

PROBING THE FAINTEST GALAXIES

The concept of a galaxy as a vast organized system of stars originates with Galileo's observation in 1610 that the Milky Way could be resolved into "innumerable" faint stars. Confirmation that many of the faint patches of light seen through small telescopes were actually galaxies like our own came in 1923, when Edwin Hubble, working with the just-completed 2.4-meter telescope at Mount Wilson in southern California, measured the brightnesses of individual stars in the Andromeda nebula. At about the same time, Vesto Slipher, working at the Lowell Observatory in Arizona, was making the first systematic measurements of the Doppler shifts of galaxies. Of several dozen galaxies measured, all but two were found to be receding. In 1929, Hubble showed that the recession velocities of Slipher's galaxies were directly proportional to their distances, thus introducing the concept of an expanding universe.

General relativity, which relates the geometry of the universe to the density of matter and energy within it, provides the framework for the modern understanding of the expanding universe. A measurement of the intrinsic curvature of space (see box 1 on page 27) would constitute a fundamental test of this framework, and the quest for this measurement has provided much of the motivation for studies of faint, distant galaxies over the last half century. As early as 1926, Hubble used counts of galaxies to infer that nebulae were distributed homogeneously on average. The ratio of the number of faint sources to the number of bright sources was observed to follow the expectations for a purely Euclidean geometry, wherein brightness falls as $1/r^2$ and volume increases as r^3 , where r is the distance from the galaxy to the observer. By 1936, Hubble had cataloged many faint galaxies from photographs taken with the Mount Wilson telescope and was trying to use galaxy counts to measure departures from Euclidean geometry.

By the late 1980s, extensive surveys had revealed a strong departure of galaxy counts from the purely Euclidean model. It appeared possible to explain this departure through the combined effects of cosmological curvature

An explosion of data from the Hubble Space Telescope and large ground-based telescopes is inspiring astronomers and helping to decipher the early history of the universe.

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and galaxy evolution. In these "luminosity evolution" models, a bright early phase of star formation in galaxies partially counteracted the dimming due to distance. An "epoch of galaxy formation" at high redshift $z > 3$, where $z \equiv (\lambda_{\text{observed}} - \lambda_{\text{rest}})/\lambda_{\text{rest}}$, produced enough blue galaxies to

explain the rather striking difference between the galaxy counts in blue wavelengths and in the infrared. Such models predicted that deep redshift surveys should begin to reveal very distant galaxies with luminosities several orders of magnitude brighter than the Milky Way. Instead, the redshift surveys revealed only less luminous galaxies at redshifts $z < 1$. Indeed, taken by itself, the measured redshift distribution showed no evidence for galaxy evolution. The excess of the counts over the no-evolution model became known as the faint blue galaxies problem, reflecting the fact that the most pronounced discrepancy was at blue wavelengths.

As these surveys were progressing, the simple picture of a single epoch of galaxy formation was being supplanted by the concept of a more gradual process, in which galaxies grew from small initial density enhancements. Over time, structures on different scales gradually merged to build up larger and larger galaxies, groupings of galaxies and rich clusters of galaxies. These ideas were intimately connected to the emerging concept of an inflationary universe, with critical density ($\Omega = 1$), permeated throughout by a sea of "dark matter" particles that interact with normal baryonic matter only through gravity. This general picture has been broadly successful in interpreting the cosmic microwave background fluctuations detected by the Cosmic Background Explorer (COBE) satellite and the measurements of large-scale structure from maps of the galaxy distribution in the nearby universe. But the hierarchical models have been less successful in explaining the luminosity distribution of present-day galaxies, and the preference for $\Omega = 1$ in such models, based on inflation, has been difficult to reconcile with the observed galaxy counts.

Most faint galaxies are unresolved or barely resolved at the resolution of 0.5 to 2 arcseconds available to ground-based telescopes. After the successful mission to refurbish the initially flawed Hubble Space Telescope, in December 1993, efforts to resolve and study distant gal-

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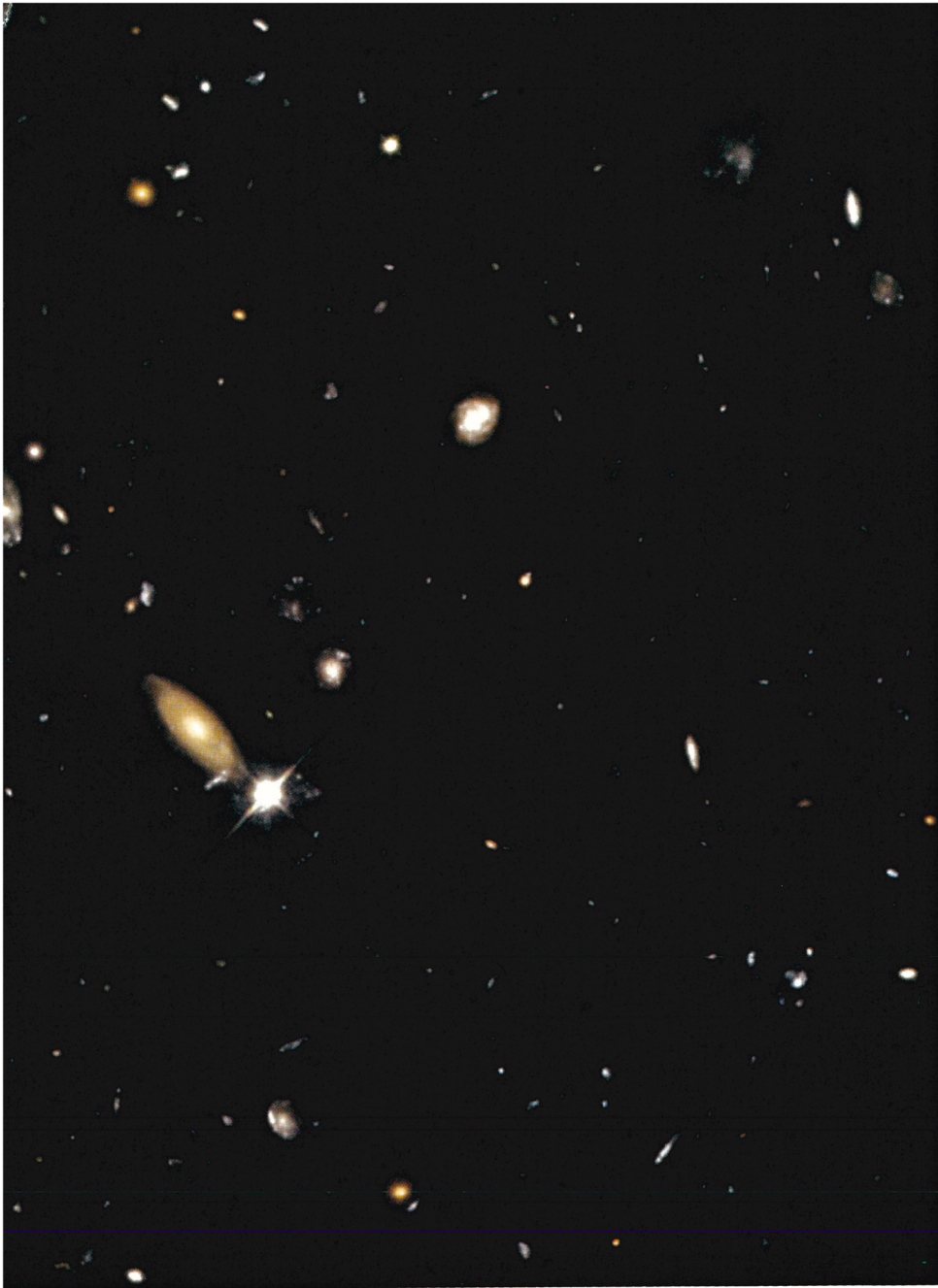


FIGURE 1. THE HUBBLE DEEP FIELD is a patch of sky 2.7 arcminutes on a side, or about $\frac{1}{10}$ the diameter of the Moon. About 25% of the entire HDF is shown here. The brightest few dozen galaxies in the image are typically at redshifts z of about 0.5. In a critical-density ($\Omega = 1$) universe with a current age of 13 billion years, light now reaching Earth from a galaxy at redshift $z = 0.5$ was emitted 6 billion years ago. For most of the galaxies in the image, we are looking back more than half the age of the universe. The look-back time to a galaxy at a redshift of 1 is 8.4 billion years, and it is nearly 12 billion years to a galaxy at redshift $z = 4$.

axies became a high priority. Observing programs focused on galaxies in rich clusters,¹ and on more randomly placed distant galaxies.² Among the important results from these observations were

- ▷ The revelation that a large fraction of faint galaxies have disturbed or irregular morphologies.
- ▷ Detection of relatively luminous blue galaxies at redshifts $z > 1$.
- ▷ An indication that the star-formation rate per unit area in galaxy disks was much higher in the past.
- ▷ The finding that at least some elliptical galaxies were fully formed and quite old at redshifts $z > 1$.

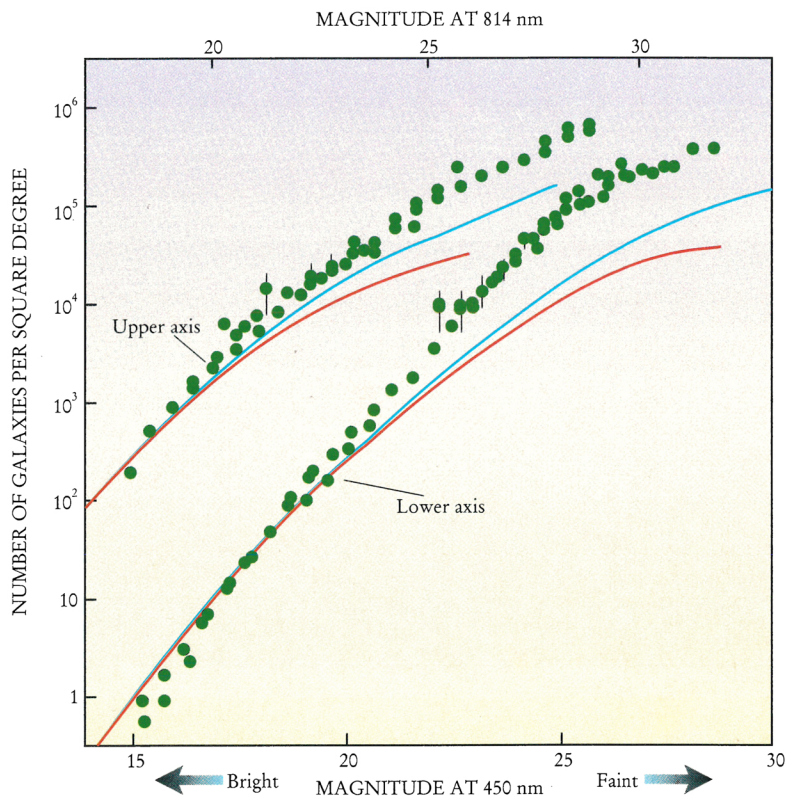
The Hubble deep field

The data available by early 1995 were enough to whet the appetite, but it was clear that the observations were

just a taste of what could be learned. For this reason the director of the Space Telescope Science Institute decided to devote much of his discretionary time in 1995 to observations of a single "deep field." The Hubble deep field (HDF) is in essence a deep core sample of the universe, acquired in a 10-day exposure. The patch of sky chosen for HDF observation was essentially random, except that great care was taken to avoid foreground obscuration by dust in our own Galaxy, or contamination by bright nearby stars or galaxies. The field was observed through filters centered at roughly 300, 400, 600 and 800 nm, to provide constraints on the redshift and age distribution of galaxies in the image.

An important component of the deep-field campaign was the immediate dissemination of both the raw and reduced data set to the community at large. Wide access to the data stimulated intensive follow-up efforts (roughly 30 nights of follow-up observations were scheduled at major ground-based observatories over the succeeding six months) and a heated race to produce the first interpretive papers.

FIGURE 2. GALAXY COUNTS. The number of galaxies per square degree of sky versus the logarithm of their brightness (measured in magnitudes). The red curve shows a nonevolving model with a critical-density universe ($q_0 = 0.5$) and the blue curve shows an open-universe model ($q_0 = 0.01$). These models include the effects of curvature; the excess of the counts over the models is indicative of the strong evolution in galaxy numbers or luminosities over the history of the universe. Closed-universe curves would fall below the critical-density curves.



The Hubble deep field, about a quarter of which is shown in figure 1, is a patch of sky 2.7 arcminutes on a side, which is the roughly the angular size of the period at the end of this sentence viewed from reading distance. The faintest galaxies in the image have visual magnitudes of about 30, equivalent to one photon per week hitting the human eye. This HDF image reveals galaxies about 15 times fainter than can be seen in the deepest images taken from the ground.

Census of the deep field

The deep-field line of sight passes through the Solar System, the galactic plane near the Sun, the halo of the Galaxy and random galaxies and clusters of galaxies at large distances. The HDF contains only about ten visible foreground stars in our own Galaxy. These stars probe the outer structure of the Galaxy and the faint end of the stellar luminosity function. Studies of faint stars in the HDF and other deep Hubble Space Telescope fields indicate that hydrogen-burning low-mass stars are unlikely to be the source of the “missing mass” needed to bind the Galaxy.³

The overwhelming majority of objects that appear in the field are galaxies, with nearly 3000 detected to the faint limit of the images. The galaxies appear in a variety of sizes, brightnesses, colors and shapes. Some of them appear as small arcs, the result of gravitational lensing by foreground objects. The lensed galaxies are useful in that they can reveal the mass distribution of the lensing galaxies and the presence of intrinsically faint, more distant objects that are not otherwise detectable.⁴

Morphology of the galaxies

Locally, most large galaxies appear in the familiar spiral or smoother elliptical shapes. At luminosities as high as that of the Milky Way, there are relatively few galaxies with unfamiliar shapes; irregular galaxies are more common at lower luminosities. Even before the HDF observations were initiated, it was not easy to organize most fainter galaxies in terms of well-known local classifica-

tions, and it was found that the fraction of peculiar galaxies rises rapidly to dominate the numbers at faint magnitudes. Some part of the effect may come from the fact that the light we see is redshifted from the ultraviolet, in which galaxies have a more irregular appearance that reflects the distribution of young, hot star-formation sites. At higher redshifts, we also see only the regions of highest surface brightness, and that may result in a much more contrasty, irregular appearance. However, a large part of the effect may be real evolution, and the more irregular faint galaxies may correspond to a younger, more intense star-forming period in the galaxies’ lives, when most of the light from the objects could have been produced by a few star-forming sites.

Galaxy sizes and number counts

Measurements of the distribution of sizes and brightnesses of galaxies provide fundamental tests of cosmological models. Although gaps in our knowledge of how galaxies form and evolve make it unlikely that the number counts and size distribution can be used to derive the cosmological parameters, matching these distributions is nevertheless a challenge that every cosmological model must now meet.

As one might expect from looking at the images, counting galaxies and measuring their sizes are not something that can be done completely unambiguously. For example, at fixed brightness levels, big galaxies are harder to detect than small ones because their light is spread over more pixels and hence subject to more noise. Also, in cases where there are several peaks in the light distribution, it is not clear whether the source should be counted as one galaxy or several. In spite of such difficulties, counts from different research groups, measured with different algorithms, agree quite well.

The galaxy number counts at 400 nm and 800 nm are

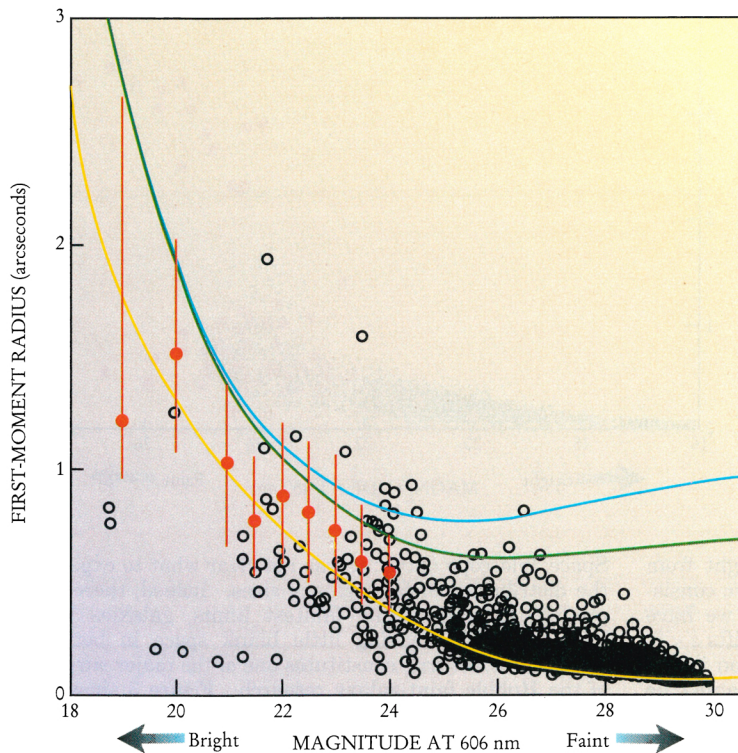


FIGURE 3. ANGULAR RADII OF GALAXIES in the Hubble deep field (red points), computed from the intensity-weighted first moment of the pixels above a fixed detection threshold. Black circles represent measurements of the individual galaxies in the image. The top and middle curves show model predictions for an ideal disk galaxy the size of typical spiral galaxies today, for cosmological densities $\Omega = 1$ and $\Omega = 0.1$, respectively. Even in the bounding case of $\Omega = 0$, angular diameters do not decrease significantly beyond redshift $z = 2$, which corresponds to 26th magnitude for our fiducial galaxy. The bottom curve shows the predicted angular diameter for a typical giant elliptical galaxy. The very different behavior of the two types of galaxies is due to their different radial brightness profiles and to the effect of truncating the profiles at a fixed surface-brightness limit. This truncation makes the elliptical galaxy's angular-diameter-versus-magnitude relation very insensitive to cosmological curvature.

shown in figure 2. Preliminary model fits to the counts tend to favor cosmologies that are either open or dominated by a cosmological constant, but there are enough uncertainties in galaxy star-forming histories that the

counts alone do not provide a definitive test.⁵ Independent of the models, the turn-over in the counts at faint magnitudes suggests that our census of the distant universe now probes beyond the era when most of the galaxies formed most of their stars.⁶

However, upper limits on the total extragalactic background at optical wavelengths (that is, the brightness of the night sky after subtracting contributions from sources and diffuse light in the Solar System and Milky Way) are

Box 1: Galaxy Counts, Sizes and Cosmological Curvature

The historical motivation for counting galaxies was to test the concept of curved spacetime—in essence, to measure the curvature of the universe. In recent years, it has become clear that the counts of galaxies are strongly influenced by evolutionary processes, undermining any straightforward attempt to measure curvature. Nevertheless, interpretation of faint-galaxy counts still requires an underlying model for how surface densities, brightnesses and angular sizes of standard (nonevolving) candles and measuring rods should change with redshift.

The expansion factor $R(t)$ of the universe from the Einstein field equations is

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2},$$

where G is the gravitational constant, ρ is the mass density, Λ is the cosmological constant and k is the sign of the space curvature ($-1, 0$ or $+1$ for a universe that is open, flat or closed, respectively). The expansion rate at present is represented by the Hubble constant H_0 . If the cosmological constant is zero, the curvature is determined entirely by the matter density and is encapsulated in the parameter $q_0 \equiv 4\pi G\rho/3H^2$.

The apparent magnitude m_λ of a distant source is related to its absolute magnitude M_λ by

$$m_\lambda = M_\lambda + k_\lambda(z) + E_\lambda(z) + 5 \log d_L + 25$$

The apparent magnitude m_λ is $-2.5 \log(f/f_0)$, where f is the incident flux from the source and f_0 is the flux in the same bandpass from a standard source (the star Vega, for example). M_λ is the apparent magnitude a source would have if it were at

a distance of 10 parsecs. In the above equation, $k_\lambda(z)$ incorporates the frequency shift and the bandpass dilation due to redshift, and $E_\lambda(z)$ incorporates the changes in flux due to source evolution. The spectral evolution of galaxies is encapsulated in $E_\lambda(z)$. Cosmological curvature is encapsulated in the luminosity distance d_L , which, in the absence of a cosmological constant, is given by

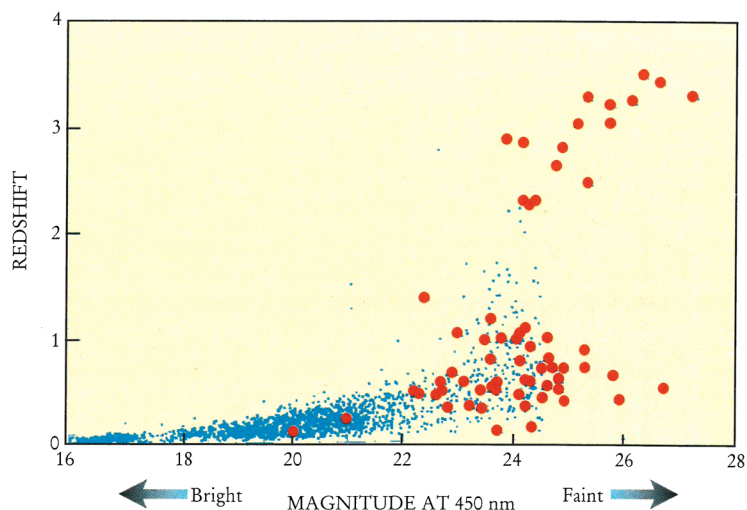
$$d_L = \frac{c}{H_0 q_0^2} \left[q_0 z + (q_0 - 1)(\sqrt{1 + 2q_0 z} - 1) \right]$$

Galaxy angular sizes θ are related to their physical sizes l by $\theta = l(1+z)^2/d_L$.

If the co-moving density of galaxies is conserved, the number of galaxies per unit redshift per steradian depends only on the volume element (which depends on curvature in a slightly different way than d_L does). Intrinsic evolution in the numbers of galaxies (that is, merging) affects the projected counts of galaxies only mildly if there is no star formation associated with the merging process. Processes that might change the star formation rate in galaxies (such as merging, tidal interactions or changes in the ionizing background radiation field) can have a bigger effect on the counts, making small galaxies that might otherwise be invisible bright enough to be seen at high redshift.

The models shown in figures 2 and 3 include the d_L and k_λ terms but do not include E_λ or any evolution in the co-moving density or physical sizes of galaxies. In addition, the process of detecting galaxies invariably introduces some bias into the statistical distribution of sizes and magnitudes, which must be accounted for before making detailed comparisons with models.

FIGURE 4. REDSHIFTS of faint galaxies as a function of magnitude at about 450 nm. The red points represent galaxies in the Hubble deep field whose redshifts have been measured from the Keck Observatory in Hawaii. The other points are from surveys of brighter galaxies done from the Keck Observatory and the Anglo-Australian Observatory in New South Wales, Australia. The pronounced bifurcation for the HDF galaxies has to do with the fact that many were selected by colors to lie at redshifts $z > 2$, and the extreme difficulty of measuring redshifts for galaxies with $1 < z < 2$ at optical wavelengths due to the lack of strong features in the mid-ultraviolet spectra of galaxies.



still a factor of several above the integrated light from galaxy number counts. So there is still one more consistency check to be made before we can be sure we have accounted for all the luminous material at redshifts $z < 5$. It is still possible that much of the star formation in the universe is hidden in galaxies of a type that cannot be detected in the HDF, because either they have very low surface brightnesses or they are shrouded in dust. Programs to observe the HDF at lower wavelengths are under way to search for galaxies shrouded in dust.

At the time of the 1993 refurbishment of the Hubble

Space Telescope optics, it was not clear what to expect for the distribution of faint galaxy sizes. Indeed, there were predictions that at the faintest limits, galaxies would largely overlap, leaving little blank space in between. That this is not true constitutes one of the major surprises of the Hubble faint-galaxy research. Figure 3 shows the relation between apparent brightness and angular size (the half-light radius). The small angular sizes at faint magnitudes imply that, on average, the faint galaxies are physically more compact than the Milky Way. This conclusion does not depend on the detailed redshift distribu-

Box 2: Now You See It, Now You Don't—Identifying High-Redshift Galaxies by their Lyman Continuum Break

For galaxies with redshifts $z > 2$, the Lyman edge of hydrogen begins to shift into the 300 nm Hubble deep field bandpass. Opacity within stars and the interstellar medium within galaxies creates a strong spectral discontinuity that can be used to identify high-redshift galaxies. In a typical star-forming galaxy, the flux drops¹⁰ by at least a factor of ten between 95 nm and 90 nm. This discontinuity has been exploited with great success in recent ground-based surveys, and provided a strong motivation for including the 300 nm filter in the HDF observations. At redshifts $z > 3$, hydrogen within the intergalactic medium itself begins to absorb a significant amount of light along the line of sight to distant galaxies, providing a natural filter that can be used to identify young, high-redshift galaxies with a high degree of confidence.

The figure shows a model spectrum of a star-forming galaxy at redshift $z = 3$, superimposed on the throughput curves of the HDF filters. Such a galaxy would appear blue in its optical colors but would be virtually undetected at 300 nm. At higher redshifts ($z > 4$), a similar galaxy would disappear from the 450 nm “blue” filter; at still higher redshifts, it would vanish from the optical (606 nm) filter. At redshifts $z > 6$, the opacity of the intergalactic medium makes galaxies disappear even from the reddest bandpass. Exploring the universe at such high redshifts requires infrared detectors.

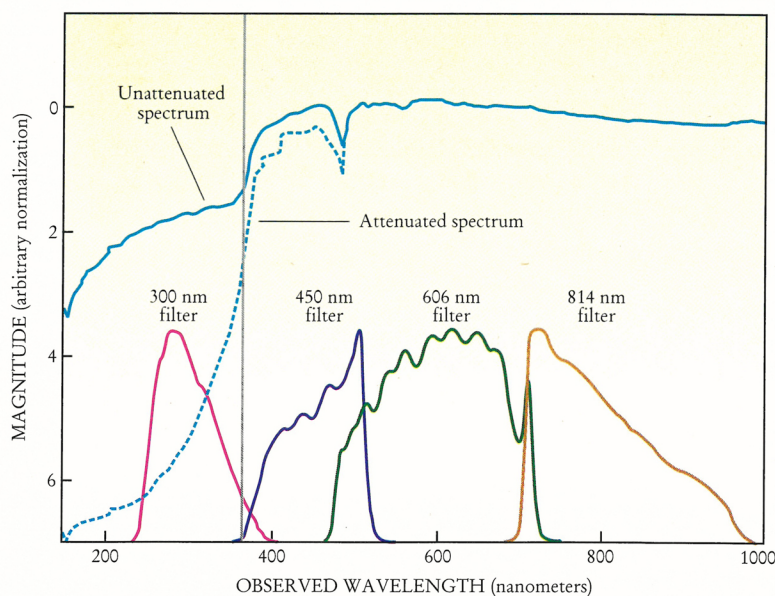
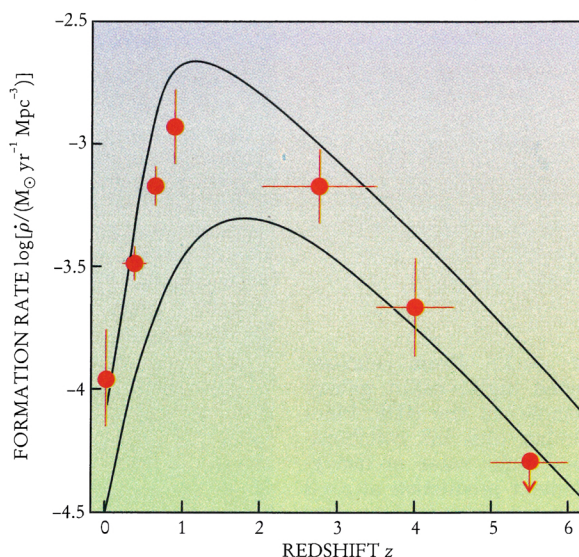


FIGURE 5. HEAVY-ELEMENT FORMATION RATE as a function of cosmic time and redshift, as deduced from the colors and brightnesses of galaxies in the Hubble deep field and from ground-based redshift surveys at brighter magnitudes. The curves show the evolution derived independently from observations of heavy-element abundances seen in gas clouds along the line of sight to distant quasars.⁹ The top curve is for a model in which galaxies continually accrete gas from the intergalactic medium. The lower curve is for a model in which galaxies eject some of their gas during the star-formation process. The two models also use different assumptions about the fraction of gas already in galaxies by the evolutionary time corresponding to a redshift z of 4.



tion of the galaxies or the value of Ω . What is not yet clear is whether these small galaxies eventually merge to form galaxies like our own, or whether they represent a population of low-mass galaxies that was briefly visible in the past but has since faded into near invisibility in the present.

Redshifts

One of the most important follow-ups of the HDF imaging has been to obtain spectroscopic redshifts for as many objects as possible. This type of work is not well suited to the space telescope itself but is best carried out with the largest ground-based telescopes. Separate groups from Caltech, the University of Hawaii and the University of California have used the Keck telescope on Mauna Kea to obtain redshifts. In keeping with the spirit of the HDF project, these groups reduced their data rapidly and made the results available on their World Wide Web sites.

Redshift measurements now exist for almost 80 objects in the HDF proper and many more objects in the surrounding "flanking fields" area. The available redshifts are plotted in figure 4 against the B magnitude, which is a measure of the flux from the galaxy at an observed wavelength of 450 nm; the figure also shows data from surveys covering much larger areas of the sky. The jump toward high redshifts in the HDF sample is a striking illustration that current technology has now reached the sensitivities necessary to probe the very early universe. This represents a truly dramatic breakthrough from the situation of just a couple of years ago, when virtually no normal galaxies beyond a redshift of one were known.

Redshift samples hold out the exciting prospect of making it possible to map the evolution of large-scale structure. The rate at which the relatively smooth structure seen in the microwave background evolves into present-day sheets, walls and filaments of matter is extremely sensitive to the cosmological density Ω and to the nature of the dark matter. The HDF redshift distribution shows a pronounced nonrandom clumpiness, indicating that the line of sight passes through several sheets of galaxies.

The Lyman edge of hydrogen (at 91.2 nm, or 13.6 eV) creates a spectral discontinuity that has been used to identify galaxies at high redshifts (see box 2 at the left). Several of the redshift surveys have specifically targeted such high-redshift candidates.⁷ The 16 confirmed sources with $z > 2$ yield a co-moving density comparable to, or slightly higher than, the local space density of massive galaxies ($M > 10^{11}$ solar masses). The diameters of high-redshift galaxies are typically smaller than those of local massive galaxies, and their individual star-formation rates

are rather modest, ranging from 3 to 30 solar masses per year. Studies of the chemical abundances and structural scaling relations of present-day elliptical galaxies and spiral galaxy bulges (collectively known as spheroidal systems) favor an epoch of very rapid star formation lasting 10^8 to 10^9 years and terminating when supernovae drive the remaining gas from the protogalaxy. The star-formation rates detected in the HDF $z > 2$ galaxies are about an order of magnitude too low to be consistent with this picture. It is possible that the luminous objects are missing from the HDF either because they are enshrouded in dust or because their formation happens at very high redshift. On the other hand, it is possible that the chemical-evolution arguments are wrong and elliptical galaxies form late through the wholesale merging of smaller objects.

Galaxy colors

Roughly 90% of the galaxies in the HDF are too faint for spectroscopy from even the largest telescopes. For those sources, the only information on redshifts and ages comes from colors measured through the four HDF filters. However, even this sketchy information is a tremendous improvement over what was available previously. Galaxy colors have been used by several groups to derive "photometric redshifts," with reasonable consensus that the majority of galaxies for which at least two colors can be measured are at redshifts $z < 2$.

Such techniques to estimate redshifts can provide interesting constraints on the history of star formation and production of heavy elements throughout cosmic time. Elements such as oxygen, magnesium and silicon are synthesized in massive stars and recycled into the interstellar medium by supernova explosions. The HDF observations measure the rest-frame ultraviolet light emitted from high-redshift galaxies, and this light is produced by the same massive stars that produce most of these elements. Thus the luminosity per unit volume measured at various redshifts in the HDF and in ground-based redshift surveys can yield a rough measure of the formation rate of these elements. The rate of heavy-element production in galaxies today is about a factor of four too low to have produced all of the present-day enriched material. Ground-based surveys prior to the HDF suggested that the heavy-element production rate was higher

Box 3: Future Deep Surveys

Several follow-up observations on the Hubble deep field itself will be carried out over the next year and a half. Repeat imaging in the near-infrared will look for time variability of objects, including possible supernovae. Important contributions are expected from the new infrared and ultraviolet detectors just installed in the Hubble Space Telescope. The space telescope will also observe a second deep field in the southern sky. X-ray observations are planned for the Advanced X-ray Astrophysics Facility satellite, scheduled for launch in 1998.

Ultimately, detailed study of the high-redshift universe will require larger telescopes and more sensitive detectors, especially in the infrared. Initial plans are under way to build a next-generation space telescope, optimized for observing at wavelengths longer than those accessible to Hubble. This telescope will be able to obtain spectra of all the objects detected in the HDF, providing detailed information on their distribution in space (and time), on their internal dynamics and on their ages and chemical abundances. The sensitivity at longer wavelengths will open a window at redshifts greater than 10, providing, at least in principle, a view of the formation of the earliest stars, a mere 10^8 to 10^9 years after electrons and protons combined to form atoms in the early universe.

at $z \approx 1$. From color-selected high-redshift galaxy samples in the HDF, Piero Madau and his collaborators⁸ infer rates of heavy-element production at $z \approx 3$ that are three times higher than the present-day rate and equal to the present-day value at $z \approx 4$. (See figure 5.)

Support for this picture is provided by studies of the chemical abundances in intergalactic gas, seen along the line of sight to quasars, which produce a curve strikingly similar to that seen in figure 5 from completely independent arguments.⁹ Further support comes from the fact that the integral over the heavy-element production rate from these curves produces a total mass density in heavy elements close to that inferred from observations of the local universe.

Extending to other wavelengths

Observations of the HDF made with the Infrared Space Observatory (ISO), the Very Large Array and Multi-Element Radio Linked Interferometer Network (MERLIN) radio telescopes and ground-based infrared detectors make the HDF the best-studied patch of sky across much of the electromagnetic spectrum. The ISO and radio observations contain only a handful of sources, but they are among the most interesting in the HDF. The fact that any sources were detected with the ISO suggests that the reprocessing of starlight or nuclear activity by dust could be an important contribution to the total luminosity of at least a few of the galaxies, leading to speculation that much of the star formation that took place 5–10 billion years ago could be largely hidden from the optical images.

The ground-based images in the 1–2 μm band add additional wavelengths that considerably reduce the uncertainties in photometric redshifts for the brightest 300 or so galaxies. These images are refining the estimates for the global star-formation history deduced from the optical images and spectroscopic redshifts.

Future work

The flood of new data on both the HDF and other deep surveys is clearly having a huge impact on studies of galaxy evolution. From the analysis to date, a sketchy picture emerges of an extended epoch of galaxy formation at redshifts $1 < z < 2$ (the peak of the metal-production rate in figure 5), with the stars formed mostly in objects that were physically smaller than present-day massive galaxies.

There is much to be done to test whether this general picture is correct. There are relatively large uncertainties

in the estimates of the present-day density of heavy elements and of the rates of star formation. It is not clear how to reconcile the relatively rapid rate of evolution and chemical enrichment in the overall galaxy population from redshifts of $z = 0$ to 2 with evidence for very slow evolution in the properties of large galaxies out to redshifts $z = 1$. The disparity is particularly puzzling because most of the enriched material at

$z = 0$ is bound up in these large galaxies. At the faintest depths of the HDF, it is possible that many of the galaxies are low-mass objects forming stars in short-lived episodes. Further detailed studies of the spectra of faint galaxies should clarify the situation. Analysis of the strengths and widths of spectral features are beginning to provide constraints on the masses of these systems and their chemical abundances. Deep-infrared observations (see box 3 above) will provide information on the extinction due to dust and on the history of star formation in high-redshift galaxies, while ultraviolet observations and infrared spectroscopy will probe evolution in the crucial redshift range $1 < z < 2$.

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