THE DIRECTOR'S INTRODUCTION

Fig. 1. This is a model of the Inamori Magellan Areal Camera and Spectrograph (IMACS) to be mounted on the Magellan I telescope. When complete, this wide-field instrument will be used in high-redshift studies of the universe.

The Postdoctoral Program

The research of the senior staff of the Observatories is described in the pages that follow. However, it is only part of the scientific activity on Santa Barbara Street. Another key component is the postdoctoral program. This program is the principal way in which the Observatories contribute to the education of young astronomers; but it does more than that. The constant flow of new faces and new ideas through the Observatories makes a significant contribution to the intellectual life of the department. It is a contribution to the future as well as to the present: the majority of Observatories Staff Members first came to Santa Barbara Street as postdocs.

There are usually about a dozen postdoctoral fellows and associates at the Observatories: three Carnegie Fellows, funded by the institution; up to three Hubble Fellows, funded by the Space Telescope Science Institute; and a half dozen postdoctoral associates, funded by grants to individual researchers. Unlike those in laboratory sciences such as biology, many astronomy postdocs are free agents. The Carnegie and Hubble Fellows, in particular, are completely independent researchers, doing the science they want to do in the way they want to do it. This is a great challenge as well as a great opportunity for a still-maturing scientist, and our fellows almost invariably make the most of the opportunity. Indeed, former Observatories postdocs have been extremely successful in their later careers and populate many of the leading astronomy positions.

Carnegie postdocs work on a wide variety of problems either on their own or in collaboration with Observatories staff. A few examples follow.

Carnegie Fellow Jason Prochaska uses the light from extremely distant quasi-stellar objects (QSOs) to probe the contents of the universe. The view of the universe normally provided by telescopes, whether optical, radio, or x-ray, is a biased one, because it is dominated by those objects that are copious emitters of optical, radio, or x-radiation. QSO light tells us about QSOs, of course, but it is also an unbiased probe of all the space through which the light travels on the way to our telescope. This probe reveals a very different universe, filled with gas, which leaves telltale absorption lines in the QSO spectrum. The challenge is to relate the objects detected by this technique to the luminous objects seen in usual observations. The strongest absorption lines are believed to be produced in the disks of young galaxies, but proof of this has been hard to find. Prochaska has used very high resolution spectroscopy of these systems to demonstrate that they are in ordered rotation, consistent with the hypothesis that they are indeed disk galaxies or, at the very least, rotating collapsing protogalaxies.

Another take on a somewhat later stage in galaxy evolution is provided by Carnegie Fellow Scott Trager's study of elliptical galaxies and spiral galaxy bulges. These are both spheroidal systems thought to be products of the earliest phase of galaxy formation. The spectrum of a collection of young (less than 1 billion years old) stars differs markedly from that of a collection of old (10 billion years old) stars. However, the differences between the spectra of 5 and 10-billion-year-old stellar populations are quite subtle. It is these small differences that Trager searches for. He has found that the bulges of spiral galaxies with big bulges (such as the Andromeda galaxy) are quite old, having formed very early in the history of the universe, while the bulges of at least some disk galaxies with small bulges are quite young—no older than their own disks. This suggests that the two types of spiral galaxies form in reverse order: the large bulges may form as elliptical galaxies and then accrete their disks, while small bulges may form from the disks themselves.

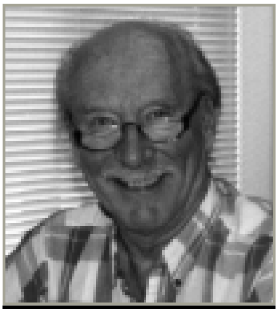
One can directly study the earlier history of elliptical galaxies by observing them at high redshifts. As Pat McCarthy and Eric Persson describe in following

Fig. 2. The Andromeda galaxy M31.

pages, high-redshift ellipticals are very red, and are most easily discovered using a combination of visible light and infrared observations. Persson, McCarthy, and Hubble Fellow Ron Marzke are leading Carnegie's participation in a collaborative project with the Institute of Astronomy at Cambridge University. This project mates an infrared detector system from Cambridge with an optical system produced by Persson's infrared instrumentation group to form the most powerful infrared survey instrument extant. Mounted on the du Pont telescope at Las Campanas, this instrument is producing the most extensive deep-infrared survey yet obtained. When combined with optical observations, these data will form the basis for Magellan telescope studies of early elliptical and starburst galaxies, and the evolution of clustering in the universe.

Department News

The Observatories continue to grow as scientific, technical, and support staff are added. Most of the growth has been driven by Magellan's need for instrument builders, programmers, operations staff, etc. Finding yet another unused basement space that can be turned into new offices has become a constant preoccupation. Two new Staff Members were appointed during the past year to replace Allan Sandage and George Preston, who are both retiring. John Mulchaey received his Ph.D. in 1994 from the University of Maryland and has been a fellow at the Observatories ever since. He is a leader in the study of groups of galaxies, the most common but most neglected galactic environment. Mulchaey's work has revealed surprising new properties of groups of galaxies, including some in which all the galaxies have merged into one giant object.


George Preston


John Mulchaey.

Michael Rauch received his Ph.D. in 1993 from Cambridge University. He worked at the Observatories and at Caltech, and is now on the staff of the European Southern Observatory. Dr. Rauch's field is absorption-line QSOs. This is an area of long-standing importance for understanding the contents and structure of the universe; it has undergone a significant flowering in recent years due in significant part to Dr. Rauch's work. Unlike Prochaska's work in the same area, Rauch's focuses on the lowest-density systems, which are thought to be primordial gas clouds that have not yet condensed into bound systems.

Dr. Luis Ho began a five-year appointment as Staff Associate. Dr. Ho's principal interest is the incidence and properties of black holes in the centers of galaxies. Such black holes manifest themselves in two ways: by their gravitational pull on the surrounding stars, and by powering active galactic nuclei (AGNs). He has shown that such AGNs are much more prevalent than previously thought, suggesting that most, if not all, large galaxies harbor a supermassive black hole in their centers.

Another very welcome addition is Mark Phillips, who was appointed Associate Director of the Las Campanas Observatory. Dr. Phillips was a long-time staff member and former Associate Director of the Cerro Tololo Inter-American Observatory (CTIO) in La Serena, Chile, and he is a leading authority on supernovae. His calibration of the luminosities of supernovae is central to recent work using them as cosmological probes. He has moved across the street from CTIO to El Pino to continue his supernova research, and to work with LCO director Miguel Roth to manage the increasingly complex Las Campanas operation.

The Magellan Project

The enclosure and mount of the Magellan I telescope are essentially complete. Only minor additions to the telescope control system software remain. Work on the aluminization system continues; it is expected to be ready for a first coating of the primary mirror in the spring of 2000. Figuring was completed for the primary mirror at the Steward Observatory Mirror Laboratory (SOML) and for the f/11 secondary mirror at Contraves. Both mirrors are superb, meeting or exceeding specifications at all levels. Unfortunately, slow progress on the f/15 silicon carbine secondary mirror has forced a suspension of that effort. By mid-1999, the primary mirror support system (also being produced by SOML) was nearing completion, and the mirror and mirror cell were shipped to Chile in the fall of 1999.

Meanwhile, erection of the Magellan II enclosure has reached the halfway point. All steel for the fixed lower part of the enclosure is in place, but completion of the rotating upper half awaits delivery of the remaining steel from the fabricator in Spain. Assembly of the telescope mount is well under way at L&F Industries in Huntington Park, California. The Magellan II primary mirror was successfully cast in the fall of 1998 at SOML, and work on the back side of the mirror is nearly complete.

The IMACS spectrograph for Magellan I passed its preliminary design review in April 1999. Fabrication of the optics for the collimator and long camera, and fabrication of mechanical com-

Fig. 3. The Magellan Project's facilities at Las Campanas include the dome for the first telescope, as shown in the foreground. The enclosure for the Magellan II telescope is under construction in the background.

ponents should begin by the end of 1999. The mechanical design of the Kyocera Echelle Spectrograph is also near completion. Design work on the DDI infrared spectrograph continues, but progress has been slowed by the need to complete the infrared camera, described earlier, for the du Pont telescope. Most of the glass for the optics has been delivered, and polishing of elements should begin in the latter half of 1999.

—Augustus Oemler, Jr.

ALAN DRESSLER

One of the great mysteries of modern astronomy is the nature, amount, and distribution of the dark matter that dominates the universe. A principal direction of Alan Dressler's research has been to try to map the distribution of dark matter on cosmic scales by tracing its presence through the gravitational pull it exerts on galaxies. By finding the "peculiar velocities" of thousands of galaxies in our cosmic neighborhood, Dressler and his colleagues discovered a huge concentration of dark matter, which they named the Great Attractor.

Alan Dressler

Fig. 4. Observatories' postdoctoral fellows and associates (from left): Scott Trager, Scott Chapman, Lin Yan, Ben Weiner, Swara Ravindranath, Ron Marzke, and Jason Prochaska.

This year marked a milestone in the study. Data from the new technique called *surface brightness fluctuations* have at last been brought to bear on the problem. Many of the new measurements were made with the du Pont CCD cameras and relied on the excellent observing conditions at Las Campanas Observatory. The data took almost 10 years to obtain, and provide the most accurate peculiar velocities to date. In three new papers, Dressler and his colleagues John Tonry of the University of Hawaii, John Blakeslee of Caltech, and Ed Ajhar of the National Optical Astronomy Observatories confirm the existence of the Great Attractor. Additionally, the researchers were able to see, for the first time, the weaker flows of galaxies into much smaller mass concentrations, as well as the flows away from voids—places where few galaxies are seen and the corresponding mass density is thought to be very low. The higher resolution and sensitivity of these new dark-matter maps will allow a much better determination of the extent to which the galaxy distribution traces the dark matter. This information is crucial to interpreting the large-scale structure of the universe as mapped by galaxies, and to understanding the role of dark matter in galaxy formation.

Another theme of Dressler's research involves the question of how galaxies formed and evolved over cosmic time. Astronomers have the unique ability to look back in time as they look far out into space. With their colleagues, Dressler and Gus Oemler have been using large ground-based telescopes and the Hubble Space Telescope to observe distant galaxies to determine their properties at earlier times. This collaboration, known as the MORPHS Project, has produced two major papers this year. The papers describe the connection between galaxy morphology (structure) and star-formation history in galaxies seen as they were 5 billion years ago. Among the conclusions of this work is that bursts of star formation were much more common in galaxies at that epoch, in contrast to the steadier star-formation rate characteristic of galaxies today. Additionally, the scientists found that because these starbursts were often shrouded by dust, their importance had been underestimated in earlier work.

The MORPHS study concluded that elliptical galaxies—the spheroidal systems that are most common in regions of high galaxy density—are generally old, nearly as old as the universe, but that over the last 5 billion years many spiral galaxies—disk galaxies with ongoing star formation—have been transformed to a dormant kind of disk galaxy called an S0. The specific mechanisms responsible for this change remain elusive and are still under study by the group.

Over the next two years Dressler will devote considerable effort as principal investigator of the IMACS instrument, a sensitive multiobject spectrograph and camera with a very wide field. When mated with the new Magellan I telescope, this instrumentation will open new territory in the high-redshift universe for Dressler and colleagues to study the evolution of galaxies with lookback time.

Wendy Freedman

Big Bang cosmology makes a number of predictions, one of which is the expansion of the universe. However, the Big Bang theory does not predict how fast that expansion is, or what the density of matter in the universe is. These quantities, which describe the fundamental, global nature of the universe, must be determined by observations. For the past 15 years, Wendy Freedman has been working on a project to measure the Hubble constant—the rate of the expansion of the universe. The Hubble constant, when combined with a value for the average density of mass/energy in the universe, yields a measure of the universe's age.

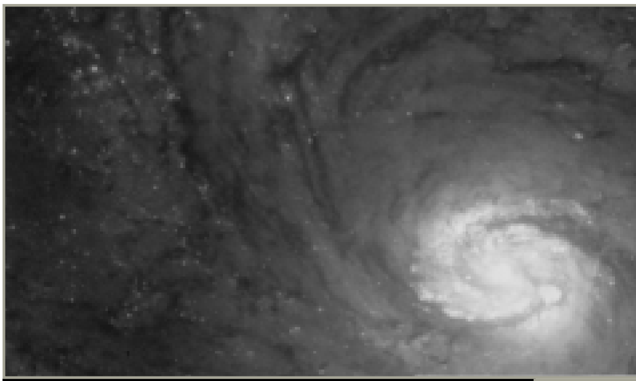


Fig. 5. The galaxy Messier 100 is shown here as imaged by the Hubble Space Telescope.

Freedman is a principal investigator, with Robert Kennicutt of the University of Arizona and Jeremy Mould of the Australian National University, of a group of 27 astronomers located across the U.S. and in Canada, Great Britain, and Australia. For the past eight years, the group has been using the Hubble Space Telescope (HST) to improve accuracy in the measurement of the Hubble constant. Most of the effort in the HST project has been aimed at measuring the distances to galaxies using a relation between the period and luminosity of Cepheid variables—pulsating stars that are used to measure distance. Turbulence in the Earth's atmosphere makes these measurements impossible from the ground for all but the nearest galaxies. As part of the Key Project, the team measured Cepheid distances to 18 galaxies and discovered about 750 Cepheid variables. Even with the HST, however, the range for discovery of Cepheids is limited to distances less than about 80 million light-years. To measure the Hubble constant, it is necessary to measure farther out. To do so, the scientists tied the Cepheid distances into other methods that are based on more luminous objects visible at greater distances, such as luminous supernovae, and spiral and elliptical galaxies.

Wendy Freedman

Using four independent methods, all calibrated by the new HST Cepheid distances, Freedman and collaborators found a value of the Hubble constant of 71 km/sec/megaparsec with a total uncertainty of 10%. The current best estimates for the average density of matter in the universe suggest a lower value than was previously thought; it is now believed to be about one quarter of the so-called critical density. This new value, when coupled with a Hubble constant of 71, yields a universe that is about 12 billion years old. This age agrees well with recent results from the *Hipparcos* satellite, which give very similar ages for the oldest stars in our galaxy.

Several years ago, the preferred theoretical models suggested that we live in a critical-density universe. Under that scenario, values of the Hubble constant of 70 or 80 led to a universe that is 8 or 9 billion years old. This result was in apparent conflict with the then-current estimates for the ages of globular clusters at 15 billion years. This paradox is very simply resolved, however, if we live in a low-matter density universe. We might still live in a universe at critical density (if there is another component of energy, perhaps due to the so-called cosmological constant), but the new Hubble constant results do not require this possibility.

Luis Ho

Luis Ho's arrival at the Observatories last fall coincided with a particularly eventful time, the birth of his son Hansun. After the inevitably hectic period of moving across the country, the transition to LA life was smooth. It did not take long for his wife, Sandra, and daughter Mya to appreciate the virtues of sunny southern California.

Ho's work primarily focuses on two themes: physical processes in galactic nuclei and the properties of young, massive extragalactic star clusters. The study of the central regions of nearby galaxies has entered an exciting era with the advent of powerful new instruments such as the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST). Ho and his collaborators are using STIS to obtain high-resolution, spatially resolved spectra of the nuclear regions of a large sample of galaxies. These data yield kinematic measurements of gas and stars, information that can constrain the central mass distribution in an unprecedentedly large number of galaxies, and thus verify the existence of massive black holes. The same data also give exquisite spectral information that allows Ho to probe the stellar population and gas properties on spatial scales of a few parsecs. Ho is also taking advantage of the fantastic imaging capability of the HST to study the structure of spiral galaxies' bulges. The HST data reveal a bewildering array of fine structures previously unknown from ground-based images such as spiral arms, dust lanes, star clusters, and compact nuclei.

Luis Ho

In an effort to better understand the physics of low-luminosity, active galactic nuclei (AGNs)—common in most large nearby galaxies—Ho has initiated a suite of observational programs using the HST, x-ray satellites, and ground-based radio telescopes. The goal of these programs is the same: to characterize the properties of nearby galactic nuclei at many wavelengths. These nuclei have been virtually unstudied because of their extreme faintness. The initial results are startling: the broadband spectral energy distributions of low-luminosity AGNs look remarkably different from those of the traditionally studied, high-power AGNs, such as Seyfert nuclei and quasars. This information strongly suggests a difference in the process by which the central black holes accrete matter in the two classes of AGNs; a suspicion confirmed by theoretical calculations made with colleagues at Harvard.

Ho recently started work in two rather different directions. With Mark Phillips and collaborators at Cerro Tololo Inter-American Observatory, Ho joined an ambitious study, which employs a large-format camera to monitor a large number of galaxies with redshifts up to 0.1. The primary objective is to search for local supernovae and to characterize their properties as a function of their environment. Another objective is to search for flashes of light from galactic nuclei. These flashes are a unique signature predicted from the tidal disruption of stars caused by massive black holes, which are believed to be ubiquitous in galactic nuclei. With John Mulchaey, Gus Oemler, and Steve Shectman, Ho is also using the du Pont telescope at Las Campanas to obtain morphological data and integrated optical spectra of a large sample of "local" (redshifts less than 0.1) galaxies. The intention is to assemble a library of reference data to serve as a useful present-epoch benchmark for future optical studies of more distant galaxies.

William Kunkel

Kunkel's research has focused on the internal dynamics of the Large and Small Magellanic Clouds (moderate-size satellites of the Milky Way) using observations from the motion of carbon stars. Carbon stars were selected as test particles because of their age: they are old enough to have completely decoupled from the motions of the gas, and no longer retain traces from the earliest phases of galaxy formation. Because of these features, carbon star motion is expected to represent the median dynamic behavior under gravity alone. Up to now, astronomers have assumed that the motion of gas is a reliable tracer of gravitational forces. Kunkel, in collaboration with Serge Demers of the University of Montreal and Mike Irwin of the Royal Greenwich Observatory, discovered significant deviations between the stellar and gas motions in both Magellanic Clouds. The data acquisition phase of the study was completed in 1998, and 1999 has been dedicated to the final interpretive exercise.

The Magellanic Clouds are satellites on highly elongated orbits. They receive episodic impulses of mechanical energy generated by tidal forces each time they approach one another or the Milky Way. These tidal impulses offer an opportunity to "tweak" the behavior of gravity in a known way, facilitating specific tests that are easily replicated in a computer simulation. Comparison of the behavior seen in the numerical simulation with that observed in the carbon stars reveals serious difficulties with otherwise well-established tradition. The most serious problem is the distribution of dark matter. According to established lore, it is expected to follow gravitational forces exclusively, yet somehow sustain a spatial distribution different from that of observed matter, which congregates at the centers of dark matter complexes. Other conundrums addressed include the surprise that unlike carbon stars in the Milky Way, carbon stars in the Magellanic Clouds are found far from current sites of star formation. Large amounts of energy (and traditionally, a very long time) are required to carry carbon stars from their birth locations to where they are seen today. Mechanisms are thus needed to "stir things up," and tidal impulses are the outstanding candidates.

Since numerical simulations have clarified the global dynamic picture of gravitational processes in the Magellanic Clouds, the results of the present study indicate that significant nongravitational forces are acting on the gaseous components of the local satellites. Eventually, the significance of these findings is expected to impact how reliably one can trust the information about the spins in small galaxies, which is inferred from observations of rotating gas disks. More important, the findings will affect inferences about the distribution of gravitational potentials from such observations.

In the future, Kunkel intends to explore the gas/stars discrepancies in the nearest of the more remote galaxies: IC1613 and NGC6822. These are examples of systems experiencing occasional tidal impulses, and NGC3109 is one in which such impulses (stirring spoons!) are expected to be absent.

Patrick McCarthy

The stars that constitute the bulk of the mass of galaxies emit most of their luminous energy at wavelengths longer than 0.5 microns. These cool, giant stars have masses comparable to that of the Sun and lifetimes of billions of years. At large distances, the cosmological redshift has shifted this radiation to the near-infrared (IR). Most surveys of high-redshift galaxies have been confined to visible wavelengths, and thus sample ultraviolet (UV) photons emitted at the source. The emitted and observed wavelengths are related by $\lambda_{emitted} = \lambda_{observed}/(1 + z)$, where z is the redshift. The ultraviolet luminosity of galaxies is often dominated by a small population of massive stars that produce 100 to 1,000 times more luminosity per unit mass than stars like the Sun, but have lifetimes that are measured in millions rather than billions of years. The UV luminosities of galaxies thus reflect their present star formation rates, while near-infrared luminosities are a far better tracer of the total stellar mass.

For the past few years Patrick McCarthy and colleagues have been applying near-infrared techniques, from Las Campanas and from orbit, to study faint and distant galaxies. Together with Staff Member Eric Persson and Hubble Fellow Ron Marzke, McCarthy has embarked on an ambitious survey of faint galaxies in the near-infrared. Using a unique camera containing a mosaic of four large near-IR detectors, the scientists are surveying an area of the sky four and a half times the area of the full Moon. This survey will yield a sample of between 2,000 and 4,000 old galaxies at large redshifts, and will allow the astronomers to precisely measure their spatial clustering—an important clue in understanding the growth of density irregularities in the early universe.

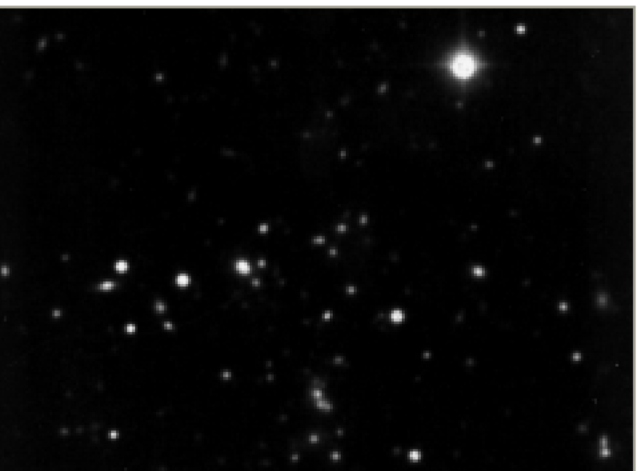


Fig. 6. This is a near-infrared and optical image of a cluster of galaxies with a redshift of nearly 1. The picture is a composite of images at 0.5, 0.8, and 1.6 microns. Old galaxies are strongly clustered around the central object, a luminous radio source. These data were obtained with the du Pont telescope at Las Campanas.

Spectroscopy in the near-infrared offers a new window on galaxies at large redshifts. McCarthy and postdoctoral associate Lin Yan have used the near-IR spectrometer on board the Hubble Space Telescope to measure the star formation rates of galaxies with redshifts between 1 and 2. Yan and others find that the star formation rate at a redshift of 1.5 is 17 times larger than the present rate. This high rate of star formation is a factor of two to three times greater than the rate derived from ultraviolet measurements and implies that roughly 50% of the stars in the present universe were formed as recently as 5 billion years ago. This is in stark contrast to the very inactive and old galaxies that are the targets of the survey described above. These results highlight the fact that galaxy evolution is not a uniform or homogeneous process. The life history of a galaxy is greatly influenced by the environment in which it begins. Some reach maturity early in the history of the universe, while others lie dormant until some stimulus drives the conversion of gas into stars.

Andrew McWilliam

Andrew McWilliam's research focuses on nucleogenesis and galactic chemical evolution. His goal is to understand where and how the elements were produced by studying the composition of very old stars and stars born in different environments.

Stars produce most of the elements in the universe; supernovae (SNe) are particularly important sources. Theoretical models of SNe and other astrophysical enrichment events are very crude and require observational constraint. Stars of low mass are very long-lived and span the age of our galaxy. Such fossil stars can be used to trace the history of chemical evolution. In general, the oldest stars are the most metal-poor because fewer supernovae had occurred before the very early epoch when the stars formed.

Most stars contain the chemical signatures of many supernovae (over 100 million SNe have occurred in our galaxy), so the amplitude of abundance variations from individual SNe are usually insignificant. The abundance variations of individual SNe are more evident in stars composed of ejecta from only one or a few supernovae. These stars are very metal poor and very rare. They show large abundance variations, some with detectable amounts of the radioactive element thorium, which can be used to measure the age of the galaxy. In 1998 and 1999, there were two searches for extremely metal-poor stars. Staff Members George Preston, Ian Thompson, and McWilliam conducted the first search toward the galactic bulge; the second was done by McWilliam in metal-poor dwarf spheroidal galaxies (dSph). At present, stars with metal abundances near 10^{-3} those of the Sun are confirmed, and two candidates near abundances of 10^{-4} solar have been identified.

McWilliam and Director Emeritus Leonard Searle have produced a model of stochastic chemical evolution to understand the 300-fold dispersion of strontium abundance in extremely metal-poor stars. The model assumes a distribution of supernovae Sr/Fe ratios from the most metal-poor stars; the ratios are selected randomly from this distribution and then mixed. Figure 7 shows predicted and observed abundances; note the excellent fit. The unusual position of two stars with metal abundances near 10^{-4} solar constrain the model, and suggest that stars composed of material from individual supernovae have metal abundances near $10^{-3.2}$ of the Sun.

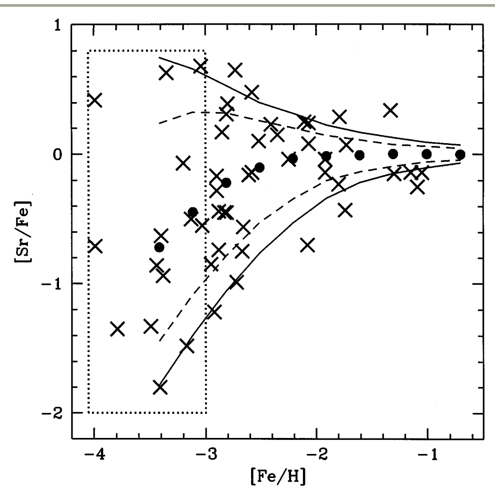


Fig. 7. The figure shows the observed abundances of Sr/Fe (crosses) compared with predictions. The region bounded by the dotted lines indicates the stars used to set the initial distribution in Sr/Fe ratio, while solid lines show the predicted evolution (5, 15, 85 and 95 percentiles) of Sr/Fe. Filled circles indicate the predicted evolution of the median Sr/Fe ratio.

The compositions of other environments permit tests of the chemical evolution paradigm. To this end, McWilliam and Tammy Smecker-Hane of UCI used the Keck telescope to acquire spectra of red giant stars in the Sagittarius dSph. The results show a large spread in metallicity and unusual abundances of O, Mg, Si, Ca, Al, and Na. One explanation for this spread is that the Sagittarius dSph experienced an extended quiescent period of several billion years followed by a burst of star formation, with the composition of the metal-rich population coming from metal-poor (10^{-2} of solar) type Ia supernovae.

McWilliam acquired CTIO spectra of 70 galactic-bulge red giants, and 12 spectra using the Keck I with Mike Rich of UCLA. The scientists found unusual enhancements of O and Eu at solar metallicity. These elements are mostly made by type II SNe (with short progenitor lifetimes), which indicates a rapid formation timescale for the galactic bulge on the order of one billion years. It is remarkable that the bulge reached solar metallicity so quickly.

Eric Persson

Recent rapid improvements in the quality and size of near-infrared imaging array detectors have led to significant advances in several areas of astronomy. Persson is leading a group of Carnegie scientists and engineers in the development of telescope instrumentation that exploits these new devices. They have built one wide-field survey camera for the du Pont 2.5-m telescope, and are currently designing infrared instruments for the two Magellan 6.5-m telescopes at Las Campanas. The group has started a number of projects with the new camera, the most demanding of which concerns the discovery, measurement, and follow-up spectroscopy on distant galaxies—particularly those whose properties and remote distances are such that they can only be studied at near-infrared wavelengths.

Until recently, it has been difficult to find significant numbers of these galaxies. This is solely due to technical reasons: detectors and cameras have not been large enough to cover large areas of sky. For the next several years, the Persson group will survey one square degree of sky to find and accurately measure the brightnesses of thousands of high-redshift galaxies. It will then be possible to estimate their distances and intrinsic luminosities, and study their clustering tendencies in space. Another objective of the survey is to discover large numbers of abnormal galaxies that exist at great distances. Persson and others have serendipitously found distant galaxies that emit virtually all of their energy in the infrared range. While these galaxies are fairly easy to detect in the near-infrared, they can be completely invisible in the deepest optical searches. They are so rare that prohibitively large areas of sky must be surveyed to find new examples. Preliminary spectroscopic evidence on a handful of such galaxies indicates a heterogeneous population: some are likely to be intense star-forming galaxies buried within optically opaque dust clouds, while others appear to be passively evolving objects in which star formation ceased several billion years before. These objects will be prime targets for Magellan instrumentation.

For the past 70 years, astronomers have tried to determine the distance scale of the universe. Persson and Carnegie collaborators hope to advance this field by studying newly found type Ia supernovae. These objects are widely 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, which appear to follow a well-defined development of brightness over time as they rise to a maximum luminosity and then decline. Because the intrinsic luminosities of supernovae at maximum light are essentially the same event-to-event, relative distances to their remote counterparts, observed in host galaxies billions of light years away, can be determined in a fairly straightforward manner. However, it is vital to be certain that the local supernova events are physically the same as their distant counterparts. At near-infrared wavelengths, type Ia supernova light curves appear to be very similar to one another. With the new infrared camera on the 2.5-m telescope, Persson's group will monitor the many new supernovae found each year and create a database that will calibrate distances to the remote objects.

Mark Phillips

Supernovae are among the most violent and energetic phenomena observed in the universe. The high temperatures reached inside a supernova explosion energize a wide range of nuclear reactions, which synthesize new heavy elements. These elements are then dispersed into interstellar space along with the products of the fusion reactions that originally powered the progenitor star.


Mark Phillips

The shock wave produced by a supernova can trigger the collapse of neighboring molecular clouds, leading to the formation of new stars. Some of these new stars will eventually end their lives as supernovae. This alternating cycle of the birth and death of stars has led to the steady heavy-element enrichment of the universe, making possible life as we know it on Earth.

Because of their extreme brightness at maximum, supernovae are potentially powerful "standard candles" for probing the geometry and expansion of the universe. The type Ia supernovae, which are thought to be the complete thermonuclear disruption of a small, very dense stellar remnant called a white dwarf, are especially attractive candidates. They display a high degree of homogeneity and can be observed to very great distances because of their immense luminosities at maximum light (up to 10 billion times that of the Sun).

Since the early 1980s, Mark Phillips has carried out observations of supernovae to understand in more detail the nature of these events and to calibrate their usage as standard candles. Several years ago, Phillips showed that the peak luminosities of the type Ia supernovae were not identical, but that these objects could still be used as standard candles because the luminosity of each event was correlated with the rate of decline from maximum light, which could be measured independently. Calibrating the exact dependence of this correlation has required obtaining precise light curves for a large number of supernovae. In addition, a method had to be devised for deriving the absorption of the light of each supernova due to dust in its "host" galaxy. Phillips and his collaborators developed a technique for measuring this absorption, which then allowed them to correct the observed peak brightness of the supernova for this "missing" light. From this work, Phillips and his collaborators have been able to determine a value of the Hubble constant (a measure of the present rate of expansion of the universe) of approximately 65 km/sec/megaparsec.

Phillips has also been heavily involved in the 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 the future, it should be possible to probe the star-formation history of the universe by carrying out comprehensive searches for such distant supernovae.

Phillips and his collaborators are also using very distant type Ia supernovae to measure the expansion rate of the universe at earlier epochs. These observations have led to a surprising result: we seem to be living in an accelerating universe. Although unexpected, this finding has a certain attraction since it leads to an age of the universe that is consistent with the ages of the oldest stars in our galaxy. Nevertheless, these observations are sensitive to the possibility that the luminosities of the type Ia supernovae have evolved with time. During the next few years, Phillips plans to focus his research on testing the latter prospect through systematic observations of supernovae at a variety of redshifts and environments.

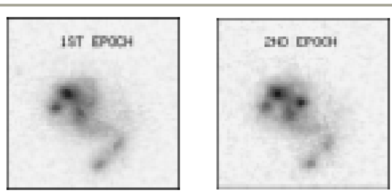


Fig. 8. These are images of the $z = 0.95$ galaxy 3-221.0 in the Hubble Deep Field. The first epoch image was taken in December 1995; the second epoch image was obtained two years later in December 1997. Note the appearance of a supernova in the second epoch image.

George Preston

George Preston, with Carnegie collaborators Andrew McWilliam, Stephen Shectman, and Ian Thompson, is engaged in the astronomical equivalent of looking for radium in pitchblende. He is searching for extremely rare astronomical relics—the earliest generations of stars formed in the Milky Way. The signature of these relics is the virtual absence of elements heavier than helium in their atmospheres. They are identified by wholesale examination of spectra from the myriad of stars that inhabit the dense central bulge of our galaxy.

The very first generation of stars was made of Big Bang material, that is, hydrogen and helium with a trace of lithium. All the heavier elements have been produced by nucleosynthesis in massive stars that explode as supernovae after they exhaust their fuel supplies. Debris from the first supernova explosions polluted the galactic gas. Out of this gas, future generations of stars formed. Continual repetition of this process for the past 15 billion years or so has gradually increased the heavy-element content of the universe to its present level.

The second generation of stars contained no more than one-tenth of a percent of the metal content of the Sun. These stars comprise no more than one-tenth of a percent of the stars formed since the beginning of time. These are the objects sought by the Carnegie team. Because they are made of gas enriched by single, or at most a few, supernova events, their chemical compositions tell what particular combinations of heavy elements are produced in various supernova explosions. What little was learned about the "yields" of supernovae from an earlier Carnegie survey reveals that these explosions are not all alike. Their debris exhibits enormous variety, which means that the accumulation of all the chemical elements to their present levels is a complex process of which we have only a dim comprehension.

The Carnegie team conducted the first phase of their new search for extremely metal-poor stars in

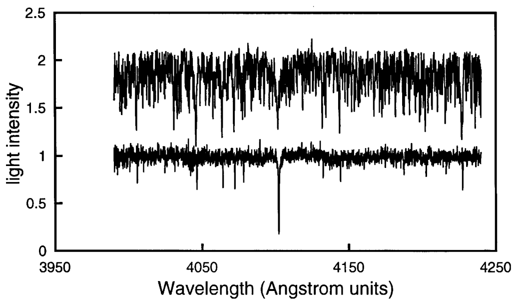


Fig. 9. This image shows spectra (plots of light intensity versus color progressing from blue to red) for two stars. The spectrum of the Sun with present-day levels of heavy elements (above) looks like a picket fence. The spectrum of CD -38:245, a star of similar temperature but with 10,000 times fewer heavy elements (below), looks almost featureless. Such stars are rare but unmistakable.

1997 and 1998 at Las Campanas using the Swope and du Pont telescopes. They performed CCD photometry in 50 star fields in the galactic bulge with a special set of filters that identify metal-poor candidates among the 100,000 red giants present. Unfortunately, the metal-poor signature can be forged by a few other exotic groups of stars—those with very high velocities, powerful chromospheric emission, or large carbon excesses. GRISM[1] spectroscopy of the metal-poor candidates initiated at the du Pont telescope in 1999, however, eliminated the forgers to produce a list of bona fide metal-poor stars. "We don't even know where the carbon in our bones came from," says Preston. He expects that in the next decade spectral analysis of these extremely metal-poor stars at the Magellan telescopes will shed light on this and many other questions about the creation and evolution of the chemical elements in the universe—and in our bones.

Miguel Roth

The interstellar medium contains all of the components from which stars are formed. It changes continuously as stars evolve and return part of the processed material to the medium. There are two particularly interesting phenomena in the processing of the interstellar medium: supernovae explosions and planetary nebulae (PN). Both phenomena, particularly the supernovae explosions, are sources of heavy elements.

Over the past five years, Roth has been involved in the study of "old" PNs. These nebulae arise from stars of intermediate mass that, during their evolution, expel an important fraction of their mass. The material that surrounds the evolved and very hot star at the core of the PN contains several distinctive elements, in particular, hydrogen, nitrogen, and oxygen.

Miguel Roth

PNs display a great variety of shapes; old ones tend to be rather spherical, with the star displaced from the geometrical center. This shape is indicative of the interaction of the PN with the medium that surrounds it. Spectroscopic determinations of the relative abundance of the elements H, N, and O can be correlated with optical and infrared images to understand the mechanisms involved in the origin and evolution of these objects.

A comparable scenario can be pictured when studying the evolution of the much more energetic expansion of material from supernovae explosions. Roth has looked at the interaction of some supernova remnants with the interstellar medium. In these cases, radio techniques were used to study the "clumpy" distribution of molecular species such as CO and H_2. When these data were correlated with tracers of star formation, the possibility of induced star formation became apparent. This may well be one of the mechanisms that trigger the formation of new generations of stars. Our Sun was formed as a consequence of such an explosion.

Sequential star formation is also probably present in areas surrounding what are known as HII regions. In some cases, very massive and short-lived stars ionize their surrounding medium and compress it as the HII region expands. Analysis of infrared images obtained at Las Campanas and

1 A GRISM is a special combination of diffraction Grating and pRISM used to analyze starlight.

images obtained with the Hubble Space Telescope confirmed the existence of a new generation of very young stars in the surroundings of a massive cluster known as R136. This cluster is located in the Tarantula Nebula, in the Large Magellanic Cloud.

Roth is collaborating with Mark Phillips (see above) to study the evolution of light curves of supernovae in infrared light. Using the evolution of the light curve, it is possible to determine accurately the peak luminosity of supernovae (Phillips Law). This information will allow the researchers to determine the distance to the host galaxies of these objects and the rate of expansion of the universe.

Infrared measurements have been mentioned several times in this essay. Accurate determinations of the luminosities of astronomical objects require the use of what are known as standard stars. It was necessary to establish a reliable list of such standards—rather tedious but fundamental work. Astronomers at Las Campanas devoted many nights to the systematic measurement of a body of such new stars, and researchers all over the world now use these standards.

Stephen Shectman

During the past year, Stephen Shectman spent five months in residence at the Las Campanas Observatory working on the control system for the Magellan I telescope. This work was conducted in collaboration with many members of the Magellan Project staff, particularly Joe Asa, Greg Bredthauer, Dave Carr, Emilio Cerda, Charlie Hull, Matt Johns, and Frank Perez.

There are several highlights from the control system work. For instance, the precision optical tape encoders were installed; they provide accurate information about the position of the telescope axes. The servomotor drives and amplifiers were brought into reliable operation, and accurate servo control of the telescope mount was implemented. When the telescope is tracking the position of a star, the telescope's motion is controlled to an accuracy of a few hundredths of an arcsecond. In order to achieve this precision, the positions of the large structural components of the telescope mount must be maintained to within about 1 micron.

An accurate time-base, using signals from the Global Positioning System, was also installed in the system. A small telescope and TV camera were attached to the side of the mount, and a map of pointing corrections was derived by measuring more than 100 star positions around the sky. These corrections were needed for the manufacturing tolerances and mechanical flexure of the telescope structure, which are many times greater than the allowable uncertainties in the telescope's positioning. The computer control system uses the pointing corrections to set the telescope to within a few arcseconds of any position on the sky. The telescope mount and its control system are now reliable enough and safe enough to allow the primary mirror and cell to be installed.

Shectman has also been working with Hubble Fellow Rebecca Bernstein on the construction of MIKE, the high-resolution optical spectrograph for Magellan. This spectrograph features separate optical paths for the red and blue parts of the spectrum. These permit the optical design, dispersing elements, antireflection coatings, and detectors to be optimized separately for the red and the blue. The spectrograph will be able to measure the entire optical spectrum of an object between 3,300 and 10,000 angstroms in a single observation, with a resolution of a few tenths of an angstrom.

During the past year, Shectman and Bernstein finalized the optical design of the spectrograph, ordered and received all of the optical glass, and sent the first components to the optical contractor for polishing. They also worked with consulting engineer Steve Gunnels to define the mechanical structure of the device.

Working with engineers from L&F Industries, Shectman also conducted a design study for a major modification of the 2.5-m du Pont telescope at Las Campanas. This modification would add a Newtonian focus and corrector to the top end of the telescope, where a mosaic CCD camera could be used to image a one-square-degree-area of the sky. This area is more than six times larger than can be observed with a comparable mosaic camera at the present Cassegrain focus. Such a wide-field camera would be particularly interesting for conducting wide-area photometric surveys as well as real-time searches for distant supernovae, gravitational lens events, and variable stars. These examples require massive computational power, which has only recently become available and affordable.

Ian Thompson

The distances and ages of globular clusters—spherical systems consisting of upwards of 100,000 stars in our galaxy—are key stepping-stones on the path to understanding the age and scale of the universe. Globular clusters are among the oldest components of our galaxy. Previous measurements of the distances to them have compared the characteristics of different types of stars found in our solar neighborhood (for which we can estimate distances) with the same types of stars found in the clusters. For various reasons, measurements of the globular cluster distances suffer from systematic errors and remain the limiting factor in determining the ages of these objects.

Ian Thompson

Ian Thompson, with colleagues at the Observatories and the University of Warsaw, has a different approach to this distance problem. Observations of detached eclipsing binary stars allow a geometric measurement of distances. These systems are composed of two separated stars that orbit about each other, with the orbital plane in the line of sight to the stars. As one star passes in front of the other, the total light is modulated. Analysis of the shapes of these eclipses permits a measurement of the relative sizes of the stars and their separation. After additional observations are made of the variations of the radial velocities of the two stars, the absolute dimensions of the system can be derived from a simple application of Kepler's laws of gravity. Once the absolute sizes of the individual stars in the binary are known, the distance to the system can be measured by comparing the apparent brightness of the stars to their surface brightness as estimated from the infrared colors.

Thompson is searching for these exceedingly rare stars using the Swope 1-m telescope to monitor a selection of nearby southern globular clusters. Many nights of continuous monitoring are needed to detect the eclipses and then measure their orbital periods. Detailed measurements of the shape of the light curves are made with the du Pont 2.5-m telescope. When the Magellan telescopes are operational, the radial velocity curves will be measured with the echelle spectrograph. Although only one or two eclipsing binaries are expected to be detected in each cluster, these will be sufficient to overhaul our imperfect knowledge of their distances and ages. This research, and the collaboration with George Preston, Andrew McWilliam, and Steve Shectman in the search for extremely metal-poor stars, will show the new way in which the smaller telescopes at Las Campanas will be used in the upcoming Magellan era. Resources will be devoted to extensive surveys for interesting objects that can be studied in greater detail with the twin telescopes.

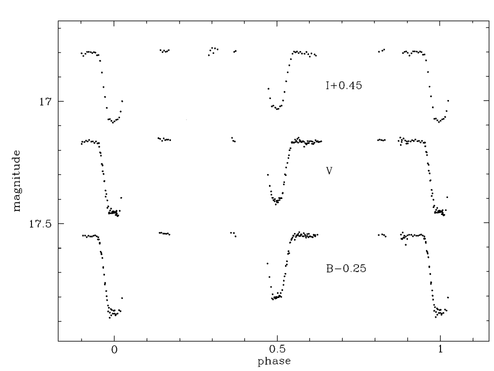
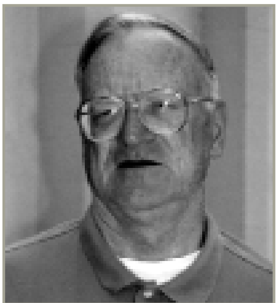


Fig. 10. This image shows light curves of a detached eclipsing binary in the globular cluster Omega Centauri, as measured in the blue, visual, and near-infrared. The eclipses occur at phases 0.0 and 0.5, and the different depths of the eclipses indicate that the two stars in the binary are not equally bright.

Ray Weymann

Much of Ray Weymann's time during the past year was devoted to organizing, convening, and editing the proceedings of a workshop entitled "Photometric Redshifts and High Redshift Galaxies." The event was held in the William T. Golden Auditorium at the Observatories in Pasadena during April 28-30, 1999. Stimulated by research using the Space Telescope NICMOS camera (described below), the workshop was attended by about 65 astronomers from the U.S. and abroad. Photometric redshifts use direct images of galaxies taken in several bandpasses to estimate the redshift, or distance, of galaxies. The virtues of this technique are that it can produce redshifts of huge numbers of galaxies much more efficiently (in terms of telescope time), and it can view the bodies to much fainter brightness levels than can the more accurate method of measuring galaxy spectra with large telescopes. A closely related topic that was addressed involves the search for extremely distant galaxies to trace the history of star and galaxy formation in the very early phase of the expanding universe. The proceedings of the workshop are in volume 191 of the Astronomical Society of the Pacific Conference Series published in late November. Lisa Storrie-Lombardi, formerly of the Observatories and now at Caltech, and Robert Brunner and Marcin Sawicki (also of Caltech) collaborated with Weymann to organize the workshop.



Ray Weymann

The impetus for the workshop came from research using observations with the infrared NICMOS camera on the Hubble Space Telescope. The observations, combined with previous visible light observations in the Hubble Deep Field, provided a set of images ideally suited for both the determination of photometric redshifts and the search for a very high redshift galaxy. This search yielded one galaxy that was confirmed to have a redshift of $z = 5.6$ based on spectroscopic observations made with the Keck telescope. The images that identified this as a likely candidate for a very high redshift galaxy are shown in Fig. 11. The main goal of the current research is to see whether, and how well, astronomers can estimate both the redshift of the galaxies using the photometric redshift technique and simultaneously estimate the internal dust absorption of the ultraviolet light associated with stars being formed in the galaxy or protogalaxy. It has recently become apparent that correction for this absorption is crucial to obtaining a true picture of the rate at which stars have been forming in the history of the universe. This is far more difficult than estimating only the redshift since the colors of a galaxy undergoing a vigorous burst of star formation, coupled with moderately heavy dust absorption, closely mimics the colors of a galaxy with only moderate star-formation rates and little or no dust absorption.

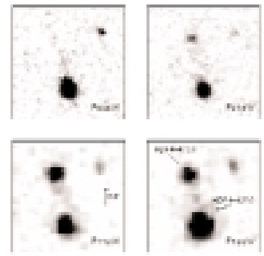


Fig. 11. These are Hubble Space Telescope images of a galaxy at a redshift of 5.6. The images labeled F606W and F814W were taken with a visible light CCD camera, and those labeled F110W and F160W were taken with the infrared NICMOS camera. The galaxy, labeled HDF 4-473.0, is relatively bright in the two infrared images, much fainter in the F814W image, and invisible in the shortest-wavelength image, F606W. The brightness ratio of these images has a distinctive signature indicative of a high-redshift star-forming protogalaxy and illustrates the use of the photometric redshift technique. The redshift of this very distant object was confirmed using the Keck telescope on Mauna Kea after several hours of exposure.

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 the properties of intergalactic hydrogen gas clouds and their association with galaxies with the predictions from computer simulations of the evolving universe. These data are being augmented by spectroscopic redshifts of galaxies close to the quasar (in angle, not distance) observed with the 2.5-m du Pont telescope.

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Ann Zabludoff, *University of California at Santa Cruz*
Dennis Zaritsky, *University of California at Santa Cruz*

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[1]From August 10, 1998
[2]From October 10, 1998
[3]From November 1, 1998
[4]From June 1, 1999
[5]To August 31, 1998
[6]To December 31, 1998
[7]From September 1, 1998
[8]From July 1, 1998
[9]Deceased February 5, 1999
[10]From October 5, 1998
[11]Retired June 30, 1999
[12]From April 1, 1999
[13]To August 31, 1999
[14]From December 1, 1998
[15]From September 28, 1998
[16]To September 10, 1998
[17]To September 30, 1998

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