Primeval Galaxies

The first galaxies to form after the "big bang" have not been seen, but there is good reason to believe they could be. The characteristics of older galaxies suggest what those of younger ones would be like

by David L. Meier and Rashid A. Sunyaev

Since the speed of light is finite, the astronomer can in principle look back in time almost to the creation of the universe by observing objects so distant that their light has taken nearly 16.5 billion years, the current best estimate for the age of the universe, to reach the solar system. In particular there is the intriguing prospect that at those great distances one could observe galaxies in the process of formation. Since it is believed most galaxies formed the same way, the investigation of such primeval galaxies should help to explain how our own galaxy came into being 13 billion years ago. The search for primeval galaxies has not yet been successful, partly because they would be difficult to distinguish from other faint objects such as quasars. Moreover, they should be so far away that many may be too faint to be detected with current telescopes.

The situation should improve in 1985, when the superpowerful space telescope is scheduled to be launched by the Space Shuttle. With 10 times the resolution of the best optical instrument now available, the space telescope should be able to detect stellar objects 100 times fainter than any that have been detected so far. Even diffuse objects such as distant galaxies should be visible at much greater distances than they are at present. Our own work has centered on determining the properties of a primeval galaxy, for example its spectrum and the nature of its photographic image, so that astronomers will be able to identify one when they see it.

According to prevailing cosmological theory the universe began with an explosion from a superdense state in which the rate of expansion increases with the distance from the observer. The wavelength at which electromagnetic radiation from a distant object reaches the earth is increased by the velocity of recession of the object with respect to the observer. This is the well-known red shift, so named because if the radiation is in the visible region of the spectrum, it is made redder. The amount of the red shift is a measure not only of the remoteness of the object but also, since one is looking backward in time, of its age since the "big bang."

The greater the red shift, the younger the galaxy. The nearest galaxies, comparable in age to our own, are about 20 million light-years away and are receding with a red shift of .001, or .1 percent. Above a red shift of .1 quasars enter the picture. These ancient starlike objects are quite common at red shifts near 2.5. It is generally believed quasars exist at the center of otherwise normal galaxies. This suggests that the galaxies formed before the quasars, and so primeval galaxies must have a red shift of more than 2.5. An upper limit on the red shift of a galaxy in the process of formation can be determined by extrapolating backward from the present-day universe to the time when the galaxies were touching one another. That happens at a red shift of roughly 100, which represents the earliest possible time when galaxies could have been separate entities.

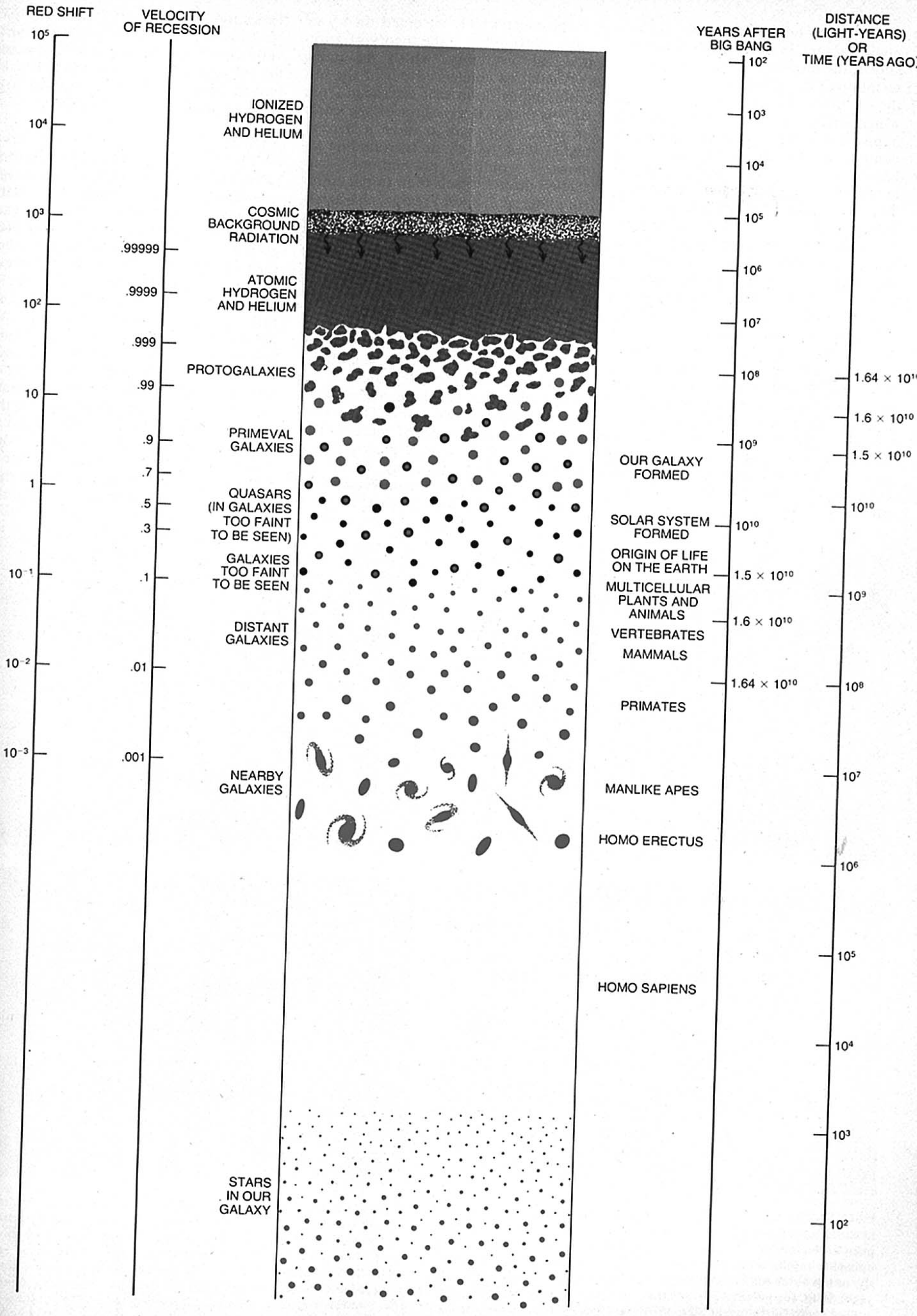
The search for primeval galaxies between red shifts of 2.5 and 100 is an extremely difficult undertaking. Indeed, no one has yet proposed a single convincing candidate for a primeval galaxy. The reason is that primeval galaxies should be quite faint at such great distances. The most distant galaxy detected so far lies at a red shift of only .75. It is even possible that the space telescope will not be able to detect normal galaxies at the high red shifts characteristic of primeval ones. There is much evidence, however, that galaxies in the process of formation have many more bright stars than they do at any other stage in their life cycle. This means that they should be much brighter than normal galaxies at the same red shift. The implication is remarkable: some primeval galaxies and perhaps all of them could be within the reach of current instruments.

The faintness of primeval galaxies nonetheless makes them difficult to distinguish from other faint objects such as quasars. Many astronomical phenomena, whatever their nature and their distance, look alike on photographic plates. Photographs that record faint objects pick up distant stars in our galaxy, distant quasars and distant normal galaxies. On sensitive photographic plates galaxies can often be distinguished from stars and quasars only by their larger and somewhat more diffuse images, and the fainter the object, the less obvious the distinction. Usually objects can be best identified by general features in their spectra: quasars have emission lines but normal galaxies do not, and galaxies have red shifts but stars do not.

None of these distinctions, however, may serve to identify a galaxy in the process of formation. The bright, hot, massive stars that are expected to exist in primeval galaxies would ionize the gas in the medium between the stars, so that the spectrum of such a galaxy would include emission lines. It is conceivable, then, that primeval galaxies might be mistaken for quasars because of their strong emission lines and large red shifts. More information is needed on the expected spectrum of a primeval galaxy and how it differs from that of a quasar.

To determine the expected spectrum we have relied on theoretical models

HISTORY OF THE UNIVERSE, presented here on a logarithmic scale, can be viewed through telescopes because of the finite speed of light. In principle the astronomer can look back in time almost to the creation of the universe by observing objects so distant that their light has taken 16.5 billion years, or the age of the universe, to reach our galaxy. The remoteness of an object is measured by its red shift: the speed of recession of the object divided by the speed of light. Here the velocity of recession is expressed as a fraction of the speed of light. To the left of the central panel are listed those astronomical objects that predominate at various red shifts. To the right of the panel, to illustrate the "look back" effect, are listed some events in the history of the earth and its biological evolution that occurred at the corresponding look-back time.


RED SHIFT
VELOCITY OF RECESSION
YEARS AFTER BIG BANG
DISTANCE (LIGHT-YEARS) OR TIME (YEARS AGO)
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
.99999
.9999
.999
.99
.9
.7
.5
.3
.1
.01
.001
IONIZED HYDROGEN AND HELIUM
COSMIC BACKGROUND RADIATION
ATOMIC HYDROGEN AND HELIUM
PROTOGALAXIES
PRIMEVAL GALAXIES
QUASARS (IN GALAXIES TOO FAINT TO BE SEEN)
GALAXIES TOO FAINT TO BE SEEN
DISTANT GALAXIES
NEARBY GALAXIES
STARS IN OUR GALAXY
OUR GALAXY FORMED
SOLAR SYSTEM FORMED
ORIGIN OF LIFE ON THE EARTH
MULTICELLULAR PLANTS AND ANIMALS
VERTEBRATES
MAMMALS
PRIMATES
MANLIKE APES
HOMO ERECTUS
HOMO SAPIENS
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
1.5×10^{10}
1.6×10^{10}
1.64×10^{10}
1.64×10^{10}
1.6×10^{10}
1.5×10^{10}
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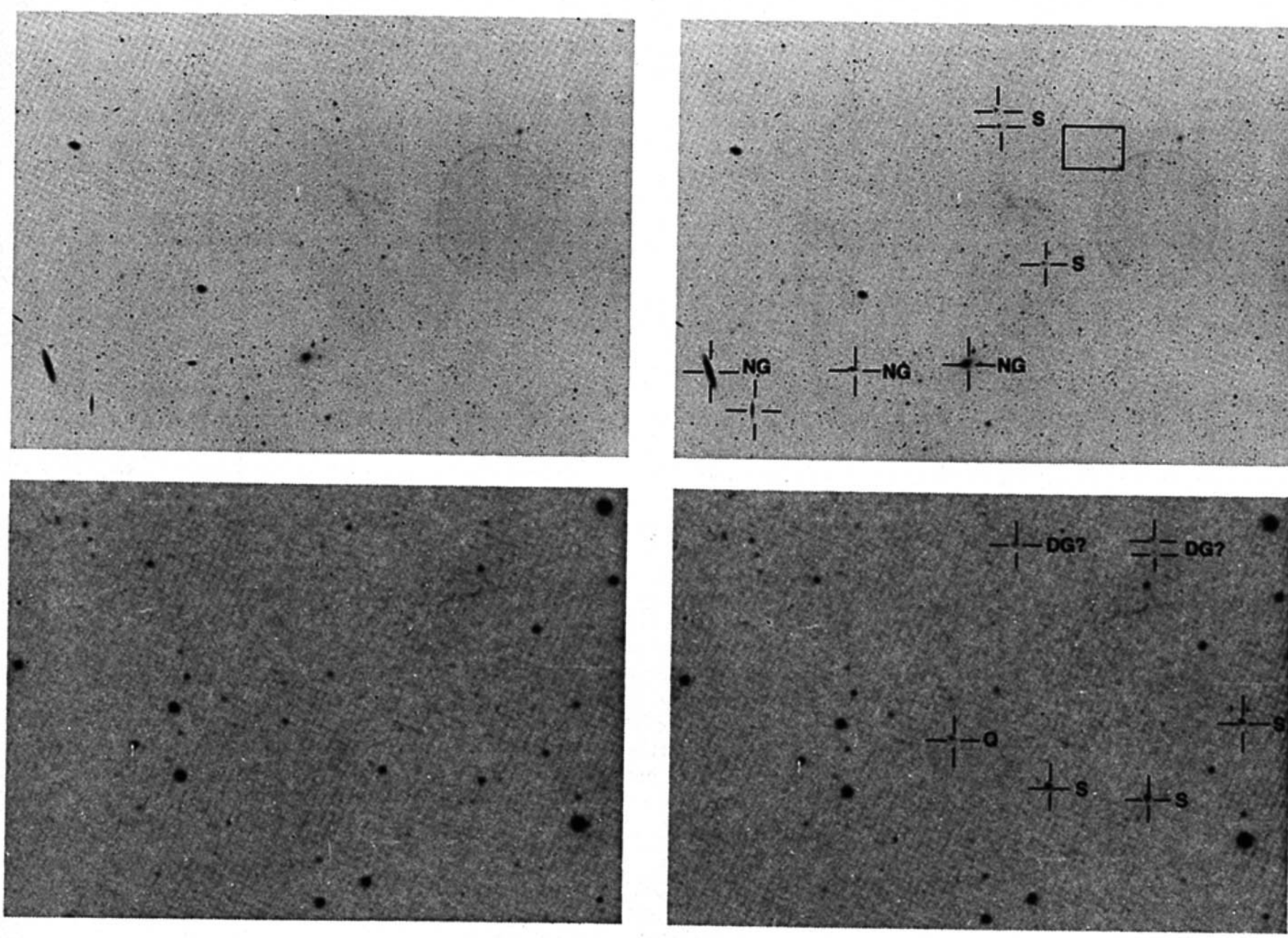
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2

of the formation of galaxies. Because many factors in such models are unknown the models are only a crude description of the real thing. Nevertheless, they provide the only information on which astronomers can depend until the happy day when a primeval galaxy is definitively identified. Such models are based on results from many different areas of astrophysics and cosmology. They incorporate the physical processes known to govern a galaxy: the macroscopic ones of stellar and gas dynamics that determine the galaxy's overall size and shape and the microscopic ones of stellar formation, evolution and death that determine the properties of the galaxy's constituent stars. Apart from the observational resemblance between primeval galaxies and quasars the two kinds of object may be related in a deeper sense. Quasars are physically distinct from galaxies, but as we have mentioned they seem to exist in galaxies and they were more abundant in the infant universe. As a result they are probably connected in some way with the formation of galaxies.

The most widely accepted theory of galaxy formation is the theory of gravitational instability, which maintains that galaxies condensed out of the hot cosmological fluid that expanded from the big bang. If a region of the early universe happened to have a density higher than that of the surrounding regions, it would be gravitationally attracted more to itself than to the ambient material. If such a region, characterized as a perturbation, was free of gas or radiation pressure, it would contract under its own gravity and hence would increase in density. This contraction process would create "droplets" out of a universe that previously was quite homogeneous.

The scale of the perturbations probably ranged from the mass of a globular star cluster (10^6 times the mass of the sun) to the mass of a large aggregate of galaxies (10^{15} solar masses). The perturbations that are the size of galaxies (10^{11} solar masses) are called protogalaxies. Initially each protogalaxy would expand with the rest of the universe, but it would do so at a slightly lower rate. After a few hundred million years it would stop expanding even though the universe continued to expand. At that point the protogalaxy would in effect be detached from the universe, free to collapse on itself and form a galaxy.

What do we mean when we say a galaxy has formed? For a protogalaxy to become a galaxy two things must happen. First, a population of stars must form from the protogalactic gas. Second, the gas and stars must come together to form the well-ordered structure of a galaxy. The second process is fairly well understood. With a high-speed computer it is straightforward to follow the collapse of a model protogalaxy by solving the equations of motion for stars and gas under the influence of their mutual gravity. Not much is known, however, about how the stars actually formed out of the gas in the course of its collapse. What little is known comes from observations of our galaxy and nearby galaxies. Such observations suggest possible events that could trigger star formation and also the



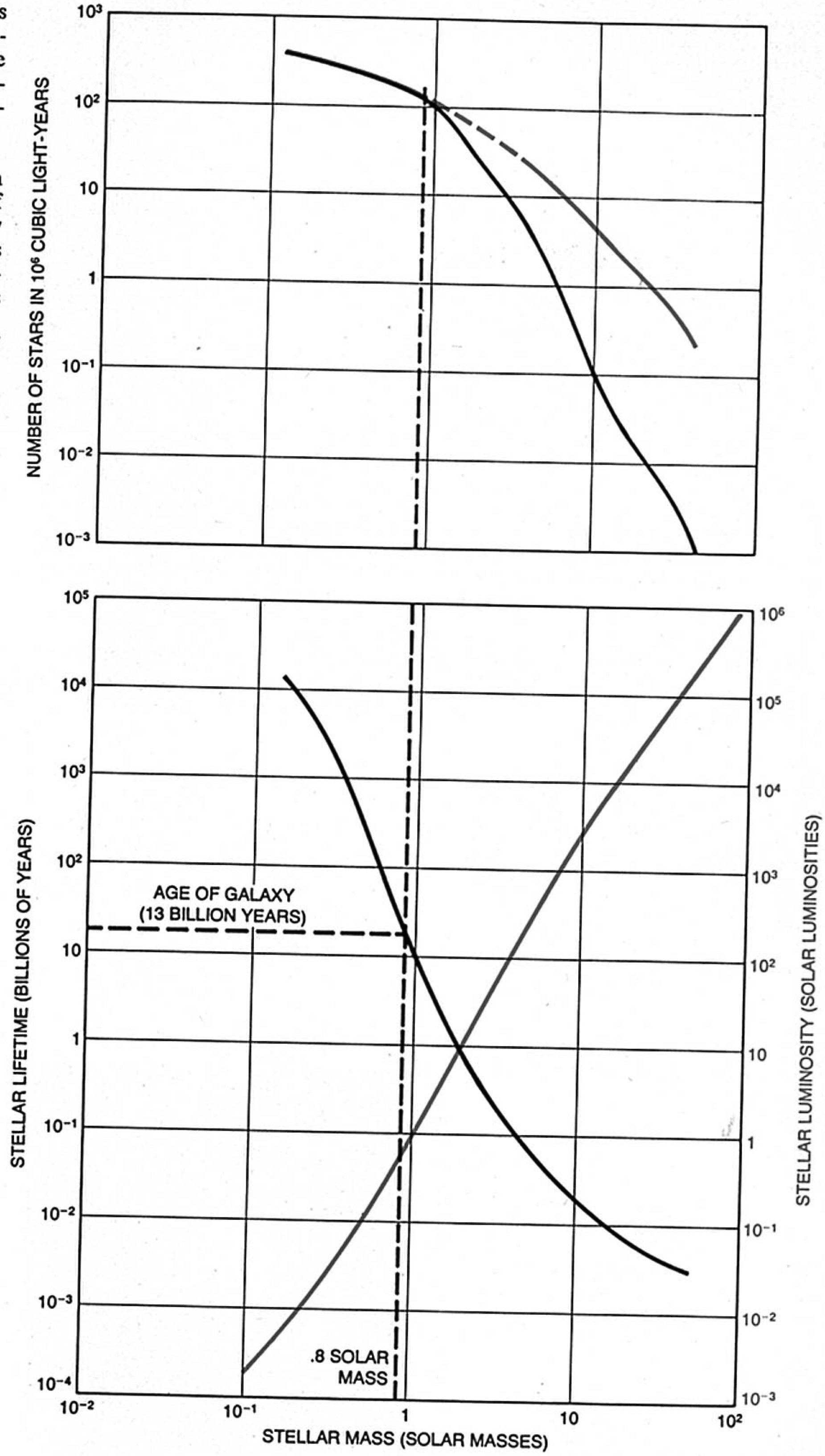
FAINTNESS OF PRIMEVAL GALAXIES makes them difficult to distinguish from other faint objects such as quasars. The negative print at the top left, made with the 48-inch Schmidt telescope on Palomar Mountain, is of a fairly large (1.5 by two degrees) region of the sky at the outer edge of the Virgo cluster of galaxies 45 million light-years from our galaxy. The positions of a few nearby galaxies (*NG*) and of some fairly bright stars (*S*) in our galaxy are marked on the duplicate of the print at the top right. The print also records a multitude of extremely faint objects. Some of them are possibly primeval galaxies. Most of the primeval galaxies, however, are probably too faint to be seen. The print at the bottom left is of the boxed region (eight by 11 minutes of arc) of the top photograph. The positions of several faint stars (*S*), a quasar (*Q*) and candidates for distant galaxies (*DG?*) in this region are marked on the duplicate at the bottom right.

proportions of stars of different masses that are created in a burst of star formation. With this information it is possible to develop a computer-generated semiquantitative description of galaxy formation.

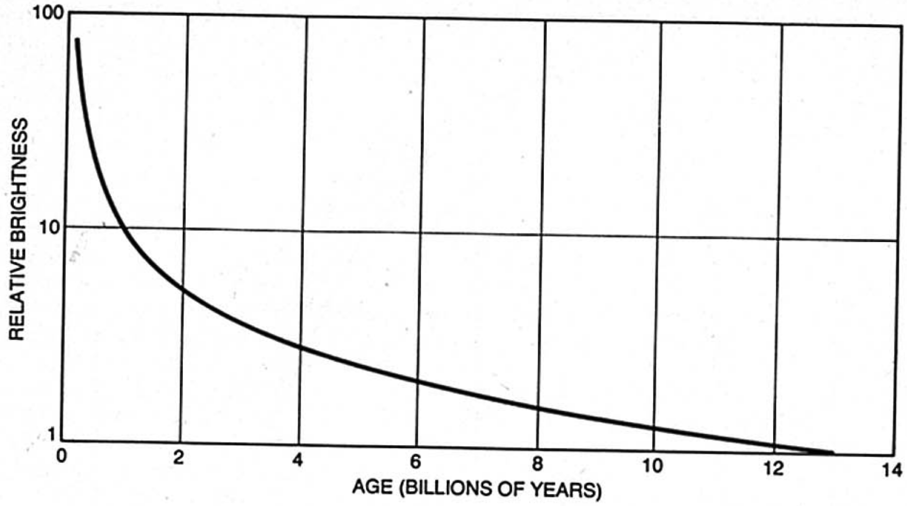
Like galaxies, stars probably form from the interstellar gas because of gravitational instabilities. Unlike galaxy formation, however, star formation is generally not a spontaneous process because the pressure of the interstellar gas is usually sufficient to prevent perturbations as small as stars from collapsing. If the gas is compressed by some violent phenomenon, the density can increase to the point where gravity overcomes the gas pressure and the perturbations contract into stars. In our galaxy the violent phenomena include a spiral density wave of the kind that is responsible for the pinwheel structure of disk galaxies and also shock waves from supernova explosions and from the expanding regions of ionized gas that surround hot massive stars. In other galaxies star formation may also have been triggered by collisions or near collisions with neighboring galaxies. In a protogalaxy the violent collapsing motion itself is probably the chief process that causes stars to form. A protogalaxy can be regarded as a system of gas clouds racing in orbit and giving birth to stars when the clouds collide.

Observations of the stars in the vicinity of the sun have made it possible to estimate the distribution of stars of different masses that will be created in any burst of star formation. Such a distribution is termed the initial mass function. The present-day local mass function—the mass distribution of stars in the neighborhood of the sun—includes many stars weighing less than .8 solar mass but only a few weighing more than that. More massive stars are scarce because such stars burn faster and hence do not live as long. The sun will live for 10 billion years, but a star with only 10 times the sun's mass would shine with 20,000 times the luminosity and would live for only 10 million years, or a thousandth as long. Stars weighing more than .8 solar mass have lifetimes that are shorter than the age of the galaxy, and so such stars that formed when the galaxy was created 13 billion years ago have died out.

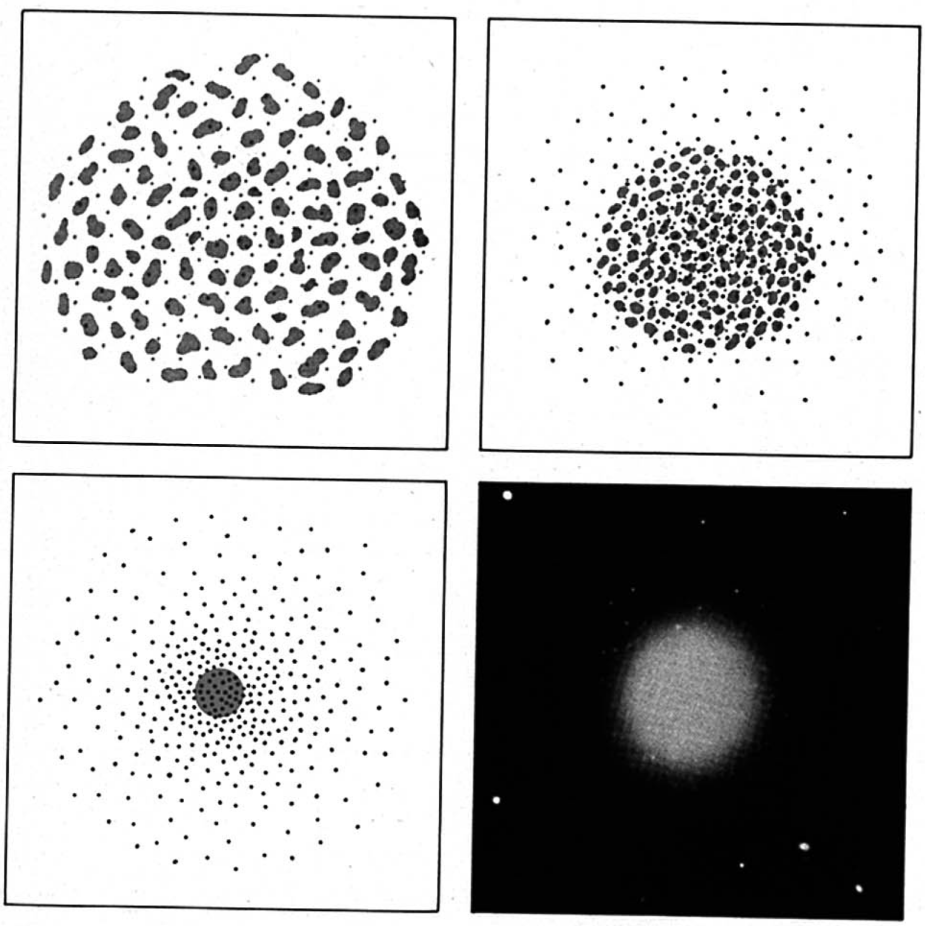
Stars weighing less than .8 solar mass have lifetimes that are longer than the age of the galaxy. The stars in this lower mass range have been increasing in number in the course of many bursts of star formation, and so the relative mass distribution of the stars must be identical with that of the stars created in any one burst, assuming of course that stars have always formed the same way. In other words, below .8 solar mass the present-day local mass function is



INITIAL MASS FUNCTION, the distribution of stars of different masses that will be created in a burst of star formation in a galaxy, is shown in the top diagram. The black curve represents the current mass distribution of stars in the neighborhood of the sun. Stars with a mass of .8 times the mass of the sun have lifetimes that are longer than the age of the galaxy, and so the mass distribution of these stars is the same as it was initially. The more massive the star is, however, the faster it burns (*bottom black curve*). Stars with a mass of more than .8 solar mass have lifetimes that are shorter than the age of the galaxy, and so the stars that formed 13 billion years ago when the galaxy was created have died out. At masses above .8 solar mass the initial mass function (*top colored curve*) can be determined by extrapolating backward in time, replacing the dead stars with live ones. Although the number of stars decreases with increasing mass, the decrease is not sufficient to overcome the increase in stellar luminosity with mass (*bottom colored curve*). This means that the luminosity of a newly formed cluster of stars is quite high and is accounted for chiefly by the bright and short-lived massive stars belonging to the cluster.



LUMINOSITY OF A STAR CLUSTER is highest when it forms because of the multitude of bright massive stars. As these short-lived stars burn out, the luminosity of the cluster decreases rapidly. "Relative brightness" is determined by dividing the luminosity of a population of stars by the luminosity at the age of 13 billion years, the age of our galaxy. That is, the relative brightness of a stellar population is a measure of how many times brighter it once was than it is now.



GALAXY FORMATION according to some computer models begins with a cluster of small massive clouds of gas about 200,000 light-years in extent (*top left*) that collide, collapse and form a population of bright stars (*colored dots*). As the clouds fall inward into a smaller volume because of their mutual gravitational attraction the rate of star formation increases. After about 200 million years the protogalaxy is roughly 100,000 light-years across (*top right*) and the first population of stars (*black dots*) has died out. The clouds of gas continue to contract at an increasing rate. After about 300 million years the gas is packed into the center of the galaxy, bringing star formation to a peak rate (*bottom left*). The dense nucleus of stars in the galaxy is perhaps only 10,000 light-years in extent. At this stage the galaxy is one of the brightest objects in the universe. From a great distance, however, even such a luminous galaxy would resemble a faint star. After this stage star formation ceases because the gas in the galaxy has been exhausted. As brighter stars die out, leaving behind the older and fainter ones, the galaxy shines less brightly but more steadily as a giant spherical structure, such as the galaxy M87 (*bottom right*).

the initial mass function. Above .8 solar mass the initial mass function can be determined by extrapolating backward in time by replacing the dead stars with living ones. The resulting relation, which was derived by Edwin E. Salpeter of Cornell University, indicates that whenever a group of stars is created, for each increase by a factor of 10 in the mass there is a decrease in the number of stars by a factor of 22.

If the Salpeter relation holds for all episodes of star formation, it has startling implications for galaxy formation and for the search for primeval galaxies. Although the number of stars decreases with increasing mass, the decrease is not sufficient to overcome the increase in stellar luminosity with mass (a factor of about 10,000 for each increase by a factor of 10 in mass). This means that the luminosity of a newly formed cluster of stars is quite high and is due chiefly to the bright and short-lived massive stars. After a short time, however, the bright stars die out and the luminosity of the cluster rapidly decreases. As a result a primeval galaxy, in which stars would be expected to form at a much higher rate than they are forming in present-day galaxies, should be quite bright.

Richard B. Larson of Yale University has developed complex computer models of three types of galaxy—spherical, elliptical and disk—in the process of collapsing. The spherical galaxy is the brightest, and so it is the best candidate for a detectable primeval galaxy. After the protospherical galaxy reaches its maximum expansion its gas begins to contract and its small internal clouds accelerate, collide and form stars. Most of these stars will continue to burn for billions of years and their orbits will be responsible for the overall shape of the galaxy. The massive stars, however, soon explode violently, hurling into the interstellar gas the nuclei of the heavy elements synthesized by nuclear reactions in their interior.

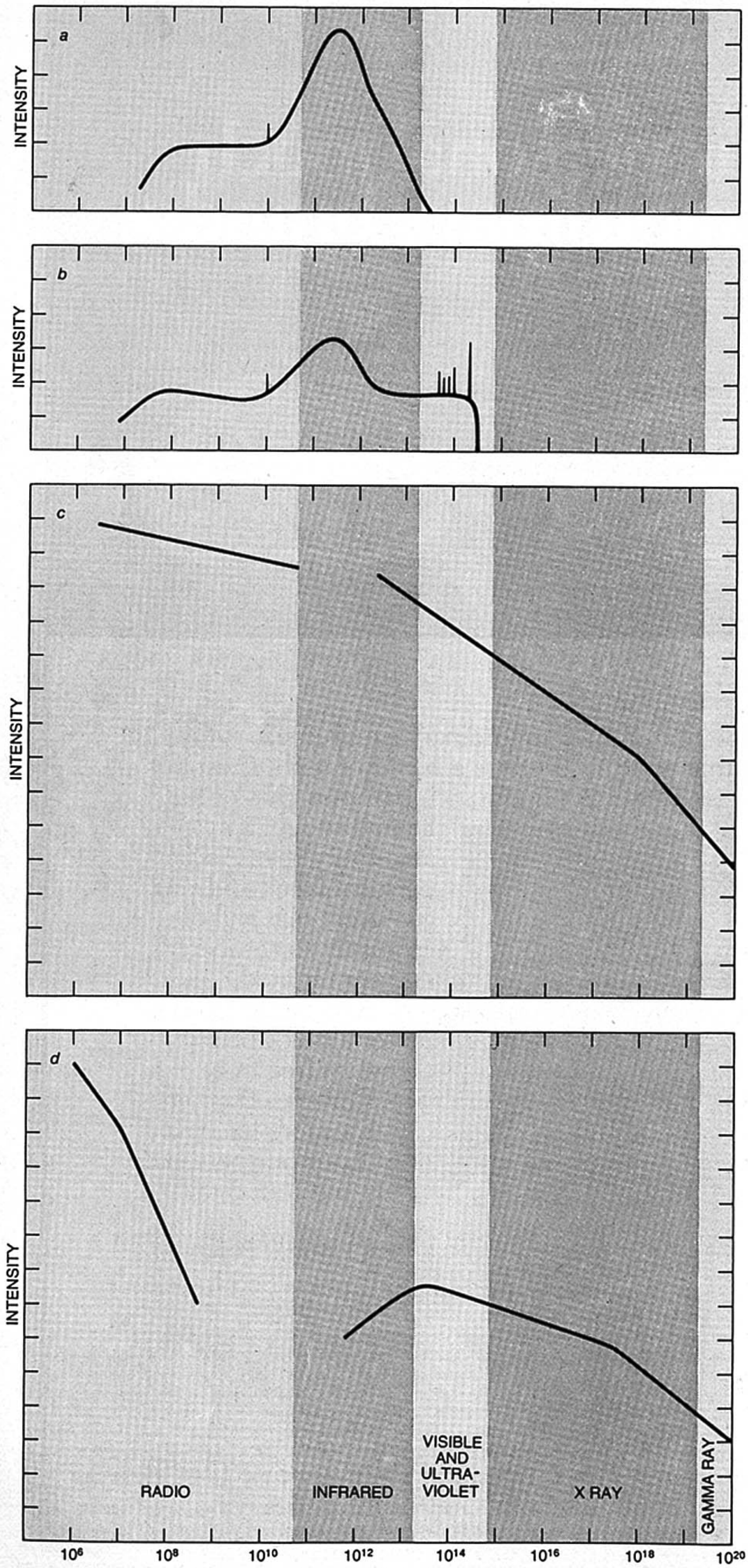
Once the stars have formed, their dynamical behavior is different from that of the gas. The orbits of the stars simply conform to the shrinking shape of the galaxy. The gas clouds, however, tend to collide with other gas clouds, so that their orbits decay and the clouds plunge toward the center of the galaxy. This causes the entire cycle of cloud collision, star formation, stellar explosion and heavy-element enrichment to proceed even faster. Eventually the gas is packed into the center of the galaxy, bringing star formation to a peak rate. Within a few thousand light-years of the center hosts of stars are shining brightly and exploding, gas is glowing and the dust of heavy elements is radiating copiously in the infrared. At this stage the galaxy is one of the brightest objects in the universe, hundreds of times more luminous than the galaxies of today.

Then the activity of the galaxy abruptly stops. The gas has been exhausted; there is no more left to collapse into stars. The remaining bright stars burn out quickly. As the stars with average lifetimes begin to die, leaving the older and fainter ones behind, the galaxy shines less brightly but more steadily as a giant spherical structure.

Such models of galaxy formation suggest that most primeval galaxies were born between 100 million and a few billion years after the big bang. That puts them at red shifts of between about 3 and 30, which is in accord with the earlier estimate we made on the basis of quasar red shifts. Through current telescopes most primeval galaxies with lower red shifts would be barely visible and those with higher red shifts would be completely invisible. Exceptionally bright primeval galaxies, however, should be quite apparent. The space telescope may be able to detect all primeval galaxies except those with the highest red shift.

The model also suggests that the ratio of the brightness of a galaxy's nucleus to the brightness of its outer regions is greater for a primeval galaxy than it is for a normal one. This means that the images of primeval galaxies resemble the images of quasars and stars, and so it is understandable that they have been difficult to distinguish. At a distance of 16 billion light-years the bright nucleus, although it would be thousands of light-years in diameter, would be only a second of arc in apparent diameter. The space telescope will be able to clearly resolve the structure of such an object. Indeed, thousands of primeval galaxies should eventually be detectable in a square degree of sky.

Working with Beatrice M. Tinsley of Yale University, we undertook to calculate the expected spectrum of a primeval galaxy. We were able to secure much information from our own galaxy, as had been the case with the determination of the initial mass function of the stars in the universe. In a primeval galaxy the infant stars and the objects associated with them should contribute to the spectrum of the galaxy. Although



SPECTRA OF MASSIVE STARS at various stages in their life cycle will contribute to the spectrum of a primeval galaxy. Massive stars shrouded by clouds of dust emit radio waves that penetrate the dust (*a*). The dust absorbs radiation of longer wavelengths but reradiates the energy of the radiation in the form of thermal emission in the infrared. Carbon monoxide in clouds of molecules contributes a sharp emission line at 115 gigahertz (billion cycles per second). The intensity of visible and ultraviolet radiation is much greater for stars in which the shrouding dust has been dispersed or destroyed (*b*). An exploding massive star leaves a remnant that emits radio waves and X rays (*c*). Pulsars also emit radio waves (*d*).

these stars and objects are distant and ancient, they are expected to be almost identical with the stars and objects in our galaxy. This close similarity is quite likely because the model suggests that heavy elements are created and distributed early in the collapse of a protogalaxy, giving an infant star the same chemical composition, and hence the same spectrum, as an infant star in our galaxy. As a result all the ingredients for determining the properties of remote and ancient primeval galaxies are present in our galaxy. To calculate the spectrum of a primeval galaxy we simply estimated the prevalence of various objects in such a galaxy, took their spectra from how they appear in our galaxy and summed the spectra according to the prevalence of the objects.

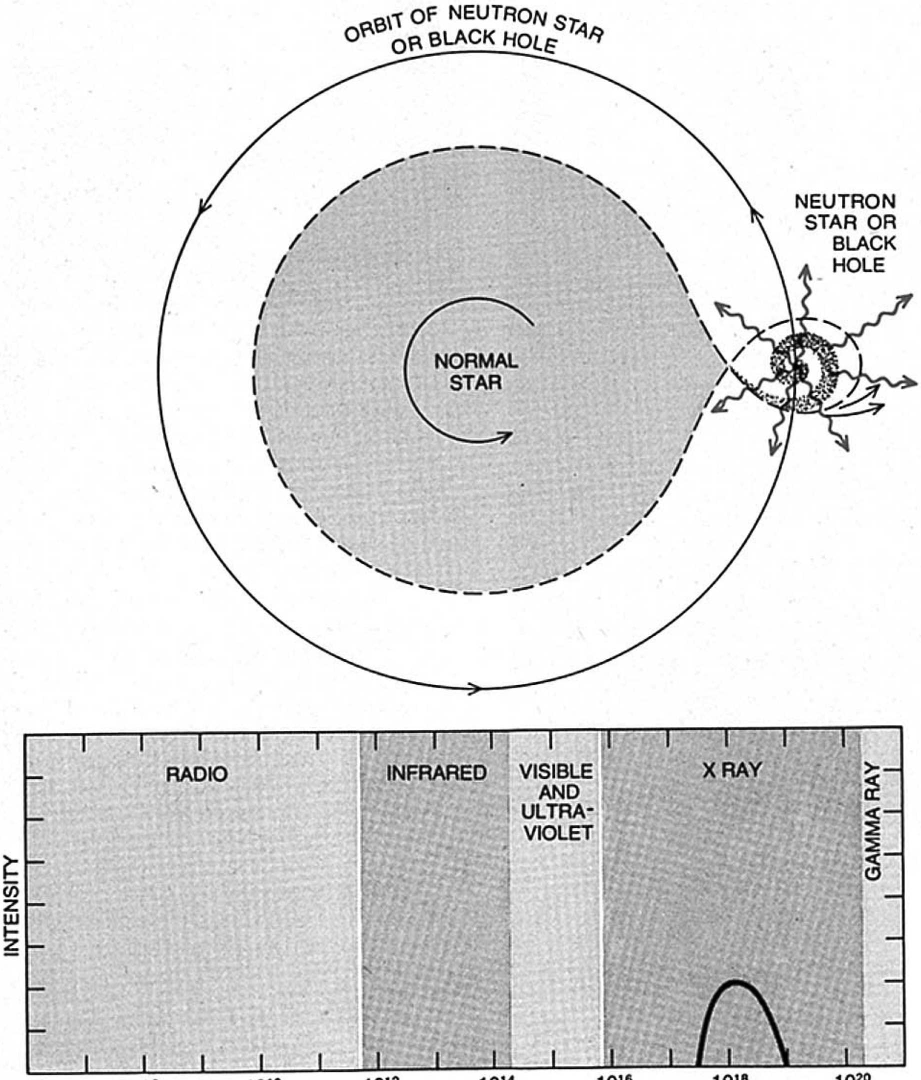
The task of determining the prevalence of objects in a primeval galaxy is simplified by the fact that most of the objects are the offspring of the massive stars that continually form and die. (The low-mass stars contribute only visible light and live too long to create any interesting objects.) Moreover, the offspring objects are as short-lived (compared with the collapse time of the protogalaxy) as the massive stars themselves, and so the number of these objects that contribute to the spectrum of the primeval galaxy is proportional to the rate of star formation. The rate of star formation in a bright primeval galaxy may be 3,000 times greater than the present rate in our own galaxy, so that we expect 3,000 times the number of massive stars and their short-lived offspring in a primeval galaxy.

The kinds of such offspring can be determined by following the evolution of a massive star from birth to death. The star is believed to form inside a cold (10 degrees Kelvin) cloud consisting chiefly of molecular hydrogen (H_2), carbon monoxide (CO) and dust grains of silicate and carbon. Molecular hydrogen does not emit much radiation, so that the only important waves emanating from the cloud are associated with the microwave-radio spectral line of carbon monoxide (at a frequency of 115 gigahertz). The star shines brightly in the visible and ultraviolet regions of the spectrum, although such radiation is absorbed by the cloud and hence cannot be seen outside it. The radiation heats the dust grains shrouding the cloud to about 30 degrees K., at which temperature the grains reradiate the energy of the star in the form of thermal emission in the infrared. A thick shell of ionized gas also forms around the shrouded star. Although the visible and ultraviolet radiation emitted by the star and gas cannot penetrate the dust grains, the radio waves can.

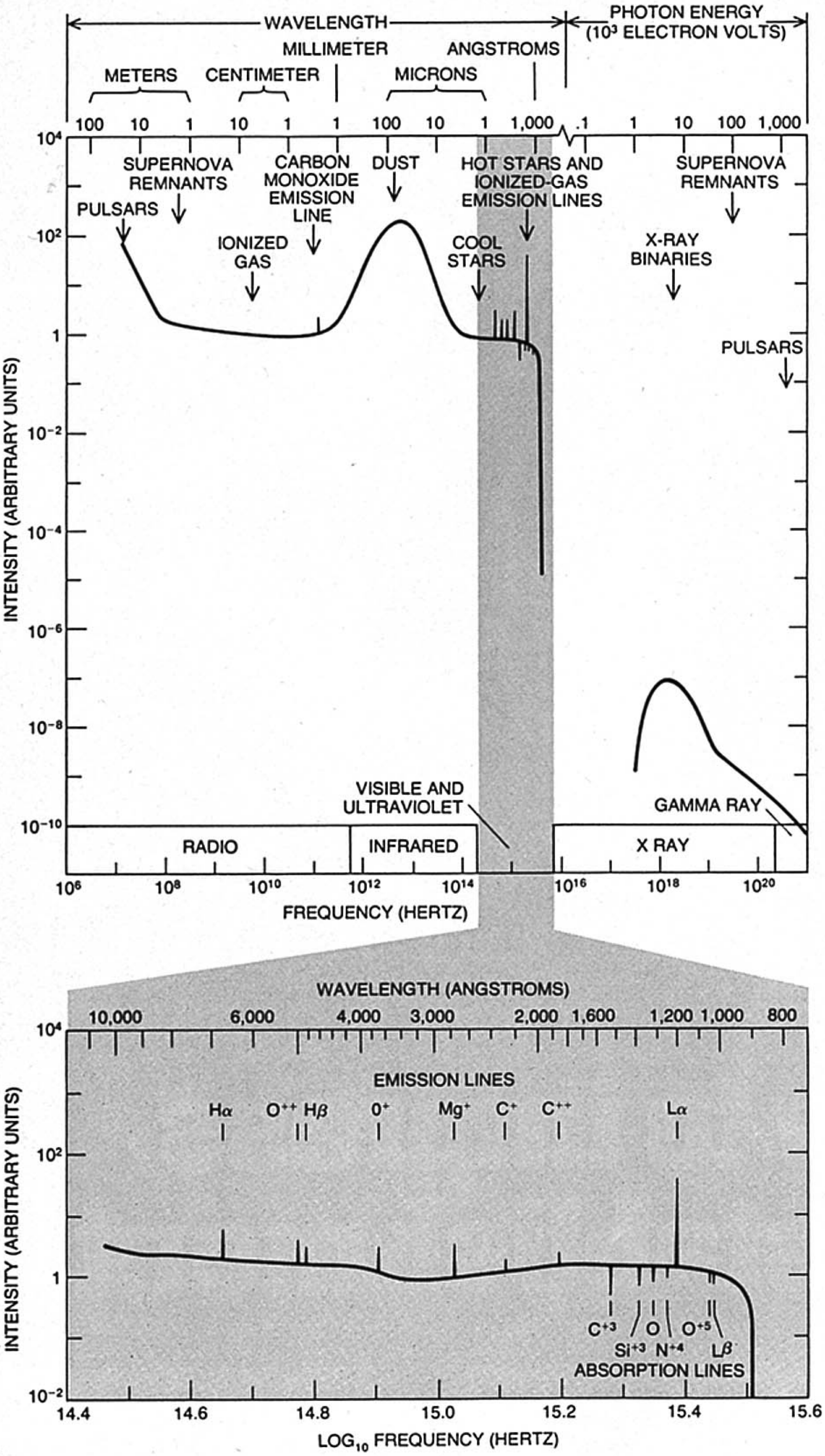
Soon the shell of ionized gas expands, unveiling the star by dispersing or destroying most of the dust grains. As a result the intensity of the infrared radiation decreases sharply and the intensity of the visible radiation increases. (The Orion nebula in our galaxy is an example of a region of visible hot stars and ionized gas.) When the massive star reaches the end of its life cycle, it explodes violently as a supernova. A supernova explosion would be a spectacular event in a normal galaxy because of the comparative faintness of the other stars. In a primeval galaxy, however, a supernova would go unnoticed at visible wavelengths because of the abundance of other bright, massive stars.

The situation is different at other wavelengths. The compact remnant of the supernova, which could be a pulsar or a black hole, and the expanding shell of gas surrounding the remnant would appreciably increase the radio and X-ray emissions of the galaxy. If the compact remnant is a pulsating neutron star, it would strongly emit radio waves and X rays. It could also contribute X rays in another unusual way. If, as is often the case, the original star was part of a binary system with a star whose lifetime is longer, the neutron star could be left orbiting the longer-lived star. Matter could then be transferred to the neutron star by means of a stellar "wind" or gravity, the neutron star pulling material off the other star. The result would be an X-ray-emitting binary system like those that have been found in our galaxy. A similar picture would apply if instead of a neutron star the binary remnant was a black hole.

Pulsars and supernova remnants probably also contribute to the spectrum by giving rise to cosmic rays. The rapidly rotating magnetic field of the pulsar and the strong shock wave of the



NEUTRON STARS AND BLACK HOLES that are the compact remains of supernova explosions could contribute to the spectrum of a primeval galaxy in an unusual way. If the exploded star was originally a member of a binary system in which the other star had a longer lifetime, the neutron star or black hole could be left orbiting the longer-lived star (*top*). Matter could then be transferred to this compact object by means of a stellar "wind" or gravity, the object pulling material off the star. This process would give rise to strong X-ray emissions (*bottom*).



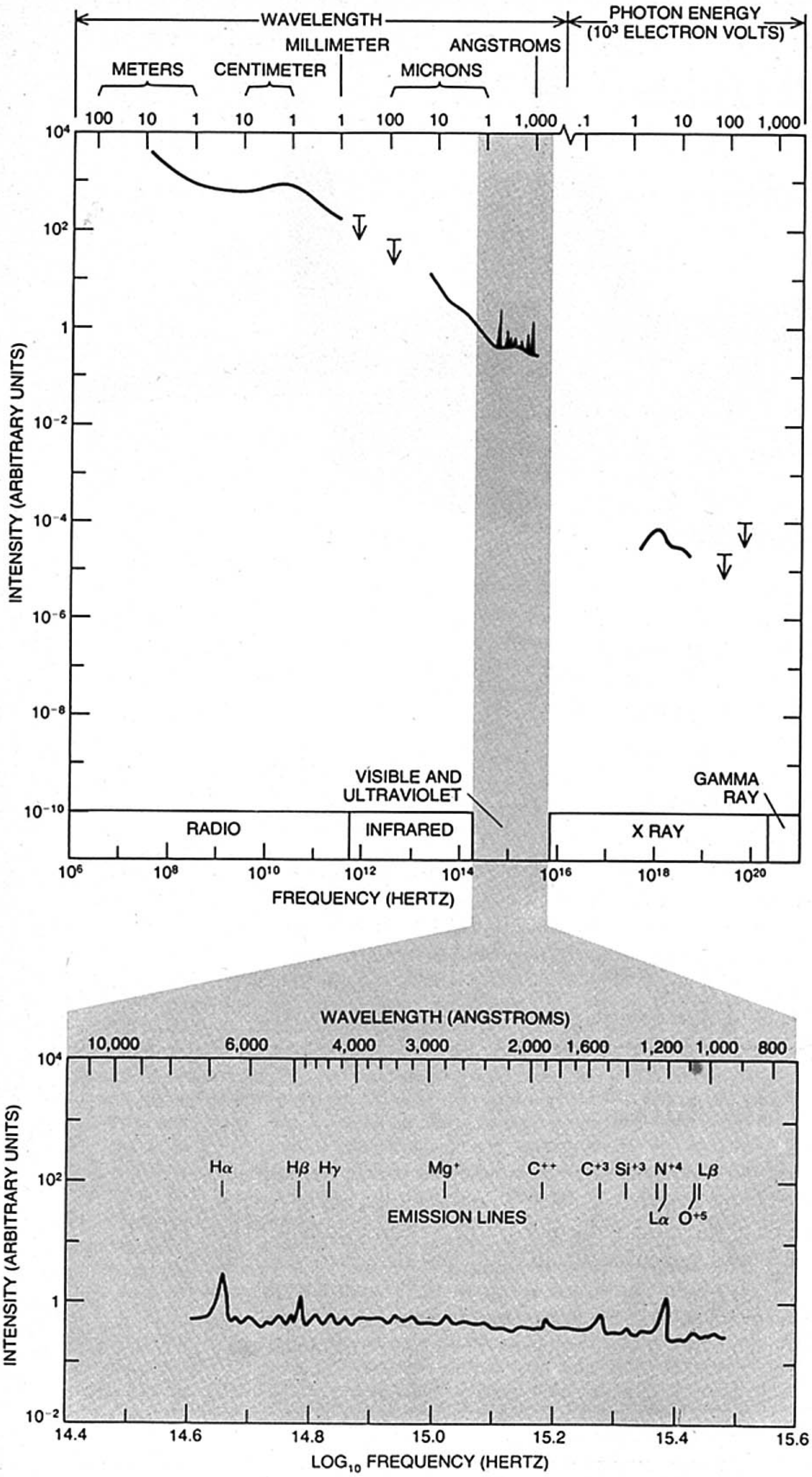
EXPECTED SPECTRUM OF A PRIMEVAL GALAXY (*top*) **is obtained by adding the spectra of the contributing phenomena, such as the ones in the illustrations on pages 136 and 138. This spectrum is the intrinsic one; the measured spectrum would be shifted in frequency to the left according to the precise red shift. The greatest uncertainty in determining the spectrum comes in estimating the ratio of the number of massive stars that are shrouded by dust to the number that are not shrouded. Here the ratio is assumed to be 1 : 1. The visible and ultraviolet regions** (*color*), **which are shown in an expanded view at the bottom, include emission lines of hydrogen (the Balmer lines** $H\alpha$ **and** $H\beta$ **and the Lyman line** $L\alpha$**), carbon (**C^{+} **and** C^{++}**), oxygen (**O^{+} **and** O^{++}**) and magnesium (**Mg^{+}**) and absorption lines of carbon (**C^{+3}**), silicon (**Si^{+3}**), oxygen (**O **and** O^{+5}**), nitrogen (**N^{+4}**) and hydrogen (the Lyman line** $L\beta$**). Lines have been broadened by Doppler shifts of gas moving at velocities of a few hundred kilometers per second.**

supernova remnant are able to accelerate electrons, protons and other subatomic particles to velocities close to the velocity of light. As these particles break away from the pulsar or the supernova remnant and interact with magnetic fields in the galaxy, they emit light and other forms of electromagnetic radiation. When they encounter atoms of the interstellar medium, they can generate gamma rays.

The spectrum of a primeval galaxy can now be obtained by adding together the spectra of the contributing phenomena. The greatest uncertainty in determining the spectrum comes in estimating the ratio of the number of massive stars that are shrouded by dust to the number that are not shrouded. We have assumed that the ratio is 1 : 1, which should suffice unless one situation strongly predominates. At red shifts of between 3 and 30 the calculated spectrum could be distinguished most easily by optical or near-infrared telescopes such as the space telescope. Other instruments that are still in the planning stage, such as orbiting far-infrared and X-ray observatories, should be able to detect distant primeval galaxies at other wavelengths.

Are there any details in these spectra that would distinguish a primeval galaxy from other objects? In the visible and ultraviolet spectrum of a primeval galaxy one expects a continuous emission spectrum from stars, a line absorption spectrum from the atmosphere of stars and a line emission spectrum from the ionized gas that surrounds hot stars. The gas and stars in a primeval galaxy are moving rapidly and randomly, so that the lines will be much broader than those of slower-moving gas and stars that are not shifted from their normal position as much by the Doppler effect. The velocities associated with the line widths should never exceed the escape velocity of a primeval galaxy: a few hundred kilometers per second. An object with such features would be a strong candidate for being a primeval galaxy.

When the quasars were first discovered, it was thought they might be primeval galaxies chiefly because of their large red shifts. The spectrum of a quasar, however, is quite different from the calculated spectrum of a primeval galaxy. The continuous spectrum of 3C 273, one of the first identified quasars, slopes smoothly downward from the infrared to the ultraviolet, whereas a primeval galaxy should have one peak in the infrared region and one in the visible and ultraviolet region. Moreover, the continuous spectrum of a quasar is often partially polarized: the light waves oscillate in a preferred direction. Radiation from a primeval galaxy, on the other hand, is expected to exhibit little or no polarization. The spectrum of a quasar also has much greater line widths, which



SPECTRUM OF A QUASAR (*top*) **is very different from the expected spectrum of a primeval galaxy, so that the two objects could be distinguished even though they might look the same through a telescope. The quasar spectrum has neither the continuous emissions nor the line emissions that would be expected from the hot stars and gas in a primeval galaxy. The spectrum of a primeval galaxy peaks once in the infrared region and once in the ultraviolet region, whereas the spectrum of a quasar slopes smoothly downward. The lines in the visible and ultraviolet regions (*color*), which are shown in the expanded view at the bottom, are broader by a factor of about 100. This intrinsic spectrum is that of the quasar 3C 273, one of the first quasars to be discovered. Measured spectrum is shifted to the left by a factor of 1 plus the red shift .158.**

suggests that such an object is a more energetic phenomenon than a primeval galaxy. The gas in quasars seems to be moving at speeds on the order of 10,000 kilometers per second. If clouds in a primeval galaxy traveled at such speeds, they would have escaped from the gravitational field of the galaxy long ago unless they were involved in a recent violent explosion or were bound to a large compact mass, such as a supermassive star or a black hole.

Quasars can also be distinguished from galaxies because their light can vary in brightness in the course of only a few months or years. Light from BL Lacertae objects, quasarlike entities with spectral peculiarities of their own, vary in intensity in only a few hours. Such variations are impossible for a collection of 100 billion stars, which cannot vary in unison. Even exploding supernovas, as we indicated above, can scarcely alter the brightness of a primeval galaxy, and they certainly cannot cause any variation in a matter of hours. Variable quasars must be extremely compact. They are probably smaller than the distance light can travel in the time it takes for the intensity of their light to change.

If quasars are not primeval galaxies, what are they? To answer this question astronomers have developed models of the region that is thought to emit the lines in the quasar spectrum. In a typical model the quasar is enveloped in a low-density gas that extends a few hundred light-years and has spectral lines with a width corresponding to a velocity of 1,000 kilometers per second. Within this region is a compact nest of dense, rapidly moving clouds of gas about a light-year in extent. The nest of clouds is the source of the broader lines in the spectrum of the quasar. At the center of the quasar is the "engine," at most a light-day in size, that emits the continuous spectrum and ionizes the denser clouds.

The exact nature of the quasar engine is the subject of current work. Three proposed models have been offered so far. In the first model the engine is a compact cluster of stars, the energy coming from a multitude of stellar collisions, supernova explosions and pulsars that are squeezed into a region with a radius perhaps only 10 times larger than the radius of the solar system. In the second model the engine is a supermassive star or pulsar, the energy coming from the gravitational contraction or rotation of a single magnetic star with a mass as great as a billion solar masses. In the third model, which is similar to the current model of binary X-ray sources such as Cygnus X-1, the engine is a supermassive black hole of a billion solar masses. The energy comes not from the black hole itself but from gas and decomposed stars that collide as they fall into it. In the collisions the gas and stars release about a tenth of their rest-mass energy (their mass at rest multiplied by the square of the speed of light). A loss of only 10 solar masses per year to the black hole would provide enough energy to power the brightest quasar and to strongly outshine a galaxy of a trillion stars.

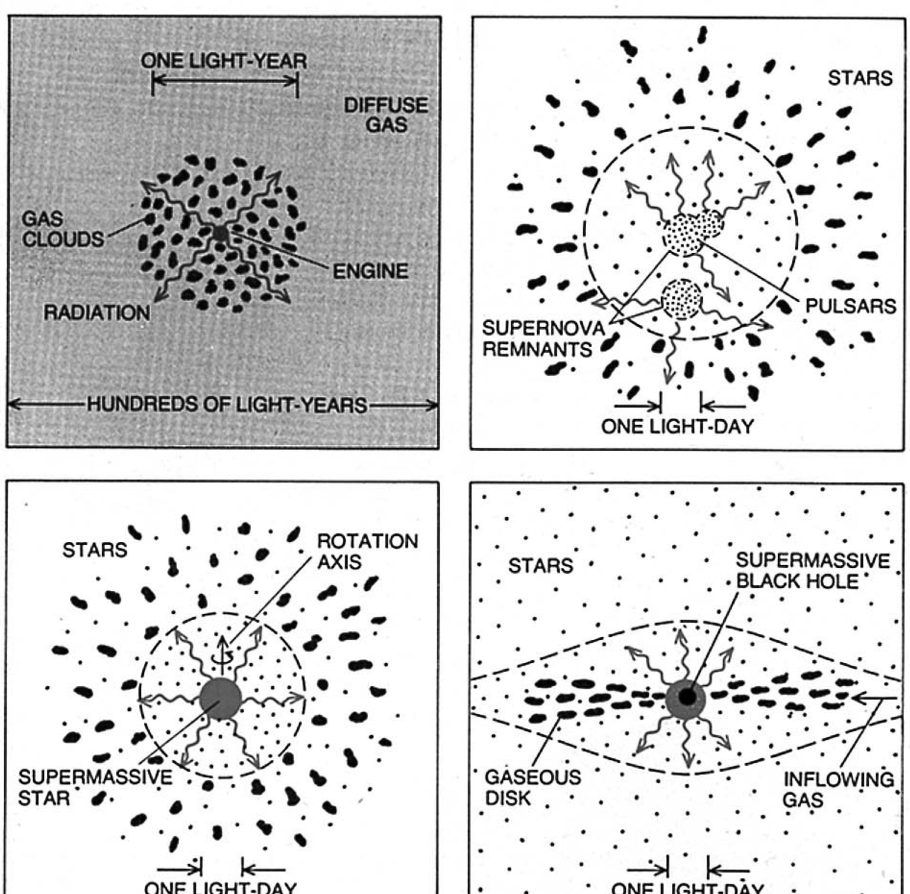
What is the origin of the quasars? The models of the quasar engine suggest that they exist at the nuclei of otherwise normal galaxies, where compact star clusters, supermassive stars and large black holes are most likely to form. The BL Lacertae objects, the extended radio sources that resemble extended radio quasars and the Seyfert nuclei, all of which are less luminous than quasars but have virtually the same spectrum, have been found in galaxies. It is reasonable to assume that quasars are simply scale-up versions of these phenomena, so bright and distant that the surrounding galaxy cannot be seen.

How do quasars form? This question remains largely unanswered. The abundance of quasars at red shifts just below the ones we expect primeval galaxies to have suggests that a quasar forms in a galactic nucleus soon after the galaxy forms. In fact, quasar formation may be a phase through which most galaxies pass when they are born. In the model of a collapsing galaxy outlined above activity need not stop when star formation stops. There may be events that cause the young galaxy to develop at its center the kind of supermassive object called for by the models of the quasar engine. (Processes that have been suggested are the collision and coalescence of stars packed into the galactic nucleus or the merging and collapse of gas clouds left over from star formation. Another possibility is that a large black hole is built up slowly from a small one that swallows up neighboring stars.) Then, by some poorly understood mechanism, the supermassive object briefly shines much brighter than the galaxy ever did. Finally the quasar dies, revealing the surrounding galaxy. At present this model is little more than speculation. Over the next few years astronomers hope to be able to uncover more evidence about how quasar formation and galaxy formation are linked.

All the evidence suggests that quasars are not primeval galaxies. Nevertheless, some primeval galaxies may have been mistaken for quasars. Before combing the skies for new primeval-galaxy candidates it will first be necessary to examine the lists of quasars already catalogued for those that have emission lines with widths corresponding to velocities of only a few hundred kilometers per second. Such an examination could be a herculean project, because hundreds of quasars have been catalogued. Moreover, the spectra of many of these quasars have not been recorded in sufficient detail. The examination would be manageable, however, if the quasars with the highest red shifts were studied first. The next step will be to obtain new candidates with the objective-prism technique. This technique records rough spectra of many objects in the sky at the same time, allowing estimates of the red shift, line widths and other characteristics to be made quickly. It is already useful in finding quasars. An objective prism employed with the space telescope will perhaps be the best bet for detecting a primeval galaxy. Through the telescope very compact objects will remain points, whereas primeval galaxies should show some detail. That may eliminate the need to make detailed spectra to distinguish between primeval galaxies and quasars.

The discovery of a primeval galaxy would constitute a major triumph for modern astronomy. Current theories of cosmology, galaxy formation and stellar evolution would have new evidence that argued strongly in their favor. In a field as complex as astronomy, however, theoretical predictions are not always accurate; it is quite possible that unforeseeable phenomena could complicate the search for primeval galaxies. For example, it could turn out that not all galaxies formed in a violent collapse of an expanse of gas and dust with a mass of about 10^{11} solar masses. Perhaps some galaxies formed from the merging of much smaller star clusters that were themselves created from the numerous low-mass perturbations (ranging from 10^{6} to 10^{11} solar masses) existing in the early universe. A primeval galaxy formed by merging would presumably be fainter than one formed by the collapsing process we have outlined, since the formation of stars would be slower.

The search could be complicated further if dust was so abundant in young galaxies that it shrouded most of the massive stars. At worst the entire galaxy could be hidden from view. It will be several years before instruments are introduced in space that could even detect the infrared radiation emitted by such dust, and it will be many years before the red shift of a dust-covered galaxy can be measured reliably. Most astronomers nonetheless believe primeval galaxies will someday be found. It will then be possible to study the formation of galaxies directly.



"ENGINE" OF A QUASAR is probably in the center of a nest of dense clouds embedded in diffuse gas (*top left*). Three theoretical models of the engine have been proposed. In the first model (*top right*) the engine is a compact cluster of stars. In the second model (*bottom left*) it is a supermassive star or a pulsar. In the third model (*bottom right*) it is a supermassive black hole.