then showed a three-arm spiral structure that agreed roughly with the spatial distribution of young blue stars and ionized-hydrogen (H-II) clouds observed optically. However, the H-I clouds were not everywhere continuous. W. W. Shane (Leiden) reanalyzed the radio observations on the assumption that the H-I clouds are smooth continuous bands. His curves plotting circular velocity against distance from the center of the galaxy now show irregularities, which are interpreted as irregularities in the gravitational potential due to increased density in the arms themselves. However, this extra density in each arm, over a region 250 parsec across, appears to be three or four times the H-I density derived from 21-cm (1430 Mcy/sec) emissivity.

The Australian radio astronomers Bolton and Kerr reported that the newly discovered radio absorption line due to OH at 1565 Mcy/sec shows evidence of motions different from those of neutral hydrogen, and a somewhat different distribution in the galaxy—possibly in thin filaments, as reported by Davies. This, together with the radially outward motion of H I (confirmed in arms on both sides of the center of our galaxy), raises the question of how spiral arms are formed and how they are maintained in a galaxy.

Bertil Lindblad reported calculations showing that, if the spiral arms contain 10 percent of the mass of a galaxy, they will maintain themselves by gravitational attraction. P. O. Lindblad programmed electronic computations of the motions of over 100 point-masses, starting with a plane array in three rotating rings. A perturbation of one of these rings causes the array to form a barred spiral with the arms leading, instead of trailing. Prendergast (Columbia University), finds that the stars in a barred spiral should move radially outward along the bar and spiral farther outward in the trailing direction.

An alternative theory is that the internal structure of a galaxy is due to gas streamers in which stars are forming, and that each streamer maintains a motion (probably influenced by magnetic fields) that carries it away from the stars formed from it. One such streamer discovered by the radio astronomers at Jodrell Bank in England was described by R. D. Davies as a faint lane of H-I emission that must be a jet or "spur" almost perpendicular to the plane of the galaxy. Oort explains this and another jet-like H-I cloud at 15° to the plane on the south side, as well as the outward motion of the spiral arms, as the results of a gigantic explosion some 200 million years ago. However, at present there is a rapidly rotating disk of neutral hydrogen, about 5×10^6 solar masses within 800 parsec of the nucleus, which shows no obvious sign of such a recent explosion. Goldberg reported that in observations from rockets above the earth's atmosphere x-rays from this nucleus were detected, providing possible evidence of a former explosion.

Quantitative observations of the arms in external galaxies are meager;

Baum reported photoelectric measures of M74, showing the high percentage of blue stars (spectral type A), and other photometric work was summarized by de Vaucouleurs. Merle Walker's high-resolution spectra obtained with an image tube at the Lick Observatory show that stars and interstellar gas have different internal motions in the peculiar galaxy NGC 1068, and E. M. Burbidge interpreted spectra of the spiral M51 in terms of helical motions around the arms. Detailed studies of M31, the nearby Andromeda Nebula, show that the center of radio emission differs from the center of optical brightness, as reported by Baldwin (Michigan), but that the circular velocities of stars from optical spectra reported by Münch (Palomar) match those of neutral hydrogen from radio spectra. However, radio observations of the nearer Magellanic Clouds by Kerr (Australia) show that H I often differs from optical measures of brightness and motion, although H-I clouds generally match the distribution and motions of blue stars.

In a summary of attempts to explain these motions and the fragmentary data, based on radio polarization measurements of magnetic fields in the galaxy, Donat Wentzel (University of Michigan) mentioned vortices in gas flowing slowly past stars, shock waves in high-velocity gas streams, and the magnetic shock waves in ionized gas. Much of the evidence indicates that these motions are caused by magnetic fields perpendicular to the planes of spiral galaxies, but how such a field can remain undistorted by internal plasma motions, and how it can influence the form of an evolving galaxy, cannot yet be predicted with confidence. One bizarre result based on solutions of the field equations of general relativity theory by Edelen (Rand Corporation) implies that stable galaxies can only occur in discrete sizes and shapes, some of which seem to be confirmed by photographs taken at Palomar.

Radio Galaxies

Matthews (Caltech) reported progress in identifying radio galaxies—the images on photographs near the center of strong radio sources or at the midpoint between a pair of radio sources. The problem is a difficult one because of poor precision (several minutes of arc error in most radio-source positions) and because some of the radio galaxies appear like faint stars—the very distant quasars. Although the study is not yet complete, the number of radio galaxies which have been identified so far is approximately as expected. However, the *types* of galaxies with strong radio emission are varied and cast doubt both on the evolutionary theory that radio emission or some kind of explosion occurs in the life of every galaxy and on the alternative theory that only certain types of galaxies can be radio emitters. Galaxies with jets and other extensions and with high-excitation emission-line spectra tend to be radio emitters, as do close pairs of elliptical galaxies and giant ellipticals near the centers of clusters. The strongest total fluxes (10^{45} ergs/sec or more) are associated with the quasars, giant ellipticals, and other structureless types, but the flat, structureless SO type of galaxy has not yet been identified among the hundred radio galaxies. Radio characteristics are similarly varied; Shakeshaft summarized radio-spectrum measures made at Cambridge as follows: on a log-log plot of flux against frequency, 80 percent are straight, 10 to 15 percent are curved downwards (too little flux at low frequencies, designated "C 1"), and 5 to 10 percent are curved upwards (designated "C 2"). There is some indication that the smaller sources, including 7 quasars, all have "C 1" spectra, but 4 other quasars have straight spectra. Davies reported that over 60 percent of the radio galaxies show polarization in radio frequencies, generally at a low level (2 to 5 percent).

In terms of the first two of the evolutionary concepts discussed earlier, Sciama claims to show that galaxies of about 10^{11} sun's mass would inevitably condense according to both steady-state and relativistic cosmologies. In both cases, the measured Hubble constant and gravitational constant require a mean density in the universe of 10^{-29} g/cm^3, whereas the observed masses and number-density of galaxies account for only 3 percent of this. The remainder cannot be neutral hydrogen because its 21-cm flux would be far larger than observed; hence Sciama assumes it to be ionized hydrogen and estimates the temperature to be 100,000°K. Thermal instability in this medium (due to increased radiation from a region of higher density) will produce concentrations of 10^{11} suns' mass in 10^{10} years. The numbers fit almost too well, and may not allow for the formation of groups and clusters of galaxies, many of which are observed. Moreover, the density 10^{10} years ago would have been far larger than 10^{-29} g/cm^3, according to relativistic cosmology.

Aging of Galaxies

However they are formed, newborn stars in a galaxy will age in a way that has been firmly established by studies of nuclear reactions in stellar interiors and by observations of star clusters of various ages. Once formed, a batch of normal stars is expected to redden and to produce novae and supernovae, returning some fraction of the mass to the interstellar medium, leaving the rest as white dwarf stars, and generally becoming fainter and redder with age. Erik Holmberg (Uppsala) finds evidence of this aging process in strong correlations between the colors, hydrogen gas contents, ratios of mass to luminosity, and mean mass densities of galaxies (*4*). Using his own photometric measures on photographs taken at the Mount Wilson Observatory and photoelectric observations of others, he has colors and luminosities (using distances from the Hubble Law) for over 300 galaxies. Data on masses (M) are limited to 25 single galaxies and mean values for 65 pairs studied statistically by Page (*5*).

After correcting the observed colors and luminosities (L) for local obscuration in our galaxy, for tilt (the obscuration due to dust in the galaxy observed), and for red shift, Holmberg finds

$$\log M/L = 2.15(C - 0.15)$$

with a correlation coefficient better than 0.9, and he uses this to estimate M for the rest of the galaxies observed. These values of M vary from 5×10^9 to 10^{12} suns and are not well correlated with color, luminosity, or type. However, the mean mass density (ρ) computed from the linear dimensions, and varying over the range from 0.1 to 30 suns per cubic parsec, is well correlated with color (C) and morphological type, which ranges from the low-density irregular form Irr I through spiral forms Sc, Sb, and Sa, stellar objects (SO), to the high-density irregular form Irr II and elliptical (E) galaxies.

Holmberg interprets this as a result of more rapid star formation at higher density and assumes that the evolutionary track of a galaxy on a plot of log ρ against C would be roughly a horizontal line (constant density) from an initially very blue color. The denser protogalaxies reddened most rapidly, becoming the elliptical galaxies and stellar objects that we see today; the less dense ones have evolved more slowly to Irr I and Sc types, and the least dense ones are probably unobservable. He points out that the lack of scattered points on this plot (no blue galaxies of high density, for instance) implies a single age for all galaxies—possible evidence against the steady-state cosmology.

It was pointed out that a volume change in collapsing gas clouds would increase log ρ by 3 or more during the life of a galaxy, in which case the evolutionary tracks could well be *along* the sequence from Irr I through Sc, Sb, Sa, SO, and Irr II to E. Moreover, other types such as dwarf ellipticals are not yet represented, and may not fall along the narrow sequence.

Page reported calculations which showed that evolving stars would not have the observed values of $M/L = 50$ to 100 after lifetimes of 10^{10} years unless a large proportion of the newly formed stars were of very low mass (0.01 sun) and said that this could not be corrected by changing n, the power of σ_g in Schmidt's formula for the rate of star formation. He expects that the size of smallest star formed depends on turbulence in the protogalaxy gas cloud, and notes that the angular momentum (roughly estimated from inclinations of lines in spectra of galaxies) shows a trend from low values for E galaxies to higher values for Sc types. There is a possibility that some of the mass in E galaxies with low angular momentum has collapsed to densities exceeding the Schwarzschild limit, in which case it would be invisible in all electromagnetic radiation, but would still influence the gravitational potential in its vicinity.

Although Bondi and McVittie disagreed with this possibility, G. Burbidge and Fowler upheld it, and Zwicky reported observations of "compact galaxies" that support it. He and Herzog have discovered on Palomar photographs 300 fuzzy images, forming a sequence from 10 seconds of arc to less than 1 second of arc, in such numbers that he expects that there is an average of one brighter than the 17th magnitude for every 2 square degrees all over the sky. Spectra of 16 of them show broad lines indicating large mass and red shifts from 1,000 to 30,000 km/sec. Quasars are probably one extreme of this sequence, and clusters of galaxies like the Coma Cluster may form the other extreme.

Other reports and comments confirm the general impression that the study of evolution of galaxies is now in an early stage of development comparable to that of the study of stellar evolution in 1935. There is an evolutionary pattern evident in the various correlations and sequences, and possibly in the variety of peculiar galaxies. More observations are needed to fill in the gaps indicated by theoretical studies, and new instruments were discussed for such purposes. Three new spectrographs have been built for the larger telescopes in the southern hemisphere (at Pretoria, South Africa, Cordoba, Argentina, and Mt. Stromlo, Australia). Leo Goldberg described far ultraviolet spectra down to x-ray wavelengths obtained by rockets fired above the earth's atmosphere. The Canadian "Alouette" satellite will carry a radio telescope above the ionosphere for measurements at frequencies down to 1 Mcy/sec, and the NASA Orbiting Astronomical Observatory program may have a 100-inch optical telescope in space by 1975.

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High-Energy Physics

At the 12th International Conference on High-Energy Physics which was held in Dubna, Russia, 5–12 August, a most exciting report was presented by J. Cronin and V. Fitch (Princeton) giving evidence for the apparent nonconservation of CP (C, charge reflection; P, parity or spatial reflection) in K_2^0 decays. The experiment was carried out in a simple and elegant manner at the alternating-gradient syncrotron accelerator at Brookhaven National Laboratory and consisted in observing that K_2^0's (the long-lived particle mixture of K^0 and $\bar{K}^0$ mesons) decay into π^+ and π^- mesons with a charged-particle branching ratio of $2.0 \pm 0.4 \times 10^{-3}$. Earlier