Andrew Carnegie founded the Carnegie Institution of Washington in 1902 as an organization for scientific discovery. Since then, Carnegie scientists have pioneered many fields. The institution is headquartered in Washington, D.C., and has five departments around the country devoted to research in plant biology, developmental biology, earth and planetary sciences, and astronomy.

Mr. Carnegie’s intention was for the institution to be home to the “exceptional” person—an individual with imagination and dedication who worked at the cutting edge of a specialty. Some of the institution’s exceptional individuals include Nobel laureate geneticists Barbara McClintock and Alfred Hershey, and Mount Wilson astronomer Edwin Hubble, for whom the Hubble Space Telescope is named.

Scientists at Carnegie today are free to investigate their specific areas of interest under the broad goals of an individual department. Researchers are given the support and equipment they need in a nurturing environment. This arrangement has produced unexpected benefits to society, among them hybrid corn and radar.

The organization is an endowed, independent, nonprofit institution. Significant additional support comes from federal grants and private donations. A board of trustees, consisting of leaders in business, the sciences, education, and public service, oversees Carnegie’s operations. An appointed president presides over day-to-day administration. Each of the five departments is independently managed by a director, aided by support staff. In addition to the scientists on staff, there is a constantly changing roster of pre- and postdoctoral fellows and associates, plus visiting investigators at each facility.

Carnegie is also involved in education at the lower levels. In 1989 President Maxine Singer launched the Saturday science school, First Light. The school encourages Washington, D.C., children to explore the world around them with the aid of a unique, hands-on curriculum. The success of First Light led to CASE, the Carnegie Academy for Science Education, which is a training ground for elementary school teachers in the art of teaching science. Recently CASE expanded its program to the study of mathematics.

Carnegie’s legacy of pioneering scientific research is vibrant today, and its unique founding principles ensure that Carnegie researchers will continue to extend the frontiers of science for decades to come.
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Top: Las Campanas Observatory is shown here in August of 2000. The twin Magellan telescope enclosures are on the right. The du Pont and Swope telescopes are seen in the distance on the left (Courtesy Luis Piotro.)

Middle: A close up of the 100-inch du Pont Telescope is shown here at night. (Courtesy John Bedke.)

Bottom: This is an image of Las Campanas in 1984.
The Antennae galaxies are seen from the ground (above) and with the Hubble Space Telescope. (See page 20.)
Augustus Oemler, Jr.
Crawford H. Greenewalt Chair for Astronomy

Since their founding nearly a century ago, Carnegie Observatories have been a world center of astronomical research. Though relatively small, the Observatories staff has had a disproportionately large impact on the course of astronomy. As we begin the 21st century, our staff continues to lead the pursuit of the great scientific issues, which were first raised by their predecessors Edwin Hubble, Walter Baade, and others. This leadership is due largely to two assets: exceptional individuals endowed with the freedom to pursue a lifetime of research, and access to some of the world’s finest facilities.

A Brief History

In 1904 George Ellery Hale, seeking clearer skies than existed near his native Chicago, obtained support from the newly formed Carnegie Institution to found the Mount Wilson Solar Observatory in the mountains near Pasadena, California. Hale, inventor of the spectroheliograph, discoverer of solar magnetism, and one of the founders of modern astrophysics, was determined to push beyond the descriptive astronomy of earlier generations to understand the internal physics of the Sun and the stars. In pursuit of this goal, stellar telescopes soon followed the initial complement of solar telescopes on Mount Wilson: first the 60-inch, then the 100-inch Hooker telescope, each the largest in the world at the time of its construction.

The Mount Wilson telescopes transformed astronomy and astro-
Carnegie astronomers seek to understand the origin, structure, and dimensions of the universe; the nature and distribution of dark matter; and the formation, evolution, and structure of galaxies. Many of the current pursuits were first begun by Carnegie astronomers decades ago, but only now are advances in astronomical tools and techniques giving hope that answers are at hand.

The fundamental cosmological parameters are the size, age, and geometry of the universe. A central theme of Observatories research since the 1920s has been the Hubble constant, $H_0$, which measures the first two of these quantities. The Hubble constant requires determining the distances to remote galaxies, and distances in the universe are extraordinarily difficult to measure. Many Observatories Staff Members work on pieces of this task, using a great variety of objects, including binary stars for distances within our galaxy, Cepheid variables for distances to nearby galaxies, and supernovae for distances to very remote objects. The work begun here 80 years ago is finally, we believe, nearing completion with a reliable, widely accepted value for $H_0$.

Work on the luminosities of supernovae by Observatories astronomers has laid the groundwork for determining values for the other two principal cosmological parameters: the deceleration parameter and the cosmological constant. These parameters describe the geometry of space and the rate at which gravity is slowing the universal expansion. They tell us what the universe is like and provide insight into fundamental physical laws.

These three cosmological parameters describe an ideal universe that is perfectly homogeneous, but in fact the real universe is not. The operation of gravity over time has led to the growth of inhomogeneities, which have formed structures on scales from that of stars to that of superclusters of galaxies. Galaxy redshift surveys conducted at Las Campanas have mapped these structures out to very large scales, substantially enlarging our view of cosmic structure. Another powerful probe of cosmic structure, traced not by galaxies but by gas, is provided by the light from quasi-stellar objects, or QSOs. The absorption lines impressed on the QSO light by gas it encounters along the line of sight pinpoint the location of the gas. This location can be used to map both the distribution of matter in the universe that has condensed into galaxies and the matter that has not. The QSO absorption lines are particularly useful probes of the structure at earlier epochs, when the development of structure was less advanced than it is today.

Galaxies are fundamental units of matter in the universe; understanding their formation and evolution is of central importance. There are complementary routes to such understanding. One method seeks to unravel the history of our own and nearby galaxies through the detailed study of their component stars and star clusters. Surveys at Las Campanas have uncovered populations of the most metal-poor stars in our galaxy, which were the first to form. They existed before generations of metal-producing stars raised the abundance of these elements, and they probe the very earliest phases of galactic evolution.

The alternative approach to galaxy evolution takes advantage of the long time it takes for light to arrive from very distant objects. This travel time allows us to directly observe earlier phases of the universe. As larger telescopes and better instrumentation have allowed us to push out to more distant objects, we have extended our view of the early universe back nearly to the epoch of galaxy formation. The next decade should see major increases in our knowledge of this critical time, as instruments such as the IMACS spectrograph on the Magellan telescope allow us to broadly survey the earliest populations of objects.
Number 813 Santa Barbara Street in Pasadena, California, is a most famous address in the astronomical world. Here the main offices of the Observatories house about 65 scientific, support, and technical staff. Though a succession of earthquakes felled many of the early buildings, the original 1912 office building still stands, and was recently restored to its early spare elegance. It, and a wing added in the 1960s, house most of the scientific and support staff, as well as an extensive library and photographic plate collection. A new building, completed in 1994, contains a lecture hall, conference room, machine shop, and electronics and instrumentation labs.

Fifty-two hundred miles southeast of Pasadena, about a dozen scientists and administrative personnel work in the offices of the Las Campanas Observatory located in the coastal resort city of La Serena, Chile. The observatory itself is located approximately 100 kilometers north of La Serena, Chile, at an altitude of 2,400 meters, in a region of dark and clear skies and excellent seeing unsurpassed by any site on Earth. The principal telescopes at Las Campanas are the Swope 1-meter telescope, the du Pont 2.5-meter telescope, and the twin 6.5-meter Magellan telescopes. Carnegie operates the latter for a consortium whose other members are Harvard, MIT, and the Universities of Arizona and Michigan. Together, these telescopes provide the principal access to the southern skies for U.S. astronomers.

The Las Campanas telescopes are notable for their exceptionally wide fields. The Swope and the du Pont are Cassegrain equatorial telescopes with a 2-degree field, whereas the Magellan telescopes are alt-azimuth, with both Nasmyth and Cassegrain foci. The Magellan telescopes have a field of 30 arc minutes at the f/11 Nasmyth foci; an f/5 Cassegrain focus with a 1-degree field is planned for the second Magellan telescope, which will enter service in 2002.

The Las Campanas telescopes are equipped with broad suites of optical and near-infrared cameras and spectrographs. Most of the instruments are designed and built in our shops in Pasadena under the direction of Carnegie astronomers. The twin Magellan telescopes are located 60 meters apart, and are connected by an underground tunnel to permit future beam combining and interferometry.

Carnegie is a very special place, and the environment of the Observatories reflects the values of an institution dedicated to enabling exceptional scientists to pursue their ideas with complete freedom. Observatories Staff Members and fellows have no other responsibility than to do great science; neither teaching, nor the search for outside funding, nor any other institutional priority need distract them from their own intellectual goals. The institution supports these goals with generous resources. The small scientific staff of about a dozen Staff Members, and an equal number of postdoctoral fellows and associates, have access to time on the institution’s three telescopes. The assurance of generous long-term support permits Observatories scientists to pursue long-term projects whose pace is dictated by the pace of discovery itself, rather than by the need to justify the next grant or the next allocation of telescope time. It is this exceptional environment that has enabled the relatively small Carnegie staff to make such disproportionately large contributions to astronomy.

All Staff Members are free to use their time as they see fit, and each uses it differently. Some develop instruments, some are involved in the affairs of the Observatories or the astronomical community, some pursue mostly their own research. Some work alone, but an increasing number are part of broad collaborative projects, both within and beyond the Observatories. The fellowship program is regarded as the final stage in the education of young astronomers. Fellows are encouraged to interact with the senior astronomers, but are free to follow their own paths.

Observatories scientists interact on a daily basis. Morning tea, held every day in the foyer of the lecture hall, attracts most Staff Members who are in town to talk about every conceivable subject, scientific or otherwise. Most gather again to eat lunch together in our gardens. The Observatories are part of a large and exceptionally lively local astronomical community, which includes scientists from Caltech, JPL, and UCLA. Weekly colloquia at the Observatories and at Caltech attract many from all these institutions.

The education of young astronomers is integral to the science conducted at the Observatories. Several postdoctoral fellows and associates are shown here.
Alan Dressler studies the large-scale structure of the universe. He is particularly interested in how galaxies formed and the effect that unseen matter, called dark matter, has on them and on the evolution of the cosmos. Although dark matter has not been observed directly, it is known to exist by the gravitational effects it has on galactic rotation rates and galaxy movements. One of the great mysteries of modern astronomy is the nature, amount, and distribution of this unseen substance. Dressler maps the distribution of dark matter by tracing the velocities of galaxies that are affected by its presence. By finding the peculiar velocities (motions that are in addition to the expansion of the universe) of thousands of galaxies, Dressler and colleagues discovered a huge concentration of the material, which they named the Great Attractor.

This research recently reached a milestone with data from a new technique called surface brightness fluctuations. The information took almost 10 years to obtain, and it provides the most accurate peculiar velocities to date. In addition to confirming the Great Attractor’s existence, the scientists discovered weaker flows of galaxies into much smaller mass concentrations. They also observed galaxies flowing away from voids, where few galaxies are seen and the corresponding mass density is thought to be very low. New dark-matter maps constructed from the data will allow scientists to better determine the extent to which the galaxy distribution traces the dark matter, which is crucial information for interpreting the large-scale structure of the universe and understanding galaxy formation.

When astronomers look far out into space they are looking back in time. To determine the properties of distant, young galaxies seen in very old light, Dressler and others are using large ground-based telescopes and the Hubble Space Telescope in a project known as MORPHS. MORPHS has produced two major findings: that bursts of star formation were much more common in galaxies 5 billion years ago than they are today, and that because these star bursts are often shrouded by dust, their importance was previously underestimated.

In addition to his scientific research, Dressler is the principal investigator for the Inamori Magellan Areal Camera and Spectrograph (IMACS). IMACS is a sensitive multiobject spectrograph and camera with a very wide field allowing hundreds of galaxies to be seen at once. When mated with the new Magellan Baade telescope, IMACS will open new territory in the high-redshift universe.

**SELECTED PUBLICATIONS**


Observational cosmology, galactic evolution, and the evolution of stellar populations are Wendy Freedman’s principal interests. For almost a decade she has been involved in determining the rate at which the universe is expanding, using the Hubble Space Telescope (HST). This expansion rate, known as the Hubble constant, has been an important cosmological problem for the past 70 years. Freedman is one of three principal investigators on the project. In 2000 the group concluded that the universe is expanding at a rate of 74 kilometers/second/megaparsec (one parsec is 3.26 light-years) with a total uncertainty of 10%.

The Hubble constant is one piece of the puzzle needed to describe the fundamental, global nature of the universe. Another piece is the density of matter. Both these quantities must be determined by observations. The observations made by Freedman and colleagues have been aimed at measuring the distances to galaxies using Cepheid variables—stars that pulsate regularly over time. Only the nearest galaxies can be observed from the ground. To measure the distance of Cepheids in far-off galaxies, observations from space are necessary. Even with the HST, though, the range for finding Cepheids is limited. To solve this problem, the scientists used the Cepheid distances calculated from the HST observations to calibrate other farther-reaching objects such as luminous supernovae, and certain spiral and elliptical galaxies. Using five independent methods, all based on values of Cepheids, the scientists found the expansion rate.

Researchers can estimate how old the universe is using a value for the Hubble constant and a value for the average density of mass/energy in the universe. Using the most current estimates for these values, the universe is 12 billion years old. If, as recent evidence suggests, the universe is accelerating, then the implied age is 14 billion years.

In other research, Freedman, with Rebecca Bernstein and Barry Madore, have made the most accurate optical measurements of the total integrated light from all galaxies and objects in the universe. This information is used to refine estimates of the total amount of star formation and ordinary matter that exists. Freedman and colleagues are also looking at globular clusters in galaxy M31 with the infrared camera NICMOS on the HST. They found that the stellar populations in the clusters of M31 resemble those in the Milky Way and that the stars outside clusters resemble those in our galaxy’s bulge.

**SELECTED PUBLICATIONS**


Freedman has used Messier 100, pictured here, in making observations of Cepheid variable stars as part of her research to determine the Hubble constant.
Luis Ho’s research concentrates on the central regions of galaxies, particularly the physical processes associated with accretion of matter onto massive black holes. Black holes are believed to power active galactic nuclei (AGNs), which are unusually violent events evident in a galaxy’s center. They find their most dramatic expression in quasars and are suspected to be pervasive in most galaxies, as are the massive black holes that feed them. Ho is a member of a large team of astronomers who use the Hubble Space Telescope to search for black holes in an unprecedentedly large number of galaxies. The team’s observations will yield the first definitive census of these objects in the nearby universe.

Material accreting onto a black hole heats up and emits radiation characteristically across the electromagnetic spectrum. This detailed spectral distribution carries important information about the physics of the accretion flow. Ho is using a suite of telescopes, ground-based and space-borne, to measure the signal from the nucleus at different wavelengths. The initial results indicate that most massive black holes in nearby galaxies are on a starvation diet. Whereas once well-fed black holes shined as brilliant quasars when the universe was only a billion years old, today they are but feeble remnants of their former glory. Though they are very weak, they are detectable thanks to instruments with superb sensitivity and angular resolution such as the Very Large Array (a network of 27 radio antennas in New Mexico), the Hubble Space Telescope, and the Chandra x-ray Observatory.

Ho also works in several other fields. He studies a class of massive star clusters recently found to be important constituents in galaxies experiencing vigorous star formation. How these “super star clusters” form and how they will survive in the future are open issues Ho is pursuing. Another area of interest concerns the measurement of distances to high-velocity, neutral hydrogen clouds. High-velocity clouds could be debris raining down on the Milky Way after being propelled upward by previous generations of massive stars. Or they could be primordial material left over from the birth of the galaxy. A key to distinguishing these competing hypotheses lies in the determination of the clouds’ distances, a topic Ho is investigating using the 10-meter Keck telescope. Ho is also interested in surveying for supernovae and using them as tools for exploring the star-formation and chemical-evolution histories of galaxies.

SELECTED PUBLICATIONS


In his research on galactic evolution, Barry Madore observes properties of nearby and distant galaxies. One problem he and others face in this area is that optical observations may obscure what is really going on. Distant galaxies appear to be more ragged and disorganized than closer ones. While this may be a result of galaxy evolution, it may also be an aspect of the observed wavelength: the expansion of the universe progressively shifts ultraviolet photons into the range sensed by the optical detectors. Madore’s recent work is focusing on this problem.

To see how the perceived morphology of galaxies changes with wavelength, Madore and Carnegie’s Wendy Freedman used the Ultraviolet Imaging Telescope aboard the space shuttle to get UV images of galaxies and compared them with images taken at Las Campanas at optical and near-infrared wavelengths. Even the basic underlying morphology can be totally transformed by the particular wavelength used. Rings and bulges, bars and asymmetries—the very building blocks of galaxy classification—come and go depending on whether the images are obtained in the UV or the red. Dust, too, can play a significant role in what is detected, as it scatters and absorbs light.

For the last few years Madore and colleagues have been developing a new computer program with a three-dimensional radiative transfer code to help resolve these issues. The program is designed to determine the apparent morphology of a galaxy at ultraviolet, optical, near-infrared, and thermal infrared wavelengths. Because of the highly anisotropic nature of small-particle scattering in the interstellar medium, the new code required an innovative technique to compensate for behavior in a randomly clumped medium such as a galaxy’s spiral arm. The program calculates the absorption, scattering, and reradiation exactly, but limits the number of directions to 26. The results are realistic high-resolution galaxy images at typically used wavelengths. The scientists will next generate images at wavelengths that are less familiar.

Madore is coinvestigator for NASA’s GALaxy EXplorer (GALEX) satellite, to be launched in 2001. GALEX will survey the entire sky in two ultraviolet bandpasses and produce images of many thousands of nearby galaxies. When the database is assembled, the scientists will run their program on the samples. This work will allow researchers to better understand the contemporary structure of galaxies and, ultimately, their evolution.

SELECTED PUBLICATIONS


Probing distant galaxies can reveal aspects of galaxy evolution and help astronomers understand why the density of matter in the universe is irregular. Patrick McCarthy looks at faint galaxies using near-infrared (IR) instruments at Las Campanas and from orbit with the Hubble Space Telescope.

The stars that constitute the bulk of the mass of galaxies emit most of their luminous energy at wavelengths longer than 0.5 microns. The farther away the parent galaxies are, the greater the shift of the radiation to the near infrared. Most surveys of high-redshift galaxies have been confined to visible wavelengths, and thus sample ultraviolet (UV) photons emitted at the source. The ultraviolet luminosity of galaxies is often dominated by a small population of massive short-lived stars that produce 100 to 1,000 times more luminosity than solar-type stars. While ultraviolet luminosities reflect the present star-formation rates in galaxies, near-infrared luminosities are better for tracing the total stellar mass.

McCarthy and colleagues at Carnegie and the University of Toronto recently applied near-infrared techniques to an ambitious survey of 20,000 faint galaxies in an area of the sky that is four and a half times that of the full Moon. They used a unique camera containing a mosaic of four large near-IR detectors and identified a population of massive infrared-bright galaxies that are very strongly clustered on the sky. These IR galaxies were found in close pairs or triples, suggesting that they are generated from galaxy interactions. By measuring the colors of these bodies at eight different wavelengths, McCarthy, along with postdoctoral associate Hsiao-Wen Chen, can determine their redshifts with modest precision. The application of this technique to the IR-bright galaxies shows that they are high-luminosity galaxies at distances of 8 to 10 billion light-years and that they are found in structures that are 20 to 30 million light-years in extent. These objects appear to be the progenitors of the most massive galaxies in the present universe, but seen only partway through their assembly process.

In the coming years, McCarthy will work toward the deployment of a new near-IR camera on the Hubble Space Telescope that will allow for observations to unprecedentedly faint levels from space. In addition, he and Observatories Staff Member Eric Persson are in the early stages of developing a very large area near-IR camera for the second Magellan telescope.

SELECTED PUBLICATIONS


Evolved red giant stars are a key to understanding where in the universe, and by what nuclear reactions, the chemical elements were produced. In particular, how has the chemical evolution of galaxies proceeded? Most of the elements in the universe were produced in stars. Supernovae—massive stars that exploded and ejected their chemical constituents—are particularly important sources.

Andrew McWilliam studies red giant stars because they provide a useful probe to study chemical evolution in the local universe: they are bright enough to be studied at great distances, and they arise from young and old populations. Additionally, since the chemical composition of their surface has remained largely unchanged, they form a fossil record of chemical evolution in the universe.

In general, the oldest stars tend to be the most metal poor because fewer enriching supernovae exploded in the early epochs. In rare cases, it is possible to find stars made from the ejecta of only one or a few supernovae. They tend to have varied chemical compositions. Although the chemical variance is not well understood by current supernova theory, it is thought that different kinds of supernovae make elements in different proportions. By contrast, metal-rich stars display the chemical signatures of many supernova events, which have homogenized and averaged the chemical composition of the ejecta.

McWilliam and colleagues recently conducted two searches for extremely metal-poor stars. The first was directed toward the galactic bulge, and the second was in metal-poor dwarf spheroidal galaxies. They found stars with metal abundances of nearly 1/1,000 of the Sun’s and two candidates with only 1/10,000 solar abundance.

To test the chemical-evolution paradigm, McWilliam and colleagues looked at stellar compositions in other environments. Using the Keck telescope, they acquired spectra of red giants in the Sagittarius dwarf galaxy. The results indicate a large spread in metallicity and unusual abundances of many elements, including O, Mg, Ca, Na, Al, Mn, Ba, and Eu. The composition suggests that the Sagittarius dwarf had a long quiet period followed by enrichment from the metal-poor stars of the old population, including the ejected envelopes of post-red-giant stars and material from type Ia supernovae.

McWilliam and colleagues also looked at spectra of red giants in the galactic bulge and found unusual enhancements of O and Eu at solar metallicity. These elements are mostly made by type II supernovae, indicating that the galactic bulge formed in less than 1 billion years, a remarkably short time in which to reach solar metallicity.

SELECTED PUBLICATIONS

Most galaxies in the universe, including our own Milky Way, exist in small collections known as groups. John Mulchaey has been interested in galaxy groups since he was a graduate student. In 1992 he led the team that discovered that some of these collections are bright x-ray sources. This discovery has provided new insights into the fundamental nature of these objects.

Using the space-based x-ray telescope ROSAT, Mulchaey and collaborators found that x-ray emission is spread over the entire volume of a group. The extent of the emission suggests that the x-rays originated in a very hot gas; observations have shown that the temperature is about 10 million degrees. Since many groups emit x-rays, the scientists believe that the gas is long-lived. However, the extreme temperature suggests that it should have already escaped the gravitational attraction from the combined mass of the galaxies and gas. The fact that the gas is still present led Mulchaey and colleagues to conclude that galaxy groups are dominated by dark matter—the elusive material that does not emit light but has a strong gravitational pull. Uncovering the nature of this dark matter remains one of the most important goals in the field of astrophysics.

Mulchaey is using two recently launched x-ray telescopes, Chandra and XMM-Newton, in his research. Chandra is the “x-ray Hubble Space Telescope,” producing images with a resolution almost 100 times better than that of previous instruments. Chandra allows Mulchaey to study the x-ray emission in unprecedented detail. XMM-Newton, on the other hand, is more sensitive to fainter x-ray sources. Therefore, Mulchaey is using this telescope to study groups at much higher redshifts, where virtually nothing is currently known. By looking farther back in time, the XMM-Newton observations will provide insight into how groups of galaxies evolved.

Although Mulchaey works extensively with x-ray telescopes, the ground-based optical telescopes at Las Campanas Observatory play a central role in his research. X-ray images alone are not sufficient to uncover the nature of galaxy groups. Follow-up observations with large-aperture optical telescopes, such as those of the Magellan Project, are necessary for information on galaxy type and specific redshift.

SELECTED PUBLICATIONS

For much of his research career, Gus Oemler has studied two interrelated questions: How have galaxies evolved to their present forms, and how are galaxy populations distributed throughout the universe? Since Hubble’s time, it has been known that populations of galaxies vary from place to place in a systematic way. For example, in densely inhabited regions of the universe, most notably in the centers of rich galaxy clusters, galaxies have lower rates of star formation and less prominent disks than in sparsely inhabited regions. Is it possible that these differences arose during the epoch of galaxy formation, and signify the effect of environment on the birthrate of galaxies of different types? Or, is it possible that the cumulative influences of interactions with their neighbors cause galaxies to evolve over time?

Oemler, Alan Dressler, and others have demonstrated that galaxies in at least some environments have evolved rapidly during recent epochs. This is easy to show: the finite speed of light means that progressively more distant objects are seen at progressively earlier ages. Galaxies in somewhat younger clusters, observed at two-thirds of their present ages, are distinctly different from nearby, older cluster galaxies. Many are forming stars more vigorously than their local counterparts, and some show deformations that suggest the results of repeated jostling by their neighbors.

It is clear that galaxies evolve, but many questions remain. Is cluster-driven evolution responsible for the spatial variations in galaxy populations? If so, what processes are driving that evolution? Finally, since observations of distant galaxies provide only a snapshot of populations at one instant of time, rather than a movie, how can we “connect the dots,” and identify specific types of young galaxies as the progenitors of later types?

Oemler, Dressler, and their collaborators are using both Hubble Space Telescope imaging and ground-based spectroscopy to study galaxies undergoing transformation in distant clusters. By carefully examining the structure and stellar populations of individual galaxies, they are beginning to unravel the history of galaxies as they fall into clusters, interact with their surroundings, and begin to evolve. Oemler, John Mulchaey, and collaborators are doing similar work on the very different environment of small groups of galaxies. Earlier work by Oemler and others has shown that members of small groups of galaxies evolve differently from members of large, dense clusters. Detailed comparison of the properties of galaxies in these two environments can illuminate the exact role that environment plays in driving galaxy evolution.

SELECTED PUBLICATIONS

A group of Carnegie scientists and engineers led by Eric Persson is developing telescope instrumentation that exploits newly improved near-infrared (IR) imaging array detectors. The team has built one wide-field survey camera for the du Pont 2.5-meter telescope at Las Campanas, and it is designing infrared instruments for the Baade and Clay telescopes. The advances will allow Persson and others to observe galaxies that can only be studied in the near infrared.

Until recently, technical limitations have made it difficult to find such galaxies. The new instrumentation will allow the Persson group to survey one square degree of sky to find thousands of these objects and measure their brightness. They will then be able to estimate their distances and intrinsic luminosities, and examine the way they cluster in space. Another objective of their survey is to discover large numbers of abnormal high-redshift galaxies.

Persson and others have serendipitously found distant galaxies that emit virtually all of their energy in the infrared range. These galaxies are so rare that prohibitively large areas of sky must be surveyed to find new ones. Preliminary evidence on a few of these bodies suggests they are a varied population: some appear to be intense star-forming galaxies buried within optically opaque dust clouds, while others seem to be passively evolving objects in which star formation stopped several billion years ago. These objects are the prime targets for the new instrumentation.

In another area, Persson and Carnegie collaborators hope to advance the study of the distance scale of the universe by studying newly found type Ia supernovae. These bodies are believed to provide the key to understanding how the timescale, geometry, and mass content of the universe can be reconciled within the framework of general relativity. Type Ia supernovae are stellar-explosion events that appear to have a well-defined brightness as they rise to a maximum luminosity and then decline. Because the intrinsic luminosities of all supernovae at maximum light are essentially the same, relative distances to remote ones can be determined fairly easily. However, to be certain that local supernova events are physically the same as their distant counterparts, the scientists looked at type Ia supernova light curves (a display of the light’s variation over time) at near-infrared wavelengths. The data indicated that they are very similar. The new instrumentation will allow Persson’s group to monitor newly found supernovae and create a database to calibrate their distances.

SELECTED PUBLICATIONS

When stars explode as supernovae they become extremely luminous. Their extreme brightness at maximum makes them potentially powerful standard candles for probing the geometry and expansion of the universe. Type Ia supernovae are especially attractive candidates. They are thought to be the complete thermonuclear disruption of a small, very dense stellar remnant called a white dwarf. They have a high degree of homogeneity, and because of their immense luminosity at maximum light (up to 10 billion times that of the Sun), they can be observed at great distances. Mark Phillips, associate director of the Las Campanas Observatory, specializes in supernovae. He studies them to understand the role they have in the evolution of the universe, and to determine how they can be used as standard candles—astronomical baselines for measuring distance.

Phillips has been heavily involved in an effort to detect very distant supernovae. Using the Hubble Space Telescope, he and his collaborators recently demonstrated the feasibility of detecting supernovae at redshifts as great as $z = 1.5$, when the universe was only one-third its present age.

In his standard-candle research, Phillips has shown that although the peak luminosities of the type Ia supernovae are not identical, they can still be used as standards. He correlated the luminosity of separate events with an independent measurement of the rate of decline from maximum light. Calibrating the exact dependence of this correlation required obtaining precise light curves for a large number of supernovae and devising a method to determine the absorption of supernovae light by the dust in the host galaxy. Phillips and his collaborators developed a technique for measuring this absorption and were able to calculate a value for the Hubble constant of approximately 65 km/sec/megaparsec.

The scientists also used type Ia supernovae to measure the expansion rate of the universe at earlier epochs. Their observations led to a surprising result: we appear to be living in an accelerating universe. This finding is attractive because it implies an age of the universe that is consistent with the ages of the oldest stars in our galaxy. Phillips is sensitive to the possibility that the observations might reflect the evolution of the luminosities of the type Ia supernovae over time. Thus, during the next few years he plans to focus his research on testing this prospect by systematically observing supernovae at a variety of redshifts and environments.

SELECTED PUBLICATIONS


George Preston is spending his twilight years of research in an Observatories team effort to find and understand extremely rare astronomical objects—the first generations of stars born in the Milky Way. Although these bodies are difficult to detect, the effort is worth it because they offer an opportunity to understand how the calcium and iron in our bones came into existence.

The very first stars were made of the Big Bang material—mostly hydrogen, some helium, minute traces of lithium, beryllium, and boron, and nothing else. Their hydrogen burned into more helium and the helium to carbon in the most massive stars of this generation by a cooking process known as nucleosynthesis. At the ends of their lives these massive stars exploded, and the expelled debris was used to form the next generation of stars. This process has repeated itself over and over again for the past 13 billion years or so, gradually enriching the heavy-element content of the Milky Way. All supernova explosions are not alike, and a principal goal of this investigation is to learn how present-day abundances of the elements arise from this variety.

Extremely metal-poor stars (EMPs) are relics of the very early generations of stars. Their signature is the virtual absence of elements heavier than helium, and they constitute no more than one-tenth of a percent of the stars formed since the beginning of time. Preston, Andrew McWilliam, Ian Thompson, and Steve Shectman use the Swope and du Pont telescopes to find metal-poor stars. The scientists employ CCD photometry with special filters to identify metal-poor candidates among the myriad of red giant stars that live in the densely populated central region of the Milky Way. Unfortunately, several other varieties of stars mimic the signature of EMPs, so the team has had to refine the search to eliminate the forgers. In 1999 and 2000, the researchers initiated GRISM spectroscopy (a GRISM is a special combination of diffraction Grating and PRISM used to analyze starlight) at the du Pont telescope, which resulted in a list of “bona fide” metal-poor stars.

Over the next decade, the scientists will use the high-resolution spectrographs of the new Magellan telescopes to measure abundances of the chemical elements in these elusive bodies. Preston and his colleagues expect that their findings will offer new insights into the Milky Way’s infancy and answer questions about the creation and evolution of the chemical elements in the universe.

SELECTED PUBLICATIONS
Objects such as quasars, stars, and hot gas are highly luminous because of the conversion of gravitational energy into radiation. In general, however, cosmic matter appears to be dominated by tenuous, dark ionized gas clouds, which permeate space in the form of large filaments or sheets. To study these clouds, known as the intergalactic medium (IGM), scientists have to observe the “shadows” they cast on the spectrum of a bright background light source. Rauch is studying the nature of this matter in the early universe using absorption lines produced by intervening gas clouds in the spectra of background quasars.

There are numerous applications for this technique. The IGM, for instance, retains a record of the conditions in the early universe: the ripples of the density distribution at early times closely correspond to the fluctuations in the absorption pattern caused by the IGM in the background quasar spectrum. The total amount of absorption is related to the total density of observable matter. And the width and depth of the absorption lines indicate the changes in the mean temperature of the intergalactic medium as a function of time, and yield information about the history of cosmic ionization.

By comparing cosmological simulations of the IGM to real absorption spectra, scientists can begin to understand the evolutionary properties of the universe. In collaboration with Caltech, Rauch is using quasar data from the Keck telescope to study the IGM. He is exploring new ways of analyzing these data and is collaborating with several other groups who are performing theoretical cosmological simulations.

Lines of sight to background quasars inevitably intersect galaxies at various stages of their development. When this occurs, characteristic metal-absorption lines appear, which allow scientists to trace the history of metal enrichment of the universe. Rauch is working on a spectroscopic survey of gravitationally lensed quasars that have more than one line of sight to the same quasar. Two closely spaced sight lines, which permeate the same cloud, provide the researchers with information on the cloud’s metallicity and the spatial extent and kinematics of the metal-enriched gas. The lensing acts like a gigantic microscope. For a galaxy at the other end of the universe, the researchers can obtain a spatial resolution of a few tens of parsecs, which allows them to probe the interstellar medium of a young galaxy at the level of individual stars and supernova explosions.

SELECTED PUBLICATIONS


Miguel Roth has been director of Carnegie’s Las Campanas Observatory since 1990. In addition to his administrative responsibilities, he studies two major processes that enrich the interstellar medium: supernovae and planetary nebulae (PNs). Planetary nebulae—gas shells emitted from red giant stars—are like supernovae in that they are sources of heavy elements.

Roth is interested in “old” PNs. These nebulae arise from intermediate-mass stars that have expelled a large portion of their material. The surrounding gaseous envelope contains several distinctive elements, particularly hydrogen, nitrogen, and oxygen. Old PNs tend to be spherical, with the star displaced from the geometrical center. This shape indicates that the object has interacted with the medium that surrounds it. To understand how PNs originated and evolved, Roth has been involved in a collaborative effort to analyze the relative abundance of H, N, and O spectroscopically and correlate the data with optical and infrared images.

The researchers used a similar approach to studying supernovae. They looked at the interaction of some supernova remnants with the interstellar medium using radio techniques. Their focus was the “clumpy” distribution of molecules such as CO and H₂. When they correlated the data with tracers of star formation, they saw that induced star formation was possible. These mechanisms may be one of the triggers that form new generations of stars.

Sequential star formation is probably present in areas surrounding what are known as HII regions. Very massive and short-lived stars can ionize their surrounding medium and compress it as the HII region expands. With images from Las Campanas and the Hubble Space Telescope, the scientists confirmed the existence of a new generation of very young stars surrounding a massive cluster known as R136 in the Tarantula Nebula of the Large Magellanic Cloud.

In collaboration with Mark Phillips, Roth is also studying the evolution of supernovae light curves at infrared wavelengths. It is possible to determine the peak luminosity of supernovae by documenting the evolution of light curves. This information allows researchers to determine the distance to the objects’ host galaxies and the rate at which the universe is expanding.

In another area, Roth was a member of a team of astronomers at Las Campanas who systematically measured standard stars. These astronomical objects are used to determine the luminosities of other bodies. Although the work was tedious, they produced a reliable list of standards that astronomers worldwide now use.

SELECTED PUBLICATIONS


In 1903, George Ellery Hale told the first trustees of the Carnegie Institution why an astrophysical observatory on Mount Wilson was necessary: it could advance the new sciences of origins and evolution, and “solve the problem of stellar evolution.” Hale argued that by comparing the physical properties of the stars with those of the Sun, the solution to stellar evolution would “simply fall out.” Although it did not quite work that way, the solution did emerge beginning in the 1940s, from data obtained principally at Mount Wilson.

The contemporary ideas of how stars age, how our galaxy formed, and how the universe is arranged have now largely been solved through many long-range programs started at the Observatories decades ago. Hubble’s discoveries in observational cosmology in the 1930s and Baade’s concept of stellar populations in the 1950s, for instance, have been integrated into a fabric that has become the present paradigm of astronomical origins.

Sandage has been involved in astronomical origins and evolution since he joined Carnegie in 1952. His first result that year was the discovery made with Arp and Baum that the main sequence termination luminosity of the globular clusters M92 and M3 were about the same as the intrinsic luminosity of the Sun. The faintness of this termination point showed that stars of Baade’s population II, which include the globular clusters, were extremely old. Determining the actual age has been a master problem that has occupied Sandage and others for the better part of the last half-century. Globular clusters, which date to the formation of our galaxy and are close to the age of the universe, are now estimated to be about 12 billion years old.

The other means to date events in the universe is to determine the rate at which the universe expands and the galaxies move away from each other. Since the early 1950s, Sandage has investigated this problem and has been involved in the various aspects of establishing the distance scale to galaxies. With Dr. Gustav Tamman, at the University of Basel, and Dr. Abijit Saha, of Kitt Peak National Observatory, the scientists determined that the universe is expanding at a rate of 58 kilometers/second/megaparsec. Using this result, we can estimate the age of the universe to be about 14 billion years. The fact that these two timescales are so close to each other is one of the strongest proofs of the standard model of observational cosmology.

SELECTED PUBLICATIONS


The universe is populated by billions of galaxies, each with dark matter, gas, and millions to billions of stars. How these galaxies assembled from the primordial plasma and evolved to their present-day masses and shapes is a central interest in current astrophysics. François Schweizer studies galaxy assembly and evolution by observing nearby galaxies, focusing on the question of how their shapes and contents are affected by collisions and mergers.

The dichotomy of galactic shapes is puzzling: Why are most galaxies disk-shaped like our Milky Way, yet a significant minority, called “ellipticals,” spheroidal and even triaxial? Schweizer’s research indicates that—far from being rare events, as was once thought—collisions and mergers are a dominant process in shaping galaxies and determining their stellar and gaseous contents. Galaxies apparently accrete gas clouds and small companions throughout their history. Yet, spectacular events occur when they collide with neighbors of near-equal mass. Such major collisions lead to rapid mergers and a complete redistribution of the visible mass. Two spirals can merge into a single remnant with all the attributes of a young elliptical: blobby appearance, kinematic subsystems, and million-degree gas. Schweizer deduces that the order of galaxies along Edwin Hubble’s famous morphological sequence is determined mainly by the galaxies’ merger history: thin-disk spirals grew gently via minor accretions, while ellipticals are the wrecks of major destructive mergers.

When two spirals collide, their rarefied atomic hydrogen is crunched, becomes molecular, and fuels the sudden birth of billions of new stars and thousands of star clusters. Some of these clusters are so dense that they survive the merger intact and orbit in the remnant galaxy for gigayears as “globular clusters.” Schweizer and his collaborators use the Hubble Space Telescope to find young globulars and study their formation and evolution. Follow-up spectroscopy with ground-based telescopes then yields the velocities, chemical compositions, and ages of the clusters. By studying the present-day birth of globular clusters, researchers can gain insights into the galactic formation processes. Schweizer’s next goal is to use globulars for dating the main star-formation episodes of elliptical galaxies.

Schweizer feels that understanding galaxy formation and evolution is part of understanding our own origin. Whereas galaxies once appeared to be “island universes,” we now see themassemble hierarchically, grow in fits and spurts and form stars that cook up the heavy elements of which planets, and we ourselves, are made.

SELECTED PUBLICATIONS

Stephen Shectman works in four main areas: developing astronomical instruments; studying the large-scale structure of galaxy distribution; searching for low-metal-abundance stars; and constructing the Magellan telescopes.

In the instrument area, Shectman has developed a series of photon-counting detectors for faint-object spectroscopy. They have been used at Las Campanas and copied by a number of other observatories. He also built the high-resolution Echelle spectrograph and the multiobject fiber spectrograph for the 100-inch du Pont telescope at Las Campanas. Currently, working with Hubble Fellow Rebecca Bernstein, he is building the high-resolution Echelle spectrograph for Magellan.

To study the large-scale distribution of galaxies in space, Shectman has participated in several galaxy redshift surveys. With collaborators Kirshner, Oemler, and Schechter, he discovered a particularly large void in the galaxy distribution. Using the C100 fiber spectrograph, the scientists also conducted the Las Campanas Redshift Survey. The survey shows the galaxy distribution becoming homogeneous on scales that are large compared with the sizes of clusters, filaments, sheets, and voids characteristic of the distribution on smaller scales.

Hydrogen and helium were produced in the Big Bang, but heavier elements are the result of nucleosynthesis in successive generations of stars. The oldest stars are characteristically deficient in heavy elements. Shectman and George Preston conducted a survey for stars with very low metal abundance. Using objective-prism plates taken through an interference filter, they selected stars with weak lines confirming the best candidates with individual spectra taken at higher resolution. This technique accounts for the majority of known stars with heavy-element abundances of less than about 1% of the value of the Sun’s. The most chemically deficient stars have abundances of about 0.01% of solar, with some variation from element to element. Stars from the first few generations provide insights into the process of star formation when galaxies were just beginning to appear.

Shectman has been Magellan Project Scientist since the project began in 1986. He participated in most of the scientific and engineering discussions during the conceptual and detailed design phases, and he wrote about one-third of the software used in the telescope control system. In addition, Shectman has been at Las Campanas during many of the commissioning activities, including the first pointing and tracking tests for the telescope mount, and the first imaging tests using the full optical configuration. He also conceived the integrated optical design for the telescope secondary mirror, field corrector, and imaging spectrograph.

SELECTED PUBLICATIONS


Distances and ages of globular clusters, spherical systems of about 100,000 stars that are among the oldest components of our galaxy, are key stepping-stones to understanding the age and scale of the universe. Previous measurements of distances to these objects have compared the characteristics of different types of stars found in the solar neighborhood (with estimated distances) with the same types of stars found in the clusters. These measurements suffer from systematic errors, which limit the determination of cluster ages.

Ian Thompson, with colleagues at the Observatories and at the University of Warsaw, is pursuing a different approach to the problem. Observations of Detached Eclipsing Binary stars allow a geometric measurement of distances. These systems consist of two separated stars in orbit around each other with the orbital plane in the line of sight to the stars. The total light is modulated as one star passes in front of the other. The shapes of these eclipses determine the relative sizes of the stars and their separation. Variations in their radial velocities and a simple application of Kepler’s laws of gravity indicate absolute dimensions of the system. The distance to the binaries can then be measured by comparing the apparent brightness with the surface brightness of the stars, as estimated from their infrared colors.

Thompson searches for these exceedingly rare stars by continuously monitoring a selection of nearby southern globular clusters with the Swope 1-meter telescope. It requires many nights to detect eclipses and measure their orbital periods. Detailed measurements of the shape of the light curves are made with the du Pont 2.5-meter telescope, and radial velocity curves will be measured with the Echelle spectrograph on the Magellan telescopes. Only one or two eclipsing binaries are expected to be detected in each cluster, but these are sufficient to overhaul our imperfect knowledge of their distances and ages.

This research, as well as the collaboration with Preston, McWilliam, and Shectman in the search for extremely metal-poor stars, illustrates the way smaller telescopes at Las Campanas will be used to discover interesting objects that can be studied in more detail with the Magellan telescopes.

Thompson also works on instrumentation for the Las Campanas telescopes. With instrument scientist Greg Burley, he is building the CCD cameras for Carnegie’s initial contributions to Magellan optical instrumentation (IMACS, the wide-angle imager and spectrograph, and MIKE, the Echelle spectrograph) as well as the guide cameras for the two Magellan telescopes.

**SELECTED PUBLICATIONS**


Ray Weymann searches for and analyzes the most distant galaxies and quasars to understand how the universe evolved. Recently he has become particularly interested in refining the photometric redshift technique used to estimate the distances to galaxies.

Photometric redshifts use images of galaxies in several bandpasses. The technique can measure a huge number of galaxies efficiently and can be used to estimate the redshifts of much fainter galaxies than the more accurate method of measuring spectra using large telescopes.

In his search for extremely distant galaxies, Weymann and colleagues made observations with the infrared NICMOS camera on the Hubble Space Telescope and combined them with visible light images from the Hubble Deep Field. The result was a set of images ideally suited for determining photometric redshifts, and for searching for a very high-redshift galaxy. The search yielded one such galaxy that was confirmed to have a redshift of $z = 5.6$ based on spectroscopic observations made with the Keck telescope. The Hubble images used to identify the far-off galaxy are shown below.

Using the photometric redshift technique, Weymann is in the process of determining whether and how well astronomers can simultaneously estimate the redshift of the galaxies and the absorption of ultraviolet light by the internal dust associated with stars being formed. Correcting for this absorption is crucial for a true picture of the rate at which stars have been forming in the history of the universe. Determining this correction is far more difficult than estimating only the redshift because the colors of a galaxy undergoing vigorous star formation, coupled with moderately heavy dust absorption, closely resemble the colors of a galaxy with only moderate star-formation rates and little or no dust absorption.

In a different field of extragalactic astronomy, Weymann is analyzing data on a bright quasar taken with the new STIS spectrograph on the Hubble Space Telescope. He will compare his observations of the properties of intergalactic hydrogen gas clouds and how they associate with galaxies with the predictions from computer simulations of the evolving universe. These data are being augmented by spectroscopic redshifts of galaxies near the quasar (in angle, not distance) taken with the du Pont telescope at Las Campanas.

SELECTED PUBLICATIONS


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