

## Space Telescope Science Institute

### *Baltimore, Maryland 21218*

This report covers the period October 2001 through September 2002.

#### 1 THE INSTITUTE

The Association of Universities for Research in Astronomy Inc. (AURA) operated the Space Telescope Science Institute for the National Aeronautics and Space Administration (NASA) in cooperation with the European Space Agency (ESA). The Institute conducted the science operations of the Hubble Space Telescope for astronomers around the world. Also, it helped develop—and prepared later to operate—the James Webb Space Telescope (JWST), which NASA intended to launch in 2010, the same year it planned to terminate Hubble operations.

The director of the Institute was Steven Beckwith.

The Institute helped the astronomical community to use Hubble's superb instrumentation to make discoveries and advance scientific understanding. As it improved Hubble's utility, accessibility, and productivity, it planned to do the same for JWST. To meet these challenges, it had a first-rank astronomy research staff, itself involved in forefront research, and it had an expert technical staff to implement its missions. Its dedicated outreach staff engaged the public in discovery and progress on major astronomical issues. Through the Institute's committees, team involvements, and collegial relationships, the community assisted in defining and improving the quality of the Institute's products and services for research and outreach. Through such expert collaborations, and in pursuit of a shared vision—*bringing the cosmos to Earth*—the Institute laid the groundwork to develop JWST with the full involvement of the astronomical community and inheriting lessons learned from Hubble.

This report recounts progress in the Institute offerings and involvements, including upgrades to the Hubble observatory in orbit, innovations in proposing for Hubble observing time as well as archival and theoretical research, new tools and content in the data archive, the ramping up of JWST, Institute academic programs, and its outreach efforts. It also reports the research progress and lists the publications of individual Institute astronomers employed by AURA, ESA, and Computer Sciences Corporation (CSC).

Following launch in 1990, Hubble overcame problems and underwent improvements by means of four amazingly successful servicing missions. The most recent occurred in March 2002, when astronauts replaced the solar arrays, the power control unit, and a reaction wheel assembly and upgraded the scientific instruments. They removed the Faint Object Camera, replacing it with the Advanced Camera for Surveys (ACS) and installed a cryocooler to revive the dormant Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). Operations staff at the Institute and Goddard Space Flight Center (GSFC) reactivated the observatory after deployment, getting the telescope back up and running quickly, and commissioning the new instruments smoothly. The ACS met or exceeded prelaunch expectations and provided large increases in sensitivity and field of view. The NICMOS functioned beautifully and seemed an even better

infrared imaging instrument than it was in 1998, when it became inoperative after Cycle 7. The Space Telescope Imaging Spectrograph (STIS) and the Wide Field Planetary Camera 2 (WFPC2) made it through the servicing mission activities with no change in performance. At the time of this report, as it carried out observations for programs selected in Cycle 11 of peer-reviewed proposals, the Hubble observatory was more powerful than ever before.

The Institute offered a number of important new opportunities in Cycle 11 to enable science with Hubble in different ways. It started the Hubble Treasury Program to promote the creation of important data sets that would be regretted if not obtained by the end of the Hubble mission. Treasury programs planned to address multiple scientific problems through coherent data sets with no proprietary rights. The Institute created the new Archival Research Legacy Program for homogeneous analysis of well-defined data sets in the archive for the purpose of generating higher-order data products, like catalogs and software tools, to enable a variety of new investigations. It also started the Hubble Theory Program, funded as part of the Hubble Archival Research Program.

The Institute received a total of 1078 proposals in Cycle 11, including 859 proposals for about 25,000 orbits of Hubble time, of which about 10,000 were requested for Treasury and Large programs, which ultimately were awarded about 40% of the orbits available. The oversubscription factors were about 8 for prime observations, 6 for parallel SNAP observations, and 3.5 for Archival and Theory proposals. The Cycle 11 peer review involved over 100 community astronomers and lasted 6 full days and evenings.

The Multimission Archive at Space Telescope (MAST) was one of the world's best and most widely used data archives. It offered users convenient search and retrieval utilities accessing data from 16 missions and surveys, including Hubble. The Hubble data archive contained about 10 terabytes of data in about 280,000 science data sets. The archive ingestion rate reached record levels of about 16 gigabytes per day and the retrieval rate was about 42 gigabytes per day. The Institute improved the tools for navigating MAST, including quick target searches, scrapbooks for perusing preview spectra and images, 'pointings' searches by observational parameters, and tailored interfaces for all MAST missions. It provided links between archived data and papers based on those data. It developed special tools to help users prepare proposals. It introduced on-the-fly reprocessing to apply the latest calibrations to data as they were withdrawn from the archive. It worked with other data centers to define the data standards and models for the National Virtual Observatory.

Since 1996, the Institute and GSFC partnered to define the mission of JWST, the 'First Light Machine' to peer back in the infrared to the era when the first stars, galaxies, and massive black holes were formed. The Institute planned to provide the Science and Operations Center for JWST and to manage the science mission. During the development phase, the Institute would be responsible for the science and opera-

tions ground system (software and hardware) and for supporting the NASA JWST Project and the development partners, including ESA and the Canadian Space Agency. In 2002, NASA selected TRW as the prime contractor for the JWST flight segment, formed the JWST Science Working Group (SWG), which includes Institute staff members Peter Stockman and Massimo Stiavelli, and chose members of the instrument teams, including Margaret Meixner and Stefi Baum from the Institute.

The Institute conducted fellowship and visitor programs and organized symposia to provide academic opportunities for staff members and the community to learn from each other and communicate scientific understanding. The Hubble Fellowship Program selected recipients on the basis of their excellence in scientific research and appraised them annually. In the reporting year, the Institute selected 12 new Hubble Fellows and supported 25 Hubble Fellows nationwide. The annual Hubble Fellowship Symposium allowed all Fellows to present their latest scientific results. The Institute Postdoctoral Fellowship Program selected the recipients based on the strength of their proposed research. In addition, the Institute hosted many regular postdoctoral fellows and graduate students, whose research was guided and supported by individual staff members. In 2002, the Institute had 2 Institute Fellows and hosted approximately 29 regular postdoctoral fellows. It also hosted 22 graduate students, about half of whom were enrolled in the Physics and Astronomy Department at The Johns Hopkins University (JHU).

The Institute conducted a variety of programs to host scientific visitors at the Institute. The Collaborative Visitor Program supported collaborators on research projects with Institute staff members for visits of one to four weeks. The Journal Club Visitor Program supported external scientists who came to give one or more seminars during visits of one to two weeks. The Distinguished Visitor Program supported outstanding astronomers to join the Institute for typically one month. In the last year, the Institute hosted 10 Journal Club Visitors and 19 Collaborative Visitors.

Each spring, the Institute organized a symposium on an astronomical topic of major interest and with important new developments. The title of the 2002 symposium was *Astrophysics of Life*. About 150 scientists participated, bringing interests that ranged from geology, biology, and chemistry to physics and astronomy.

The Institute shared Hubble's amazing discoveries and science results with the American public. During 2002, its news team issued 20 press releases and organized 5 NASA Space Science Updates and 2 major press conferences. The press coverage for the ACS and NICMOS early release observations was particularly strong, garnering front-page coverage in *The New York Times*. The 'Viewspace' initiative in informal science education excited much interest in the museum and planetarium community, with over 100 museums nationwide requesting copies.

## 2 SOLAR SYSTEM

I. Griffin was part of a team that used Hubble to determine the orbit and physical properties of the first Kuiper-belt binary, 1998 WW31.

## 3 EXTRASOLAR PLANETS

S. Casertano and R. Brown, together with A. Sozzetti (Pittsburgh/CfA) and others, carried out a program of simulations of observations by next-generation astrometric missions—SIM and GAIA—to characterize their ability to discover and measure the properties of extrasolar planets ranging from Earth to Jupiter mass. They quantified the discovery potential of both missions, especially in the domain of long-period planets, which were more difficult to discover with transits and radial-velocity studies.

S. Lubow continued investigations of gas dynamical effects in accretion disks and the Interstellar Medium (ISM). He studied disks exerting torques on planets, causing them to migrate. By means of simulations, subject to some simplifying assumptions, P. Armitage (Colorado), M. Livio, Lubow, and J. Pringle (Cambridge) determined the frequency of planets around stars and predicted their distribution with radius as a consequence of migration. M. Bate (Exeter), G. Ogilvie (Cambridge), Lubow, and Pringle conducted nonlinear simulations of planet-disk interactions that, for the first time, resolved the vertical structure of the disk. The results showed that nonlinear effects, including shocks, were important in wave dissipation. Ogilvie and Lubow analyzed the saturation of eccentric corotational resonances involving a young planet and its surrounding gaseous disk. They found that these resonances, which damped eccentricity, might weaken as a consequence of accretion. Planetary eccentricities might then grow more easily than previously suggested. Ogilvie and Lubow investigated the origin of the large-scale wave or wake that appeared in simulations of planet-disk interactions. They found that the wake could be understood as a superposition of many resonantly excited waves. Lubow and Ogilvie investigated nodal secular interactions between planets and surrounding disks. They found that these interactions could lead to a change in the inclinations of the planets and could cause warps in the disks.

E. Nelan, M. McGrath, K. Noll, A. Schultz, Lubow, G. Gatewood (Pittsburgh), I. Hanwoo (Korea Astronomy Observatory; Bohyunsan Optical Astronomy Observatory), D. Black, T. Stepinski (Lunar and Planetary Institute), and T. Targett (Cardiff) reported an upper limit to the mass of the radial velocity companion to  $\rho$  Cancri. This refuted the published results based upon Hipparcos data that had indicated the companion to be a low mass M dwarf star rather than a potential planet. This research used the FGS (Fine Guidance Sensor) to make precise astrometric measurements, which were optimized to detect a wobble in the star's position greater than about 0.3 mas over the period of its companion. None was found, placing the upper limit to the mass of the companion of 30 times that of Jupiter. This showed the companion to be substellar, either a brown dwarf or a planet.

I. N. Reid conducted a statistically rigorous comparison of the properties of stars known to have planetary companions against data for local disk dwarfs. It showed a clear increase in planetary frequency with increasing metallicity. Even so, at least 5% of solar-like stars had planetary-mass companions detectable through current observational techniques.

K. Sahu and J. Caldwell continued their efforts monitoring on-going microlensing events through PLANET (Probing

Lensing Anomalies NETWORK) collaboration, where a network of four 1-meter telescopes located at appropriately spaced longitudes was used to achieve 24-hour coverage. PLANET collaboration monitored nearly 100 microlensing events, of which more than 20 had sensitivity to the perturbations that would be caused by a Jovian-mass companion to the primary lens. No clear signature of such a planet was detected. These null results indicated that Jupiter-mass planets with separations of 1.5 to 3 AU occurred in less than 1/3 of systems. A similar limit applied to planets of 3 Jupiter masses for separations of 1 to 4 AU. These were the best limits for extrasolar planets at these separations by any technique.

Sahu and R. Gilliland explored the astrophysical implications of near-field microlensing and its effects on stellar transit observations, with a special emphasis on the Kepler mission. The main goal of Kepler was to detect a large number of extrasolar, Earth-like planets by obtaining near-continuous photometry of 100,000 F, G, and K dwarfs for four years. At the expected photometric precision of Kepler (90 micromag), the effect of microlensing by a transiting companion could be significant. This effect could be used to break the degeneracy between a planetary-mass object, for which the microlensing effect was negligible, and a more massive object of the same size. Kepler would be sensitive to white dwarfs, neutron stars, and black holes in binaries through their microlensing signatures. These observations could be used to derive the frequency of such compact objects in binaries and to determine their masses.

#### 4 STARS

R. Bohlin worked on new UV/VIS/IR absolute flux standards, using STIS observations and models to extend pure-hydrogen WD stars and solar analog stars into the IR. An observing program for a fainter extension (FASTEX) was in progress. Repeat observations of fainter stars in NGC 6681 were completed. The original four FASTEX stars were supplemented in Cycle 11 Hubble observations by two more stars at the faint end to support Galex, the astronomical community in general, and JWST in the longer term. In addition, the primary Sloan standard BD+17D4708 was observed, tying the ground based Sloan Survey directly to the ACS Sloan filters.

Bohlin worked with the SNAP program to develop a set of fundamental standard stellar flux distributions accurate to 1%. This level of precision was required over the 3500 to 17,000 Å wavelength range in order to distinguish among cosmological models.

T. Brown, A. Sweigart (GSFC), T. Lanz (UMd/GSFC), W. Landsman (SSAI/GSFC), and I. Hubeny (NOAO/GSFC) analyzed the STIS UV imaging of NGC 2808 to understand its unusual horizontal branch morphology. They found that the subluminous stars and the hottest gap in the horizontal branch distribution could be explained by a new, theoretical avenue of stellar evolution involving a late helium flash on the white-dwarf cooling curve.

T. Brown, H. Ferguson, R. O’Connell (UVa), and R. Ohl (GSFC) analyzed the FUSE spectra of the giant elliptical galaxy NGC1399. They found that the far-UV emission

could be explained by a population of hot horizontal branch stars with abundance anomalies similar to those seen in hot subdwarfs of the Galactic field. Furthermore, they placed strong upper limits on the O VI emission arising from the Fornax cooling flow—limits that were significantly lower than the expectations arising from simple cooling flow models of the X-ray emission.

A long-standing problem in globular cluster research had been to understand the physical mechanisms responsible for the special mass scale of old globular clusters (i.e., why their mass function was relatively narrow and peaked at  $M \sim 10^5 M_{sun}$ ) and why this depended only weakly if at all on the locations of the clusters (i.e., whether they were in high-mass or low-mass galaxies or the inner or outer parts of galaxies). One possibility was that this special scale was imprinted at the time the clusters formed; the other was that it was a result of the selective disruption of low- and/or high-mass clusters. M. Fall and Q. Zhang developed models that explore the second (disruption) possibility in some detail. They found that the observed peak mass and low-mass shape of the mass function of old globular clusters and its near universality could be explained well by disruption, principally by evaporation of stars by two-body relaxation. The Fall-Zhang models predicted weak variations of the mass function of globular clusters on the mass and location within their host galaxies, which should be observable with Hubble.

O. Gnedin, Fall, M. Livio, and G. Meylan, in collaboration with J. Pringle and H. Zhao (Cambridge), studied the unusual globular cluster  $\omega$  Centauri, which displayed multiple stellar populations. They calculated the escape probability for stellar winds from all Galactic globular clusters. They concluded that  $\omega$  Centauri was not special in its ability to retain winds despite being the most massive cluster and that it must have formed away from its present Galactocentric position and likely within one of the Galaxy’s progenitor halos.

Gnedin, in collaboration with D. Yakovlev, A. Kaminker, and M. Gusakov (Ioffe Institute, St. Petersburg) studied the effects of nucleon superfluidity on the cooling of isolated neutron stars. All theoretical cooling models could be classified into three main types, with faster cooling for more massive stars. For a given equation of state, the masses of slower cooling neutron stars could be determined from the comparison with soft X-ray observations.

P. Goudfrooij, in collaboration with M. Alonso (Obs. Cordoba, Argentina), C. Maraston (MPE, Germany) and D. Minniti (P. Univ. Catolica, Chile) obtained ground-based BVIJHK and WFPC2 BI photometry of globular cluster candidates in the giant, early-type merger remnant NGC 1316 (Fornax A), for which they had previously determined a merger age of 3 Gyr from spectroscopy of its brightest globular cluster candidates. They found that the optical-near-IR colors and luminosities of the brightest clusters in NGC 1316 were consistent with those of a population of 3-Gyr-old clusters of solar metallicity. Also, the luminosity functions (LFs) of the blue and red parts of the cluster color distribution were different. The ‘red’ cluster LF was well represented by a power law (consistent with the LF of globular clusters in young mergers) while the shape of the ‘blue’

cluster LF was consistent with that of ‘normal’ spiral and elliptical galaxies. After the 3-Gyr-old, metal-rich clusters fade to an age of 10 Gyr, they would form a red ‘peak’ in a bimodal cluster color distribution. This ‘red peak’ would have a color consistent with that found in ‘normal, old’ giant ellipticals of the same galaxy luminosity (taking age dimming into account). The surface-density profile of clusters in the innermost regions was lower than that of the integrated light of the galaxy, presumably due to the collective effect of extended star formation in the inner regions of NGC 1316 and tidal shocking of the inner clusters. Outside the core, the surface density profile of clusters was consistent with that of the underlying starlight, suggesting that the cluster system originally experienced the same violent relaxation as did the main body of the merger remnant. These features of the star cluster system of NGC 1316 were fully consistent with scenarios for forming ‘normal’ giant elliptical galaxies through gas-rich mergers at look-back times  $> \sim 10$  Gyr.

C. Keyes, in collaboration with J. Sokoloski and S. Kenyon (CfA), B. Espey (Trinity College Dublin), S. McCandliss (JHU), and P. Charles (Southampton), led the FUSE component of a combined X-ray, FUV, optical, and radio investigation of the cause and nature of symbiotic star outbursts. Observations of class prototype Z And throughout its recent major outburst led the group to propose a new disk-trigger model for the outburst mechanism in classical symbiotic systems.

Keyes, Kenyon, and D. Proga (GSFC) analyzed very high quality Faint Object Spectrograph spectra of AG Pegasi from four separate epochs to evaluate nebular diagnostics, physical conditions in the red giant wind, and system mass-loss mechanisms for this symbiotic nova. Simple illumination models generally accounted for the magnitude of the optical and ultraviolet emission line fluxes, where high-energy photons from the hot component ionized the outer atmosphere of the red giant. Other high ionization emission lines, such as [Ne V], [Mg V], and [Fe VII], suggested mechanical heating in the outer portions of the red giant wind. This material originated in a region where the weak wind from the hot component interacted with material lost by the red giant.

Keyes, Kenyon, Proga, R. Downes, and W. Hack continued analysis of their STIS ultraviolet survey spectra of sixteen symbiotic stars, 11 of which had never before been observed in the ultraviolet. This program facilitated a 50% increase in the number of symbiotics for which quantitative physical parameters were known.

Livio and N. Soker (Haifa) studied the effects of planets and brown dwarfs on their parent stars when the latter engulf the planetary or brown dwarf companions. They examined in particular the effects on the rotation rate and on mass loss.

Livio, in collaboration with R. Corradi (La Palma), U. Munari (Padova), A. Manipaso (Tenerife), D. Conclaves (Tenerife), and H. Schwarz (CTIO), observed the large-scale outflow from the symbiotic system CH Cygni, and determined its ionization properties.

Livio, in collaboration with R. Sahai (JPL), R. Brillant (ESO), E. Grebel (Heidelberg), W. Brander (ESO), S. Tingay (Paul Wild Observatory), and L. Nyman (ESO), measured

the jet speed in the bipolar source Hen 2-90 to be 150 to 360  $\text{km s}^{-1}$ .

K. Long pursued research topics associated with obtaining a physical understanding of cataclysmic variables, supernova remnants, and X-ray sources in nearby galaxies.

Long and C. Knigge (Southampton) developed a Monte Carlo radiative transfer code that was capable of calculating both the ionization structure of an azimuthally-symmetric wind of a cataclysmic variable and radiative transfer through this wind. Nearly all prior attempts to model the spectra of wind-dominated cataclysmic variables were limited to a single line—CIV. The new code was used to create model spectra covering a broad UV wavelength range at arbitrary wavelength resolution. The model spectra were compared to UV spectra to constrain the wind geometries and mass-loss rates of disk-dominated CVs.

Long, C. Froning (Colorado), J. Drew (Imperial College), L. Hartley, C. Knigge (Southampton), and R. Prinja (UCL) analyzed UV spectra obtained with STIS and FUSE of a variety of disk-dominated cataclysmic variables, including U Gem, UX UMa, IX Vel, V3885 Sgr, QU Car and SW Sex, in an attempt to better understand the winds and disks in these systems. Their analysis of UV and optical spectra of QU Car suggested it was extremely luminous for a cataclysmic variable, with a luminosity approaching that of a supersoft source, and that the mass-donor in the system was a C star. In the case of SW Sex, they found that lines usually attributed to the wind had shapes that change dramatically with orbital phase, which indicated that the wind from this system was not azimuthally symmetric with respect to the disk.

Long, P. Winkler (Middlebury), S. Reynolds (NCSU) and J. Raymond (SAO) continued their X-ray and optical studies of the remnant of the type Ia SN 1006. This was the supernova remnant (SNR) for which the observation of GeV gamma rays had made it the touchstone for cosmic ray acceleration models of synchrotron emission. With P. Ghavamian (Rutgers), they obtained an accurate measurement of the shock speed ( $2890 \pm 100 \text{ km s}^{-1}$ ) from Balmer-dominated filaments at the primary shock front on the NW rim and confirmed that the electron temperature was much less than ( $< 0.07$ ) of the proton temperature immediately behind the shock. With their improved measurement of the proper motion, they obtained an accurate measurement of the distance— $2.17 \pm 0.08 \text{ kpc}$ —and physical radius— $9.5 \text{ pc}$ —for the SNR. Analyzing Chandra ACIS imagery of the NE and NW limb of the SNR, they set stringent limits on the surface brightness of the X-ray halo expected around the SNR, assuming the conventional Fermi theory of cosmic ray acceleration, and showed that ejecta-dominated material extended to the edge of the SNR.

Long, P. Charles (Southampton), and G. Dubus (Caltech) attempted to understand the nature of the brightest X-ray source in the local group, a source located in the nucleus of M33. They obtained and analyzed UV-visible STIS spectra of the nucleus of M33 in the context of models of instantaneous and continuous star formation. There was no obvious signature of the X-ray source. The spectra could be modeled in terms of a small starburst of age 40–60 Myrs superimposed on an older 1 Gyr population. All of the X-ray and

optical data were consistent with a binary system consisting of a 10-solar-mass black hole and a massive companion, with similarities to Cyg X-1 and some microquasars.

J. Maíz-Apellániz studied various aspects of massive stars and their interaction with their environment, ranging from the nearest ones to those located several Mpc away. He proposed a new theory for the origin of the Local Bubble and elaborated on its possible consequences on Earth. He also analyzed in detail the interactions with their environments of two dwarf starbursts, 30 Doradus and NGC 4214, and provided the first reliable distance to the latter. He analyzed the structural properties of the nearest massive young clusters, provided a new classification scheme for them, and obtained new evidence for their role as progenitors of globular clusters.

R. Makidon, in collaboration with L. Rebull (SIRTF Science Center), S. Strom (NOAO), and L. Hillenbrand (Caltech), continued his analysis of the relationship between angular momentum evolution and circumstellar accretion disks for PMS stars in the NGC 2264 OB association. With S. Wolff (NOAO), Rebull, and Strom, he extended this analysis to other nearby star-forming regions and found evidence for a regulation mechanism early in the angular momentum history of low-mass stars.

B. Margon continued his work with a collaboration led by D. Pooley (MIT), which obtained deep Chandra X-ray images of globular clusters. Results were published on NGC 6752 and NGC 6440. In both cases large numbers of faint sources were detected, many of which were probably cataclysmic variable stars. The elusive population of close binaries in globular clusters, previously inferred theoretically to stabilize clusters against collapse, was finally being observed directly.

Margon and R. Downes, together with L. Homer, S. Anderson, and E. Deutsch (Washington), used Chandra and Hubble data to confirm the optical identification of the X-ray burster X1746-370 located in the globular cluster NGC 6441. X1746-370 was the longest period confirmed burster in a globular cluster and the only one with a period typical of the galactic population as a whole.

Margon, in collaboration with P. Callanan (University College Cork) and others, confirmed the optical identification of the intense galactic X-ray source GX17+2, probably the brightest source on the sky previously lacking an optical counterpart, despite 30 years of observation. The object, visible only in the near-IR due to high extinction, was often seen at  $K = 15$  but varied dramatically in an as yet undetermined pattern, fading by at least 3 magnitudes. They proposed that large radio outbursts observed in the source also gave rise to synchrotron flares in the IR.

Margon, in collaboration with Homer, Anderson, and S. Wachter (Washington), presented Hubble UV spectra of the X-ray pulsar 4U 1626-67 (= KZ TrA). This object was unusual even among X-ray pulsars due to its ultra-short binary period (41 min) and remarkably low mass-function ( $< 1.3 \times 10^{-6} M_{sun}$ ). In emission, the usually prominent lines of N V and He II were absent, while both O IV and O V were relatively strong. The spectra therefore provided independent support for the suggestion that the mass donor was the

chemically fractionated core of either a C-O-Ne or O-Ne-Mg white dwarf, an explanation put forward to explain the results of Chandra high-resolution X-ray spectroscopy.

E. Nelan, along with collaborators from Texas, Virginia, Yale, New Mexico, and Lowell Observatory, reported the trigonometric parallax of delta Cephei obtained with FGS. This was the most accurate direct measurement of the distance to this fundamental distance calibrator ( $\pi = 3.66 \pm 0.15$  mas). This yielded a V- band distance modulus for the Large Magellanic Cloud (LMC) of  $m-M = 18.50 \pm 0.13$ . They also reported the trigonometric parallax of the fundamental distance calibrator RR Lyrae,  $\pi = 3.82 \pm 0.2$  mas, the most accurate measurement to date.

Nelan, Makidon, and R. Saffer (Villanova) obtained high angular resolution observations of cool white dwarf stars with FGS. The object of this search was to discover binary white dwarf systems and to identify suitable candidates for follow-up studies to derive the orbital elements and ultimately to determine the mass of the individual white dwarf stars dynamically. Of 57 objects observed, 5 double degenerate systems were discovered. The occurrence rate of 10% was about what was anticipated. However, a surprising outcome of this study was the discovery of systems with angular separations that imply physical separations significantly less than 1 AU, in contrast with the expected outcome of common-envelope evolution.

Panagia, in collaboration with M. Romaniello (ESO), S. Scuderi (Osservatorio Astrofisico di Catania), and R. Kirshner, developed a new technique based on multiband near-ultraviolet and optical photometry to measure both the stellar intrinsic properties (i.e., luminosity and effective temperature) and the interstellar dust extinction along the line of sight to hundreds of stars per square arcminute. As a test case, this technique was applied with success to the study of stellar populations in the region around SN 1987A in the LMC, as imaged with the WFPC2 on board the Hubble Space Telescope by the SINS project.

C. Proffitt, in collaboration with S. Adelman (The Citadel), G. Peters (USC), and G. Wahlgren (Lund), continued to study very heavy elements in both normal and chemically peculiar B stars using coadded IUE spectra. He improved coaddition techniques and procedures for generating detailed spectral atlases of the best-observed narrow-lined stars.

In a project led by Livio, Proffitt analyzed deep STIS CCD images that targeted the brightest clump in the sub-mm disk around the nearby star epsilon Eridani to set constraints on the dust properties and catalog objects visible in the field.

In collaboration with T. Brage (Lund) and P. Judge (HAO-NCAR), Proffitt contributed to a STIS study of the 1487.9 Å N IV hyperfine line in the planetary nebulae NGC 3918. This study yielded the first measurement of a transition probability for this class of hyperfine transitions, confirming previous theoretical calculations and providing a powerful new diagnostic for very low-density plasmas.

Proffitt, in collaboration with Brage, F. Rogers, and C. Iglesias (LLNL), continued theoretical work on the radiative acceleration of heavy elements in stellar envelopes and atmospheres. He improved calculation techniques and implemented large-scale model atoms of gallium and other very

heavy elements for use in non-LTE calculations.

I. N. Reid continued work with K. Cruz (Pennsylvania), J. Liebert (UA), J. Kirkpatrick (IPAC), and J. Gizis (Delaware), on an NStars survey for previously unrecognized low-mass stars and brown dwarfs within 20 parsecs of the Sun. Analyzing 2 Micron All Sky Survey (2MASS) data, both directly and in combination with proper motion catalogues, this project identified over 250 new solar neighbors, including 80 ultracool M dwarfs (M8, M9) and 100 L dwarfs. These included an M8.5 dwarf at only 5.7 parsecs. Hubble imaging of a subset of these low-mass dwarfs indicated an apparent binary fraction of 20%, significantly lower than in higher-mass stars, with no companions at separations exceeding 15 AU.

Working with Gizis and S. Hawley (Washington), Reid completed a comprehensive re-analysis of the stellar luminosity and mass functions, combining a Hipparcos 25-parsec data set with M dwarfs from the PMSU survey. The initial mass function was best fit by two power-laws, broken at  $\sim 1$  solar mass, with an index of 1 at low masses and 2.4 (near Salpeter) at high masses. They also found that the distribution of chromospheric activity in disk M dwarfs was consistent with a constant star formation rate.

M. Robberto, S. Beckwith, and N. Panagia completed their theoretical study of the infrared emission of circumstellar disks in H II regions. Their model applied to the photoevaporated disks (proplyds) in the Orion Nebula, most of them illuminated by the O6.5 star theta1 Ori-C. Taking into account the different types of nebular radiation, they estimated the Spectral Energy Distribution (SED) of three types of sources: dusty spherical envelopes photoevaporated by the UV radiation, passive flaring disks, and photoevaporated disks. They found that in the presence of an external radiation field, relatively evolved star/disk systems displayed a variety of SED depending on a number of physical and geometrical parameters. A common feature was a peak at mid-IR and far-IR wavelengths, which accounted for the strong mid-IR excess that Robberto and co-workers detected at 10 microns from proplyd sources in the Orion Nebula.

Robberto and collaborators completed the reduction of deep 10- and 20-micron mosaics of the Orion Nebula using a data processing algorithm developed for this project. These spectacular images showed for the first time the detailed structure of the Orion Nebula in the mid-IR. Together with the classical BN/KL object and Ney-Allen nebula, a variety of filamentary structures, arcs, bright clumps, and  $\sim 150$  point sources were visible.

Robberto, in collaboration with Beckwith, Panagia, Maki-don, and J. Song (Minnesota), obtained WFPC2 photometry of point sources in Orion Nebula in bands corresponding to the Stromgren u and Johnson B. In order to obtain the mass accretion rates from the UV excess, accurate estimates of the extinction were needed. Orion, however, was known to possess anomalous extinction ( $R \sim 5$ ). Using previously published photometry and data from the Hubble archive, they were developing a new estimate of the extinction for individual stars.

K. Sahu continued his investigations to find the locations of the lenses for the observed microlensing events towards

the Magellanic Clouds. Through caustic-crossing time scales of binary events, spectroscopy of microlensed sources, and statistics of binary events, he argued the stars within the Magellanic Clouds played a dominant role as gravitational lenses. This implied that the contribution of MACHOs to the dark matter was less than 5%.

Sahu, Reid, and Hawley presented an alternative interpretation of the extremely cool, high-velocity white dwarfs found by Oppenheimer et al. in a high-latitude astrometric survey, which were claimed to be part of the dark matter halo. They argued that the velocity distribution of the majority of the sample was more consistent with the high-velocity tail of a rotating population, probably the thick disk, rather than a pressure-supported halo.

Sahu and S. Kane (St. Andrews) continued a spectroscopic study of microlensed sources towards the Galactic bulge. Through spectroscopy of 17 sources, they showed that there was an extinction shift between the microlensed population and the non-microlensed population. This implied that 65% of the microlensing events were caused by self-lensing within the bulge. The sample needed to be increased to about 100 sources to get a clear picture of the kinematics of the bulge.

Sahu, in collaboration with G. Bakos (CfA) and P. Nemetz (JATE), updated the Luyten half-second catalog with more accurate coordinates and proper motions using DSS-I and DSS-II images.

Sahu, with collaborators A. Tej (Strasbourg), T. Chandrasekhar, and N. Ashok (Physical Research Lab, India), developed a statistical method to derive the mass functions of open clusters using sky survey data such as 2MASS and the Guide Star Catalogue (GSC). They used this method to derive the mass functions in the stellar/substellar regime of three young, nearby open clusters, namely IC 348,  $\sigma$  Orionis, and the Pleiades. The mass function in the low mass range ( $M < 0.50 M_{sun}$ ) was appreciably flatter than the stellar Salpeter function for all three open clusters. The contribution of objects below  $0.5 M_{sun}$  to the total mass of the cluster was  $\sim 40\%$  and the contribution of objects below  $0.08 M_{sun}$  to the total was  $\sim 4\%$ .

Through the PLANET collaboration, Sahu carried out spectroscopic and photometric monitoring of the binary lens event EROS BLG-2000-5 during the caustic crossing. This was a unique binary lens event, wherein the source star directly passed behind the cusp—the region where the caustics meet—thereby highly magnifying the portion of source star lying directly behind the cusp. This allowed a rare opportunity to study the structure of the stellar surface in detail, measure the limb darkening parameters, and determine the mass of the lens (An et al. 2002). The limb-darkening parameters measured here were among the first for normal giants by any technique and for stars as distant as the Galactic bulge.

M. Siegel and H. Bond continued an investigation into the suitability of post-asymptotic giant branch (PAGB) stars as standard candles. Theoretical models showed that the luminosity function of PAGB stars should be sharply peaked, and the small number of PAGB stars known in globular clusters suggested that the peak lies at around  $M_V = -3.4$ . The obser-

vational effort to confirm this hypothesis included (1) establishment of a standard star system in the Gunn *u* band plus Johnson-Kron-Cousins BVI, (2) identification of field, globular cluster, and Local Group PAGB stars through multi-color observations, and (3) identification of PAGB stars in Hubble archival images of more distant galaxies.

D. Soderblom continued a program with J. King (UNLV) to measure chromospheric activity among all the G dwarfs within 50 pc, working with a Hipparcos-defined sample. They completed data acquisition, mostly at the KPNO Coudé Feed Telescope, and reduced the data. They began preparing a database of results, together with ancillary information on the targets. These observations were being used to assist with a SIRTf Legacy program led by M. Meyer (Arizona). Soderblom also continued work with B. Jones (Lick Observatory) to study solar-type stars in nearby open clusters for the variations with age of such properties as activity, rotation, and lithium abundances.

L. Stanghellini and collaborators R. Shaw (NOAO), C. Blades, B. Balick (Washington), M. Mutchler, and E. Villaver made progress in their Magellanic Cloud Planetary Nebulae (PNs) study, with the aim of understanding PN evolution in different environments. They observed about 70 LMC and 30 SMC PNe with imaging and slitless STIS spectroscopy, revealing stellar and nebular characteristics at once. They found that the LMC and SMC PN morphological types were similar to those of Galactic PNs. The ratio of symmetric-to-asymmetric PNe was higher in the SMC than in the LMC. Future completion of the samples would confirm whether morphology was related to the metallicity of the progenitor's population. They also found that the surface brightness of LMC and SMC PNe declined with physical photometric radii, as predicted by hydrodynamic models, and that the asymmetric PNe were typically low surface brightness objects. They could infer that the dynamic evolution also depended on morphological type.

Stanghellini and collaborators built a public web page to collect all their results: <http://archive.stsci.edu/hst/mcpn/>.

Stanghellini, the above collaborators, and D. Karakla worked on the STIS program of observing UV slitless spectra of LMC PNs. The monochromatic images showed good signatures of the carbon and neon lines, strongest in the UV and essential for abundance analysis. Modeling of the central stars' UV emission began.

Stanghellini, with A. Machado (Inst. de Astrofísica Canarias), Villaver, and M. Guerrero (Illinois), used the IAC sample of Northern Galactic PNs—the only complete and homogeneous PN morphological survey—to determine whether the correlations between the PN morphology and the stellar and nebular physical parameters were due to selection effects, distance determination, dust absorption, or other systematic biases—or whether they were signatures of actual links between morphology and evolution. They found that 60% of the Galactic PNe were elliptical, 26% were round, and 14% were bipolar or quadrupolar. They found that the spatial distribution of PNe varied depending on the morphological types: bipolar PNe were found closer to the Galactic Plane than either elliptical or round PNe. They also con-

cluded that the PN sample was complete up to about 7 kpc. They analyzed the distribution of PN nuclei on the logL-logT plane and found that nuclei of bipolar PNe were, on average, more massive than nuclei of elliptical and round PNe. Statistically, bipolar PNs were richer in nitrogen than round or elliptical PNs, in agreement with the hypothesis that asymmetric PNs originated from the evolution of massive progenitors ( $M > 2.5 M_{sun}$ ).

A. Suchkov and R. Griffin (Cambridge) continued the study of overluminous F stars observed with the almost three-year (2000 to 2002) Cambridge CORAVEL radial-velocity survey. Of the total 111 stars that they could adjudicate, 58% proved to be binary systems—twice the 29% found in a sample of randomly selected stars in 1997 by Nordstrom et al. This result quantified the earlier inference by Suchkov and McMaster (1999) that overluminous F stars should be mostly binaries. The rest of the program stars were found to be consistent with being either extremely old single stars, whose surface gravity was too high for their luminosities, or extremely young, possibly PMS stars, also with surface gravity anomalies.

Suchkov continued the study of candidate young and PMS F stars using the combined data from uvby and 2MASS photometry and the Hipparcos data. Many of the metal-rich F stars earlier than F5 were found to show signatures expected for PMS stars, including anomalous surface gravity, reddening, near-infrared excess, and UV excess. Stars possibly harboring hot dust disks were isolated on the basis of their intrinsic near-infrared excess. Similarly, accretion disk candidates were identified, using UV excess in combination with reddening and infrared excess as a signature. Attention was drawn to an unusual star HD 81270, which was extremely underluminous and metal rich. It had a large intrinsic infrared excess and was speeding away from the Galactic disk at  $70 \text{ km s}^{-1}$ .

Villaver, Machado, and G. Garcia-Segura (IA-UNAM) published two papers on the evolution of the circumstellar gas around low- and intermediate-mass stars. They performed numerical simulations of the gas evolution for the range of progenitor masses of PNs studying the AGB and the PN formation. Among other findings, they predicted the existence of large regions (up to 2.5 pc) of neutral gas surrounding the molecular envelopes of AGB stars as a consequence of the mass-loss experienced by the star during the AGB evolution.

N. Walborn and collaborators completed several major investigations. A comprehensive examination of the optical spectra of the earliest O-type stars led to the introduction of new types O2 and O3.5 to describe the range of the criteria. An extensive atlas of the complex, high-velocity interstellar-line profiles observed with STIS toward four stars in the Carina Nebula was published; many new velocity components were resolved. An investigation of discrepancies in the absolute magnitudes of O stars in several northern associations revealed that the B stars from which the distance moduli had been derived were not colocated. An atlas of OB stars in the Magellanic Clouds observed with the FUSE was published, showing the systematic trends with spectral type in the numerous stellar-wind features in that spectral range.

Further structural details of the 30 Doradus Nebula, including the complete interface between the central cavity and surrounding molecular clouds, were presented based upon observations with several Hubble instruments.

R. Williams continued his work on the detection and identification of faint emission lines and their uses for nebular diagnostics. He collaborated with J. Baldwin and B. Sharpee (MSU) and P. van Hoof (Queens University Belfast) on a program to obtain high signal-to-noise ratio spectra of planetary nebulae, for which they developed logic and software to make automatic line identifications via interrogation of spectroscopic databases. This procedure, named EMILI, was publicly available on the web: (<http://www.pa.msu.edu/people/sharpee/emili.html>).

Together with Baldwin, Sharpee, and E. Jenkins (Princeton), Williams developed a technique to combine both absorption and emission line analyses of nebulae to determine ion abundances, demonstrating the importance of using both types of lines when obtaining abundances.

Williams continued his work on the deconvolution of line profiles by Principal Component Analysis as a means of obtaining line intensity ratios for objects for which there was no detailed spatial or kinematical information.

With M. Della Valle (Arcetri), Williams obtained a series of spectra of the nova V382 Vel/99, for which they interpreted the spectral evolution in the context of outburst models.

In a paper on non-emitting gas in nebulae with L. Rodriguez (UNAM) and M. Goss (NRAO), Williams studied the H I gas in the Helix PN (NGC 7293) from its 21 cm radiation, discussing its relation to the CO component of the nebula.

## 5 ISM & IGM

G. Kriss, R. Telfer (Orbital Sciences), and W. Zheng (JHU) used archival FOS spectra of quasars to study the ionization and composition of the intergalactic medium. The distribution of individual quasar spectral indices showed a broad shape that matched the distribution inferred from FUSE and Keck observations of He II to H I column density ratios (Telfer et al. 2002). This confirmed that quasars were the likely sources for most of the ionizing radiation at redshifts of 2 to 3.

S. Lubow, J. Pringle (Cambridge), and R. Allen proposed a model for giant molecular clouds. The model suggested that the clouds were not in virial equilibrium. Instead, they resulted from the temporary concentration of molecular gas that was otherwise present in a distributed form.

S. Malhotra continued her research characterizing the ISM of normal galaxies using observations with the Long Wavelength Spectrograph on ISO. She led a paper that characterized the star-forming ISM of 60 normal galaxies using fine structure lines in the IR, prominent among them [C II] at 158 microns and [O I] at 63 microns. These lines were the prime coolants of the cold neutral medium and showed interesting correlations with each other and with the dust temperatures derived from the IRAS 60/100 micron continuum ratios. These lines were also used to derive the mean tem-

peratures, pressures, gas densities, and far-UV fluxes in these galaxies.

In a paper led by A. Contursi (IPAC), Malhotra carried out detailed studies of two nearby galaxies NGC 1313 and NGC 6946. They used mid-infrared spectroscopy on ISO to characterize the emission from warm dust and from poly-aromatic hydrocarbons, an important component of the ISM in galaxies.

Panagia, in collaboration with K. Weiler and M. Montes (NRL), analyzed the extensive radio emission data available for the unusual supernova SN 1998bw, which was possibly related to the gamma-ray burster GRB 980425 and represented a possible link between these two classes of objects. The radio emission could be best explained as the interaction of a mildly relativistic ( $\Gamma \sim 1.6$ ) shock with a dense, pre-explosion, stellar-wind-established circumstellar medium (mass-loss rate of  $2.6 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ ) that was highly structured both azimuthally, in clumps or filaments, and radially, with two 40% density enhancements separated by  $\sim 3 \times 10^{17}$  cm.

Panagia, in collaboration with J. Sollerman, B. Leibundgut, and F. Patat (ESO), C. Fransson, C. Kozma, and P. Lundqvist (Stockholm Obs.), S. Holland and P. Garnavich (Notre Dame), C. Challis and R. Kirshner (CfA), A. Filippenko (UCB), and C. Wheeler (Texas), studied the late-time BVRI light curves of the supernova SN 1998bw, based on template images taken at the VLT, and extended to the very last observable phases using STIS imaging observations. The supernova was found to be in a rapid decline up to more than 500 days after explosion, with no sign of complete positron trapping from the  $^{56}\text{Co}$  decay. Thereafter, the light curve was found to flatten out significantly. A possible explanation was powering by more long-lived radioactive isotopes, if they were abundantly formed in this energetic supernova.

Panagia, in collaboration with many members of the SINS project (PI: Kirshner), analyzed STIS long-slit observations of the optical and ultraviolet (1150 to 10,270 Å) emission line spectra of the rapidly brightening spot 1 on the equatorial ring of SN 1987A between 1997 September and 1999 October (days 3869 to 4606 after outburst). The observed flux ratios of optical to highly ionized UV lines were found to be greater by a factor of  $\sim 2$  to 3 than predictions from the radiative shock models. Model calculations for the observed H $\alpha$  line widths and profiles suggested that a chaotic flow existed in the photoionized regions of these shocks.

K. Sembach focused on understanding the properties of the intergalactic gas in the low-redshift universe and the interstellar media of galaxies. Highlights of this research included an extensive survey of highly ionized, high-velocity gas traced through O VI absorption with the FUSE Observatory and several studies aimed at estimating the baryonic content and physical properties of the warm-hot intergalactic medium.

## 6 GALAXIES

In a collaboration led by A. Petrosian (Byurakan Obs. and Isaac Newton Inst. of Chile), R. Allen, C. Leitherer, J. MacKenty, B. McLean, and N. Panagia, a systematic study

of the morphological characteristics of several samples of galaxies drawn from the 1401 objects that comprised the Second Byurakan Survey (SBS) was started. As a first step, they selected suitable samples that could provide information for studies of the relation between galaxy interactions and galaxy star formation activity.

H. Bushouse, K. Borne (Raytheon STX), L. Colina (Instituto de Estructura de la Materia), and R. Lucas analyzed the results of two Hubble snapshot programs in order to better understand the origin and nature of Ultraluminous Infrared Galaxies (ULIRGs). WFPC2 and NICMOS images of a large sample of ULIRGs showed that nearly all were systems of interacting galaxies, many with indications of Active Galactic Nuclei (AGN). A significant fraction of the systems appeared to be the result of the interaction and merging of several progenitor galaxies. As a class, however, the ULIRGs did not appear to represent a simple transition stage between galaxy mergers and QSOs, as had been suggested in the past.

J. Caldwell reduced data obtained as part of the WILS (Widefield Imager Lensed-Quasar Search) collaboration. The data consisted of 962 square degrees of matched UBR CCD images obtained in four observing runs. He planned to use approximately 20 million photometric measurements to a limiting magnitude of  $B \sim 21$  to select lensed-quasar candidates based on color and structure information.

S. Beckwith and Caldwell participated in the GEMS (Galaxy Evolution Morphology and SEDs) collaboration project. They began data analysis for the earliest of the 125 scheduled orbits of ACS WFC data, wherein F606W and F850LP imaging was used in conjunction with 17-color ground-based imaging to constrain the evolution of galaxy structure from  $z \sim 1.2$ .

R. de Jong, in collaboration with L. Simard (HIA), R. Davies (Oxford), and the rest of the EFAR team, performed 2D bulge/disk decompositions of a set of 800 early-type galaxies from the EFAR sample, investigating whether the classical  $R^{1/4}$  de Vaucouleurs bulge profile shape was indeed the norm or whether other 'n' values of the Sersic  $R^{1/n}$  profile shape were more prevalent. They found that most of the bright elliptical galaxies in their sample indeed had 'n' values close to 4, but that the trends toward fainter galaxies suggested a continued decrease in 'n' toward later type galaxies, strongly correlated with bulge-to-disk luminosity and scale size ratio. Furthermore, they found that the distribution of galaxies in the luminosity-radius plane was consistent with large elliptical galaxies having formed from spiral galaxy mergers, but that the low luminosity ellipticals were too small to be formed that way unless much of angular momentum was lost during merging.

de Jong, with R. Windhorst (ASU) and the Hubble Mid-UV Morphology team, performed an imaging survey of 37 nearby galaxies observed with WFPC2 in the F300W and F814W filter and 11 galaxies in F255W. They also obtained ground-based UBVRJHK imaging for most of this galaxy sample. The main goal of their survey was to quantify morphological change with wavelength, as a basis for morphological K-corrections for high-redshift work. In their first paper on this data set, they presented a preliminary analysis predominantly based on an eyeball comparison of galaxy

morphologies from the UV to the near-IR. Their first qualitative results were: (1) Most early-type galaxies showed a decrease in surface brightness going from the red to the mid-UV but little morphological change. (2) Half of the mid-type spiral and star-forming galaxies appeared as a later morphological type in the mid-UV. (3) Most of the heterogeneous subset of late-type, irregular, and merging galaxies displayed F300W morphologies that were similar to those seen in F814W but with differences due to recognizable dust features absorbing the bluer light and to UV-bright hot stars, star-clusters, and star-forming ridges.

de Jong, in collaboration with a team led by P. James (Liverpool), obtained narrow-band  $H\alpha$  imaging of 334 nearby galaxies to determine local universe star formation rates for all Hubble types and to investigate the distribution of star formation within galaxies. In their first analysis, they showed that star formation rate was correlated with Hubble type, with galaxies Sb-Sc having the highest star formation rates, but that late-type irregular galaxies had the highest  $H\alpha$  equivalent width (new-to-old stars ratio). Surprisingly, they found no correlation between  $H\alpha$  equivalent widths and the total luminosities of the galaxies.

In collaboration with M. Neeser (Observatory of Munich), P. Sackett (Mt. Stromlo Observatory), and F. Paresce (ESO), G. De Marchi used ultra-deep VLT images in the V and R bands to study the low surface brightness (LSB), late-type spiral ESO 342-G017. Surface brightness photometry, reliable for the detection of faint extended structures to a level of  $V = 27.5$  and  $R = 28.5$  mag arcsec<sup>-2</sup>, revealed a thick exponential disk with an intrinsic scale height about 2.5 times that of the thin disk and a comparable scale length, contributing 20 to 40% of the total (old) stellar disc luminosity. This was the first detection of a thick disc in LSB galaxies, generally thought to be unevolved.

L. Dressel continued to make emission line kinematic studies of the nuclei of LINER galaxies. By taking dithered STIS spectral images with Hubble, she showed that the black hole in NGC 3998 was within 1pc of the photometric center of the galaxy, in contrast to a possible offset seen in lower resolution kinematic data.

In collaboration with M. Dopita (ANU) and M. Allen (Strasbourg), Dressel used STIS to observe the nuclear spectrum of NGC 3998 from 1200 to 10,000 Å. They used emission line diagnostics to study the ionization and excitation of the gas in the nucleus of this galaxy, which was one of the brightest and most active nearby LINERs.

H. Ferguson studied galaxy evolution through a combination of investigations of nearby galaxies (gas and stellar populations) and distant galaxies. Ferguson was one of the originators of the Great Observatories Deep Survey (GOODS; <http://www.stsci.edu/science/goods/>) project, which over the following two years planned to obtain deep Hubble, SIRTf, and ground-based images and spectroscopy of roughly  $10^5$  distant galaxies in an area of 0.1 deg<sup>2</sup> and to detect several dozen high-redshift supernovae. The first GOODS supernova detections were reported in September 2002.

By analyzing the SEDs of galaxies at redshifts  $2 < z < 3.5$  observed in the Hubble Deep Field, Ferguson, C. Papov-

ich, and M. Dickinson set interesting constraints on the nature of sources responsible for reionizing the intergalactic medium at redshifts  $z > \sim 6$ . Specifically, if stars were responsible for reionization, either they formed with a top-heavy initial mass function, or they did not reside in unobscured parts Lyman-break galaxies at  $z \sim 3$ .

Ferguson, T. Brown, and E. Smith, together with M. Rich and M. Mouhcine (UCLA), analyzed WFPC2 images of the outskirts of six nearby spiral galaxies. Individual halo red-giant branch stars were resolved in every case. The metallicity distributions were found to vary from galaxy to galaxy, with more luminous, more bulge-dominated galaxies showing both a higher mean metallicity and a larger spread.

Ferguson and J. Lotz developed a Bayesian relative-likelihood technique to test galaxy evolution models against the full distribution of apparent magnitudes, colors, and photometric redshifts of galaxies in any survey. This technique was applied to constrain the epoch of formation of dwarf galaxies using HDF and SDSS data.

M. Giavalisco led the ACS imaging survey component of the GOODS project and published a review paper on Lyman-break galaxies. He continued research on galaxy evolution, in particular on the clustering properties of Lyman-break galaxies and techniques to constrain their mass spectrum. Giavalisco also worked on chemical enrichment of early galaxies, the evolution of galaxy morphology, and the properties of faint AGN at high redshifts.

As PI, Giavalisco led the definition, implementation, and execution of GOODS ACS, which was a Hubble Treasury program of 398 Hubble orbits to image the HDF-N and the Chandra Deep Field South (CDF-S) in 4 bands (B, V, i, and z). GOODS, which included coordinated observations from Hubble, SIRTF, Chandra and major ground-based telescopes, including Keck, VLT, Gemini, Subaru, and NOAO, aimed at understanding galaxy formation and evolution, including the evolution of star formation, the stellar and total mass content of galaxies, and the assembly of the Hubble sequence. GOODS ACS studied galaxies at  $0.5 < z < 7$ , including the evolution of their mass spectrum and sought to identify a large sample of high-redshift Type Ia supernovae at high redshift to understand the dynamics of the cosmological expansion and test the presence of the cosmological constant.

O. Gnedin, in collaboration with H. S. Zhao (Cambridge), used numerical simulations to investigate the effect of stellar feedback on the dark matter profiles of dwarf galaxies. They found that even the maximum feedback might lower the density in the inner dark matter cusp only by a modest factor of 2 to 6 and thus could not solve the discrepancy with observations.

P. Goudfrooij, in collaboration with G. Trinchieri (Osservatorio Astronomico di Brera), used the Chandra X-ray telescope to obtain high-resolution images of the X-ray bright elliptical galaxy NGC 5846. They detected an abundance of hot gas with a disturbed morphology on the arcsecond scale, revealing unprecedented details. The morphological peculiarities were coupled with a complex SED of the X-ray photons. The previously reported morphological similarity of the X-ray emission and the  $H\alpha$  emission was extended into the

very inner regions of the galaxy, reinforcing the idea of a close link between the hot and warm phases of the interstellar medium. Fits to the SED of the hot gas were made throughout the Chandra image. Interestingly, the energy transport into the core of NGC 5846 by heat conduction agreed with the energy radiated in the nebular emission lines. They proposed that electrons provided the gas ionization responsible for the optical line emission and conducted heat within the hot gas.

Goudfrooij, in collaboration with E. Emsellem (Observatoire de Lyon), analyzed WFPC2 images and TIGER integral-field spectroscopy of the elliptical galaxy NGC 2974 to derive the kinematics of the stellar and ionized gas components in its central 500 pc. They built a two-integral distribution function from a multi-Gaussian expansion mass model of the stellar component, which fit all available data well. The Hubble images revealed the presence of a high-contrast, two-arm spiral structure of ionized gas of a size of about 200 pc, which was confirmed by the analysis of the deconvolved TIGER data cube. This was the first time a nuclear, gaseous spiral structure had been found in a ‘normal’ elliptical galaxy. Strong departures from circular motions were observed in the gas kinematics and were successfully modeled via a density-wave model.

B. Holwerda worked on a project to determine the opacity of spiral galaxies in a Ph.D. project under supervision of Allen. The goal was to determine the dust opacities of nearby spiral and irregular galaxies by counting background galaxies detected through the foreground galaxy in WFPC2 archival data. For calibration, the project compared the number of background galaxies with simulations that added an extincted HDF frame to the original image. Holwerda made technical improvements, including drizzling the data selected from the archive, automatic detection of background galaxies, and a ‘fuzzy boundary’ technique, where an object was ‘rewarded’ for galaxy-like properties and ‘penalized’ for star-like ones. Promising initial results showed a relation between the inferred opacity and radial distance from the galaxy center.

M. Livio and T. Alexander (Weizmann Institute) showed that a significant fraction of the stars around massive black holes in galactic centers underwent extreme tidal interactions with the hole, but survived total disruption. They showed that this might explain the existence of blue stars in galactic centers.

R. Lucas continued his extragalactic research on the HDFs. He collaborated in the GOODS project, which planned to cover a wider area around the HDF-North and the CDF-South. He also observed VLIRGs (Very Luminous Infrared Galaxies—slightly less luminous than ULIRGs) using the Nordic Optical Telescope (NOT) in collaboration with S. Arribas, Borne, Bushouse, and Colina.

For the Hubble Heritage program, Lucas supported B, V, and I-band observations by WFPC2 of Hoag’s Object, an unusual ring galaxy, which might be related to polar ring galaxies and probably resulted from one galaxy passing too near another, being shredded, and captured in orbit.

Lucas collaborated on three publications on ULIRGs based on data from the Hubble snapshot programs of Borne

and M. Rowan-Robinson (Imperial College). Bushouse et al., which was an atlas of NICMOS H-band images of 27 galaxies, found that at least 85% were obvious interactions or mergers,  $\sim 93\%$  showed some sign of interaction, and  $\sim 37\%$  showed some AGN features. Colina et al., which treated the nuclear properties of the same 27 galaxies, found  $\sim 67\%$  of the galaxies appeared to have multiple nuclei,  $\sim 52\%$  had sub-L\* luminosities (implying the interactions and mergers involved sub-L\* galaxies), and only one of 49 nuclei was quasar-like. Thus, an evolutionary merging sequence possibly generated the various types of ULIRGs and QSOs based on the masses of the progenitors. Farrah et al., which presented WFPC2 V-band imaging of 23 ULIRGs from the QDOT redshift survey, found that 87% appeared to be interacting, that QSO host galaxies were typically interacting galaxies or ellipticals, and that ULIRGs were a diverse group rather than a simple transitional stage between galaxy mergers and QSOs, with local environment and progenitor morphologies driving evolution of the IR power source and the ultimate merger morphology.

D. Macchetto, Panagia, and W. Sparks, in a collaboration that includes F. Ferrari, M. Pastoriza, and C. Bonatto (UFRGS, Brazil), discussed the mid-IR photometric properties of a sample of 28 early-type galaxies observed at 6.75, 9.63, and 15 microns with the ISOCAM instrument on board the ISO satellite. The total mid-IR luminosities were found to be in the range  $(3 \text{ to } 42) \times 10^8 L_{sun}$ . The SEDs of the galaxies clearly showed that the mid-IR emission originated from dust heated at  $T \cong 260 \text{ K}$ . The masses of that hot dust component were found to be in the range 10 to 400  $M_{sun}$ .

M. Stiavelli and S. Casertano constrained the evolution of field elliptical galaxies by studying the evolution of the Fundamental Plane together with T. Treu (Caltech). They determined the Fundamental Plane properties of a sample of field ellipticals at  $z = 0.7$  by using the VLT to obtain velocity dispersion measurements and archival WFPC2 images to obtain their structural parameters. Their measurements indicated that field ellipticals formed more recently than cluster ellipticals, as evidenced by their stronger luminosity evolution and higher incidence of star forming activity.

Stiavelli studied the nuclear properties of the bulges of spiral galaxies. He obtained both WFPC2 and NICMOS images for a sample of about 100 spiral galaxy bulges and used the data to demonstrate that pseudo-bulges were on average younger than the better-known classical bulges with a de Vaucouleurs light profile. He found that nuclear sources were very common in pseudo-bulges and showed colors compatible with the bulge stellar populations. These results supported models where bulge formation was an on-going process, perhaps triggered by bar instabilities and quenched by the formation of a massive central concentration.

Stiavelli and C. Scarlata analyzed the presence of nuclear disks in the cores of spiral galaxies. They carried out a morphological analysis of archival WFPC2 F606W data to show the presence of nuclear stellar disks in some spiral galaxies. This indicated that accretion of material with decoupled angular momentum was a process occurring not only in ellipticals but also in spiral galaxies.

Stiavelli studied the evolution of substructure in dynamical systems and the transport of angular momentum. He used N-body simulations to study the evolution of substructure in both collapsing and equilibrium dynamical systems embedded in dark massive halos. He studied the effects of various dynamical processes, like global tides, clump-clump heating, clump-clump merging, and dynamical friction. The simulations suggested that spiral galaxies cannot be formed by collapse of a few large clumps but could be formed by accretion of many small clumps. He also found that the collapse of a clumpy system was not sufficient to form the extended envelope of a cD galaxy.

R. van der Marel worked with several collaborators on the structure, dynamics, and orbit of the Large Magellanic Cloud (LMC) by fitting general expressions for the velocity field to kinematical data for 1041 carbon stars. This improved significantly on previous studies of LMC kinematics, which made unnecessary over-simplifications and led to incorrect estimates of important structural parameters. For example, the new analysis implied that the LMC rotation curve  $V(R)$  had amplitude  $49.8 \pm 15.9 \text{ km s}^{-1}$ , 40% lower than traditionally believed. This in turn implied that the LMC had a larger vertical thickness than previously thought; its  $V/\sigma$  was less than the value for the Milky Way thick disk. The study also constrained the mass and extent of the dark halos of both the LMC and the Milky Way and the velocity and orbit of the LMC in the Galactocentric rest frame. The latter were found to be consistent with models for the Magellanic Stream.

van der Marel worked on a project led by E. Verolme (Leiden) on dynamical models for the nearby compact elliptical galaxy M32. The models fit high-quality stellar kinematical measurements obtained with the integral-field spectrograph SAURON on the William Herschel Telescope, as well as STIS long slit data. They implied a best-fit central black hole mass of  $(2.5 \pm 0.5) \times 10^6 M_{sun}$  and a stellar I-band mass-to-light ratio  $1.85 \pm 0.15$  in solar units. The models also provided the first constraint on the inclination of M32 ( $70 \pm 5$  degrees) and revealed the power of integral-field spectroscopy for constraining the dynamical structure of nearby galaxies.

van der Marel worked with M. Geha (Lick) and P. Guhathakurta (UC Santa Cruz) on the internal kinematics of dwarf elliptical (dE) galaxies. These were among the most poorly studied galaxies due to their faint luminosities and characteristic low effective surface brightness. Keck/ESI spectroscopy of six dE galaxies in Virgo yielded their mean line-of-sight velocity and velocity dispersion as a function of radius along the major axis. This nearly doubled the total number of dEs with spatially-resolved stellar kinematics. None of the observed objects showed evidence of much rotation, which placed strong constraints on dE galaxy formation models. The dynamically inferred mass-to-light ratios were in the range 3 to 6 (V-band solar units), consistent with an intermediate-age stellar population. There was no evidence for a significant dark matter component inside an effective radius.

S. Laine, van der Marel, T. Lauer (NOAO), M. Postman, C. O'Dea, and F. Owen (NRAO) derived central surface

brightness profiles for 60 brightest cluster galaxies using WFPC2 images. They confirmed that the large majority of bright elliptical galaxies had cores near the center, although a few had steep power-law profiles. Together with Lauer and the Nuker team, Laine and van der Marel demonstrated that the surface brightness profile even turned over near the center in some ellipticals. All these results were consistent with theoretical scenarios where galaxy mergers create central binary black hole systems, which scattered stars and converted power-laws to core profiles or even central dips.

Laine, together with S. Jogee (Caltech), J. Knapen (ING), I. Shlosman (Kentucky), N. Scoville (Caltech), P. Englmaier (MPE) and C. Wilson (McMaster), obtained optical and near-infrared imaging and interferometric CO observations of the nearby spiral galaxy NGC 5248. Through a combination of morphological and dynamical arguments, they demonstrated that this galaxy had a previously unrecognized large-scale stellar bar. This result was likely to have far-reaching implications for the properties of bars locally, as well as for the paucity of observed bars at high redshifts. A comparison of the multiwavelength data with hydrodynamical models showed that a large-scale bar could generate both the extended grand-design spirals on kpc scales and the nuclear spirals in the inner few hundred parsecs.

G. Verdoes Kleijn, van der Marel, T. de Zeeuw (Leiden), J. Noel-Storr, and S. Baum studied the gas disk in the radio galaxy NGC 4335 and constrained the central black hole mass using Hubble and ground-based observations. The upper limit to the black hole mass inferred from gas velocities fell a factor  $\sim 6$  below the mass expected from the stellar velocity dispersion. Thus, NGC 4335 possibly had an unexpectedly low black hole mass. Alternatively, the customary assumptions for the gas disk model were possibly invalid for this object despite its regular behavior.

M. Cappellari (Leiden), together with van der Marel, Verdoes Kleijn, and others, estimated the black hole mass in the counter-rotating core of IC1459 using stellar kinematics from Hubble and ground-based observations. The mass estimate was an order of magnitude higher than that obtained from gaseous kinematics. This cast doubt on the validity of both techniques, although higher quality stellar kinematical information was required to confirm this.

J. Gerssen, K. Kuijken (Leiden) and M. Merrifield (Nottingham) derived the bar pattern speeds of four barred spiral galaxies using a model-independent technique pioneered by Tremaine and Weinberg. The results were consistent with fast rotating bars, and this suggested that dark matter halos in barred galaxies were not as centrally concentrated as predicted by cosmological simulations. This result was at odds with current understanding of dark halos in non-barred spiral galaxies. In the optical, applications of the Tremaine and Weinberg technique were restricted to early-type barred galaxies. Gerssen collaborated with V. Debattista (Basel) to show from numerical simulations that the method could be applied successfully to all barred galaxies along the Hubble sequence when infrared spectra were used.

Gerssen, van der Marel and several other collaborators finished a study of the dense Galactic globular cluster M15. They used STIS to measure the radial velocities of individual

stars in the crowded central regions. These observations tripled the number of stars within the central arcsec of M15 that had reliably measured velocities. Upon dynamical modeling, the data provided strong evidence for a central dark mass component, possibly an intermediate-mass black hole. The mass was consistent with the correlation between velocity dispersion and black hole mass that had been inferred for galaxies, which suggested a new link between the structure, evolution and formation of globular clusters, galaxies, and their central black holes. However, with the available models and data it was neither uniquely implied nor ruled out that M15 had a black hole.

## 7 AGN

S. Casertano, together with T. Hamilton (GSFC) and D. Turnshek (Pittsburgh), studied the luminosity function of QSO host galaxies in archival Hubble images. They found that the hosts were optically very luminous, comparable to brightest cluster galaxies, and constituted a substantial fraction of all luminous galaxies.

A. Koekemoer, in collaboration with B. Mobasher, R. Norris (ATNF), C. Jackson (MSSSO/RSAA), and members of the GOODS team, initiated an ultra-deep radio survey at 20 cm with the Australia Telescope Compact Array (ATCA) of the CDFS. A total of 15 days of observing time were received, which were expected to allow 1-sigma sensitivities of about 10 micro-Jy to be obtained. The field contained several hundred radio-loud AGN and starburst galaxies, and the data were being used in conjunction with the deep X-ray, optical, and IR data from GOODS to investigate the relative properties of starbursts and AGN as well as the nature of radio-loud galaxies in the early universe.

Koekemoer carried out a deep optical spectroscopic survey of compact radio galaxies (CSS/GPS), working with C. O'Dea, S. Baum, A. Labiano (Kapteyn Institute), and W. de Vries (LLNL). This program aimed to study the dynamics of gas near the nucleus and the effects of interactions with the radio jets. Low-dispersion spectroscopy of these sources revealed a correlation between the gas excitation state and the size of the radio source, suggesting that the smallest sources were embedded in extremely dense gas, which gradually dispersed with increased source age, likely due to continuous interactions with the radio jets.

Koekemoer coordinated the GOODS/AGN research team at the Institute, specifically in the context of the evolution of AGN with cosmic time and their relationships with other galaxies. This work involved developing a set of models of number counts and redshift distributions of various classes of AGN, covering the entire spectrum from X-ray through to radio wavelengths. This would allow direct predictions and tests of various scenarios of AGN evolution, including evolution of the fraction of obscured AGN with redshift, and possible changes in the ratio of AGN luminosity as a function of their Eddington luminosity. The deep SIRTf data up to 24 microns, when combined with deep Chandra, optical/near-IR and radio surveys, was expected to prove invaluable in revealing how AGN evolve with redshift.

Koekemoer continued work with G. Bicknell (MSSSO/RSAA) on detailed studies of 3-dimensional spectroscopy of

emission-line gas in powerful radio galaxies, to investigate the relationships between galaxy mergers and AGN fueling in specific objects. Combined with theoretical constraints on the dynamics and energetics of the gas, these results showed that the origin of the gas was most likely related to a merger event that was also responsible for having triggered the AGN. The results were yielding valuable constraints on the timescales involved.

G. Kriss and the FUSE AGN Working Group used FUSE observations of O VI and Ly $\beta$  absorption to evaluate the relationship between UV absorbers and X-ray absorbers in low-redshift AGN (Zheng et al. 2001; Brotherton et al. 2002). In all cases, the FUSE spectra showed multiple kinematic components spanning a wide range of ionization parameters and column densities. Working with J. Krolik (JHU), they developed a physical explanation for this complexity as the natural condition for a thermal wind driven off the exposed faces of the obscuring torus (Krolik and Kriss 2001). At the critical ionization parameter for evaporation in these models, there was a broad range of temperatures that could coexist in equilibrium at nearly constant pressure. This resulted in a strongly inhomogeneous gas flow. High temperature, highly ionized gas causing X-ray absorption could co-exist with more densely clumped, lower temperature gas that formed UV absorption lines.

M. Livio examined the properties of jets in AGN and other astrophysical sources. He showed that it was possible that the same acceleration and collimation mechanism operated in all the sources.

Livio, in collaboration with A. Riess and W. Sparks, showed that a serendipitous observation of a Type Ia supernova associated with an AGN jet might indicate that jets can enhance the rates of both supernovae and novae. They also showed that these findings might help identify the progenitors of Type Ia supernovae.

Livio, in collaboration with J. Biretta and W. Junor (New Mexico), presented evidence for poloidal collimation of the jet in M87 by the accretion disk around the central black hole.

S. Lubow, G. Ogilvie, and J. Pringle (Cambridge) investigated the properties of a low-viscosity disk surrounding a misaligned rotating black hole. They found that tilt waves were generated in the disk that could propagate to the disk center and might cause jets to be misaligned with their host galaxies.

S. Malhotra and J. Rhoads continued their work on finding high redshift Ly $\alpha$  emitters using the Large Area Lyman Alpha (LALA) survey. A sample of 18 candidates at redshift  $z = 5.7$  was published and four candidates were followed up spectroscopically in collaboration with A. Dey (NOAO) and H. Spinrad (UC, Berkeley). Three out of four Ly $\alpha$  candidates were confirmed. Meanwhile, modeling of the 160 or so Ly $\alpha$  emitters at  $z = 4.5$  by stellar population showed that the equivalent width of the line could not be reproduced by stellar populations without invoking extreme stellar initial mass function, youth (age less than 10 million years), or zero metallicity. Narrow-line AGNs were a possibility, but deep X-ray imaging with Chandra had failed to detect such AGNs.

C. O’Dea, S. Baum, W. de Vries (LLNL), A. Koekemoer,

D. Axon (Hertfordshire), P. Barthel (Kapteyn Institute), A. Capetti (Osservatorio Astronomico di Torino), R. Fanti (Istituto di Radioastronomia del CNR), R. Gelderman (Western Kentucky), R. Morganti (Netherlands Foundation for Research in Astronomy), and C. Tadhunter (Sheffield) obtained STIS long slit spectroscopy of the aligned emission line nebula in three CSS radio sources in order to test models for the interaction of powerful radio sources with their environments. They found systematic offsets (roughly 300 to 500 km s<sup>-1</sup>) of the emission line velocities on one or both sides of the radio sources. There was also evidence for moderately broad lines (FWHM 500 km s<sup>-1</sup>) and complex emission line profiles. Comparing the CSS kinematics with those of the Baum et al. (1990) sample of extended radio galaxies revealed that the three CSS sources exhibited kinematics that distinguished them from typical low redshift large radio galaxies, in the sense that the CSS sources tended to have larger values of the side-to-side velocity difference. The complex kinematics, side-to-side asymmetry in the velocity variations, the lack of a signature of Keplerian rotation, and the association of the velocity variations with the radio lobes were consistent with the motions being driven by the expansion of the radio source. Clouds with densities in the range 100 to 1000 cm<sup>-3</sup> could be accelerated to the observed range of velocities for bow shock velocities in the range 0.05 to 0.2 c—consistent with proper motions observed in the much smaller CSOs (0.1 to 0.2 c) and with expansion velocities estimated from spectral aging.

P. Padovani, in collaboration with H. Landt, and P. Giommi (BeppoSAX/ASDC), investigated why BL Lacertae objects (BL Lacs) had values of the Ca H and K break (a stellar absorption feature) lower than low-power radio galaxies and whether its use was justified to separate the two classes. They found that the Ca H and K break value decreased with increasing jet powers and anti-correlated with the radio core dominance parameter but not with extended radio emission. They concluded that the Ca H and K break value of BL Lacs and radio galaxies was a suitable indicator of orientation.

Padovani continued his work on BeppoSAX data of blazars. In collaboration with L. Costamante (MplfK), G. Ghisellini (OAB), P. Giommi (BeppoSAX/ASDC), and E. Perlmutter (UMBC), he presented new BeppoSAX observations of four flat-spectrum radio quasars (FSRQ) having effective spectral indices typical of high-energy peaked BL Lacs. The BeppoSAX band in one of the sources, RGB J1629+4008, was dominated by synchrotron emission peaking at  $\sim 2 \times 10^{16}$  Hz, as also shown by its steep (energy index  $\alpha_x \sim 1.5$ ) spectrum. This fact made this object the first known FSRQ whose X-ray emission was not due to inverse Compton radiation. Two other sources displayed a flat BeppoSAX spectrum ( $\alpha_x \sim 0.7$ ) but with indications of steepening at low X-ray energies. This was also supported by ROSAT and multifrequency data and a synchrotron inverse Compton model, which suggested synchrotron peak frequencies of  $\sim 10^{15}$  Hz, typical of ‘intermediate’ BL Lacs for which the synchrotron and inverse Compton components overlapped in the BeppoSAX band.

## 8 CLUSTERS & COSMOLOGY

M. Dickinson was the Principal Investigator of the GOODS Legacy Science Program with SIRTf. This project planned to obtain the deepest observations with that facility at 3.6 to 24 microns in order to study the evolution of stellar mass in galaxies and their energetic activity (from star formation and active nuclei) out to  $z = 5$  or beyond. A Hubble Treasury program (M. Giavalisco, PI) obtained deep, four-band imaging of the two GOODS fields with the ACS. The GOODS Legacy program planned to commence observations shortly after the launch of SIRTf in 2003. Dickinson continued preparing for the Legacy observations and playing a leading role in the ACS program. He was active in the collection and compilation of ground-based optical and near-infrared data on the GOODS fields. He analyzed the evolving global stellar mass density at  $0 < z < 3$  using the best data currently available and found that only 5 to 15% of the present-day stellar mass density was in place at  $z \sim 3$ , building rapidly to 50 to 75% by  $z \sim 1$ . Dickinson continued research on a variety of other projects and publications concerning the evolution of galaxies, galaxy clusters, distant active galactic nuclei, and cosmology from high redshift supernovae.

M. Fall collaborated with P. Moller (European Southern Observatory), S. Warren (University College, London), and P. Jakobsen (ESA) on a long-term project to determine the nature of the damped Ly $\alpha$  absorption-line systems. These systems, detected in the spectra of background quasars, were generally believed to represent the interstellar components of high-redshift galaxies. However, until this project, little was known about their stellar components, including the morphologies and sizes of the galaxies. Moller et al. obtained deep STIS and NICMOS images of the fields around many quasars with known damped Ly $\alpha$  absorption and VLT spectra of the candidate galaxies. Contrary to current belief, they found that the damped Ly $\alpha$  galaxies were similar to the galaxies detected by emission alone (i.e., Lyman-break galaxies) when compared at the same redshift and luminosity. This had implications for a wide range of issues concerning galaxy formation.

Fall collaborated with S. Savaglio (JHU) to determine the metal and dust content of the absorbing gas in the foreground of gamma-ray bursts. They found that the columns of metals and dust in the gamma-ray bursts were higher than those in most damped Ly $\alpha$  systems. This was consistent with the idea that the gamma-ray bursts occurred in regions of active star formation, where the columns of interstellar material, including metals and dust, were high. The lines of sight to background quasars, on the other hand, sampled random lines of sight through galaxies, or perhaps even those with lower-than-average dust columns.

V. Kulkarni (South Carolina) and Fall reexamined the relation between the global mean interstellar metallicity in damped Ly $\alpha$  systems and their redshifts. There were several recent claims that this  $Z(z)$  relation was flat or nearly so (by Pettini and Wolfe and their collaborators). This was contrary to intuition and to models of cosmic chemical evolution, which indicated that the mean metallicity should increase from  $Z \sim 10^{-2} Z_{sun}$  at  $z = 3$  to  $Z \sim Z_{sun}$  at  $z = 0$ . Kulkarni

and Fall found instead that the existing data on metallicities in damped Ly $\alpha$  systems in fact supported a rising  $Z(t)$  relation, consistent with the models of cosmic chemical evolution.

A. Koekemoer, in collaboration with S. Baum, C. O’Dea, J. Mack, and A. Laor (Technion), continued a STIS Far-UV imaging and spectroscopic study of nearby cooling-flow clusters. This study revealed striking large-scale, coherent structures of Ly $\alpha$  emitting gas, together with complex knots of UV continuum emission, distributed around the central galaxy and also associated with the radio lobes. The ratio of Ly $\alpha$  flux relative to H $\alpha$  and to the UV continuum were used to address the question of how the gas was ionized; photo-ionization by hot young stars was possible for a very limited range of parameter space, while additional energy supplied from shocks or directly from the ICM, as well as possible effects from unusually low abundances, were investigated to explain the high observed ratios of Ly $\alpha$  to H $\alpha$  in a number of regions. These studies also showed that the dust content of the extended gas was low, with substantial dust being present only in dense, localized regions.

A. Koekemoer, collaborating with E. Schreier, N. Grogin (JHU), and other members of the CDFS team, published the results from their deep, multi-band WFPC2 observations of 40 X-ray sources within the CDFS field. The detailed WFPC2 morphologies and colors allowed classification of the host galaxies of the X-ray sources and investigation of the different populations of objects revealed by ultra-deep X-ray surveys. A principal result from this study was that the optical counterparts of the X-ray sources were composed of two sub-groups: (1) an optically bright population, containing a mixture of low-redshift spirals, ellipticals, starbursts, and AGN, and (2) an optically fainter group, apparently part of the faint blue galaxy population, with X-ray emission consistent with being produced by higher redshift (up to  $z = 2$ ) obscured AGN. This represented a significant extension of the population of nearby, moderate-luminosity AGN to cosmological distances, thereby directly enabling studies of their evolution and relationships with normal galaxies.

M. Livio examined models for Type Ia supernovae and their implications for the determination of cosmological parameters. He demonstrated that the recent indications of an accelerating universe could not be an artifact of the existence of two classes of progenitors of Type Ia supernovae.

Livio, in collaboration with A. Riess and others, discovered the farthest known supernova, at redshift 1.7, and showed that this supernova was consistent with an accelerating universe dominated by dark energy.

Livio’s book *The Accelerating Universe* was published in German, under the title *Das Beschleunigte Universum*.

Livio, in collaboration with L. Siess (Brussels) and J. Lattanzio (Monash) calculated the evolution of the first (primordial) stars in the mass range 0.8 to 20 solar masses from the pre-Main Sequence to the asymptotic giant branch phase (and up to carbon ignition for massive stars). They showed that primordial low- and intermediate-mass stars could have been significant contributors to the production of carbon and nitrogen.

L. Lubin, M. Postman, and J. Oke (DAO/Caltech) contin-

ued a Keck/KPNO/Hubble program to study massive clusters of galaxies at redshifts approaching 1. Their latest research revealed a strong change with redshift in the measured star formation rates and morphologies of the cluster galaxies, as well as evolution in the global relations (e.g., the  $L_x - \sigma$  relation) between the cluster galaxies and the intracluster gas. These results suggested that infall from the field population and transformation of galaxy morphologies was actively occurring during this epoch. For example, the fraction of early type (E+S0) galaxies in rich clusters was a factor of 1.5 times lower at  $z \sim 0.9$  than in nearby clusters. This evolution implied that early-type galaxies were forming out of the excess of late-type (spiral, irregular, and peculiar) galaxies over the approximately 7 Gyr timescale.

L. Lubin, in collaboration with C. Fassnacht, exploited a new technique to detect small groups of galaxies in the previously unexplored redshift range of  $z = 0.3$  to  $0.9$  through their association with gravitational lens systems. This program permitted them to better constrain the mass models in gravitational lens systems and to study the evolution of groups of galaxies. They planned to observe the discovered groups in X-rays using the Chandra Observatory in order to measure their gas and dark matter properties. The first 100 ksec observation of B0712+472 at  $z = 0.2909$  was scheduled for 2002.

B. Mobasher, in collaboration with L. Cram (Sydney), J. Afonso (Imperial College) and A. Hopkins (Pittsburgh), completed a deep, wide-area radio survey at 1.4 GHz, using ATCA. The survey covered an area of  $3 \text{ deg}^2$  and was complete to  $\sim 40$  micro-Jy. This was the deepest and the most homogeneous radio survey available over such a large area. Using the 2-degree Field (2dF) multi-object fiber spectroscopic facility and optical/near-IR/mid-IR imaging observations, these data were used to address deep micro-Jy radio source counts, the nature of faint radio population, and dust-free star-formation rate from 1.4 GHz and  $H\alpha$  fluxes.

Mobasher and Afonso discovered the closest Extremely Red Galaxy (ERG) at  $z = 0.65$ . This was the first ERG with detection at mid- and far-IR wavelengths, allowing a detailed study of the nature of these sources. The SED of this ERG best fit a combination of a starburst (with a star-formation rate of  $470 M_{\text{sun}} \text{ yr}^{-1}$ ) and a dust-enshrouded active nucleus ( $A_v = 5$  to  $6 \text{ mag}$ ).

Mobasher, R. Ellis (Caltech), Cram, M. Sullivan (Cambridge) and M. Treyer (Marseille) performed a comparative study of different star formation diagnostics (radio 1.4 GHz,  $H\alpha$ , UV), investigating the origin of the difference in star formation rates for the same object, estimated from different diagnostics.

Mobasher completed study of the near-infrared Fundamental Plane of elliptical galaxies in two clusters at  $z = 0.07$ . This showed a scatter similar to that in the Coma cluster and the optical Fundamental Plane. A relation was also found between the near-IR M/L ratios and mass of ellipticals, with a shallower slope than what was found in optical wavelengths. Using the strength of the near-IR (2.3 micron) CO absorption line features, the effect of intermediate-age stellar population on the scatter in the NIR FP of ellipticals was studied.

Mobasher, in collaboration with D. Carter (Liverpool John Moores), T. Bridges (Anglo-Australian Telescope), B. Poggianti (Padova), the University of Tokyo, and National Astronomical Observatory of Japan (NAOJ), completed a wide-area photometric and spectroscopic survey of dwarf and giant galaxies in the Coma cluster. Using the strength of spectroscopic line indices for  $\sim 500$  galaxies in this sample, the following issues were addressed: formation and evolution of dwarf and giant galaxies, environmental dependence of their properties, luminosity function of cluster galaxies, age and metallicity of elliptical and SO galaxies, and dynamical evolution of dwarfs.

Mobasher and B. Tully (Hawaii) completed near-IR imaging observations of a sample of spiral galaxies with known distances from SNe Ia. Results were to be compared with distances derived from the near-IR (K-band) luminosity-velocity width relation.

P. Padovani worked on a high-redshift Lyman Break galaxy with S. Savaglio (JHU) and N. Panagia. Very Large Telescope (VLT), high-resolution observations of MS 1512-cB58 ( $z = 2.724$ ,  $V = 20.64$ ) revealed, with unprecedented detail along a galaxy sight line, the  $\text{Ly}\alpha$  forest due to intervening clouds in the intergalactic medium (IGM), with indications of a possible excess of absorption close to the galaxy. This high-density region was at least  $60 h(65)^{-1} \text{ Mpc}$  comoving wide, but the large  $\text{Ly}\alpha$  absorption of the galaxy itself prevented the detection of a possible structure extending down to the galaxy. This excess of  $\text{Ly}\alpha$  clouds was suggestive of two possible scenarios: the presence of a supercluster of  $\text{Ly}\alpha$  clouds not associated with MS 1512-cB58 or a high density of gas associated with the environment of MS 1512-cB58.

D. Macchetto and Panagia, in collaboration with A. Saha, A. Dolphin and J. Christensen (NOAO), A. Sandage (OCIW), and G. Tammann (Basel), continued their Hubble program to calibrate the peak brightness of type Ia supernovae (SNIa) by studying the case of NGC 3982, the parent galaxy to SN 1998aq. The resulting distance modulus was  $(M - m)_0 = 31.72 \pm 0.14$  ( $22 \pm 1.5 \text{ Mpc}$ ). The derived V and I band luminosities were fully consistent with the mean of the eight normal SNe Ia previously calibrated with Cepheids. Together they yielded  $H_0 = 60 \pm 2(\text{internal}) \text{ km s}^{-1} \text{ Mpc}^{-1}$  based on an assumed LMC distance modulus of 18.50.

Panagia, as a member of a wide collaboration (the Supernova Cosmology Project) led by S. Perlmutter (LBL), continued his studies of high redshift supernovae. Using four large subsets of data from the Supernova Cosmology Project, which surveyed about 12 square degrees, thirty-eight supernovae were detected at redshifts 0.25 to 0.85. In a spatially-flat cosmological model consistent with the results obtained by the Supernova Cosmology Project, the rest-frame Type Ia supernova rate was found to be  $\sim 1.5 \pm 0.3 \times 10^{-4} h^3 \text{ Mpc}^{-3} \text{ yr}^{-1}$  at a mean redshift  $z \approx [F020]0.55$ .

H. Bond and Panagia, in collaboration with S. Palen and B. Balick (Washington), A. Hajian (USNO), and Y. Terzian (Cornell), combined two epochs of Hubble Space Telescope WFPC2 imaging data with ground-based expansion velocities to determine distances to three planetary nebulae (NGC 6578, NGC 6884, and IC 2448).

Panagia, in collaboration with H. Lamers and W. de Wit

(Utrecht), Romaniello, Scuderi, M. Spaans (Groningen), and Kirshner, analyzed the WFPC2 observations of the inner kiloparsec of the interacting galaxy M51 in six bands from  $\sim 2300$  to  $9000 \text{ \AA}$ , which were obtained in 1994/95 as part of the SINS project. Clear evidence was found that the formation of massive stars outside clusters (or in very small clusters) was occurring in the bulge of M51, with an estimated star formation rate of  $(1 \text{ to } 2) \times 10^{-3} M_{\text{sun}} \text{ yr}^{-1}$ . This suggested that the ongoing massive star formation in the bulge of M51 was fed or triggered by the interaction with its companion about  $4 \times 10^8$  yrs ago. The mode of formation of massive stars in the bulge of M51 possibly resembled the star formation in the early universe, when the CO and dust contents were low because of the low metallicity.

M. Postman, T. Lauer (NOAO), B. Oegerle (GSFC), and M. Donahue obtained a new measure of the space density of galaxy clusters over the redshift range  $0.2 < z < 1.2$ . The measurement was derived from an automated search for galaxy clusters within a contiguous  $16 \text{ deg}^2$  I-band survey in the north Galactic hemisphere. The estimated redshift distribution of the cluster candidates was consistent with a constant co-moving density over the range  $0.2 \leq z_{\text{est}} \leq 0.8$ . A decline in the cluster space density by more than a factor of 3 over this redshift range was rejected at  $> 99.9\%$  confidence level. This result represented the best constraint on cluster number evolution done in the optical spectral range. The fact that the estimated space density of massive distant clusters agreed well with that seen locally supported a scenario where the space density of clusters had evolved very little, if at all, over the past half a Hubble time. A percolation analysis revealed that 10 to 20% of the spectroscopically confirmed distant clusters were linked into superclusters at overdensities between  $10 < \Delta\rho/\rho < 50$ , similar to what was seen in the local cluster distribution. This suggested that there had been little evolution of the cluster-cluster correlation length for  $z < 0.5$ .

Postman worked with numerous collaborators on the Sloan Digital Sky Survey to study the clustering of galaxies and the mass distribution of clusters found in the survey.

J. Rhoads worked on high-redshift galaxies and on gamma-ray burst afterglows. Rhoads and S. Malhotra used their Large Area Lyman Alpha (LALA) survey to identify a sample of Ly $\alpha$  galaxies at redshift  $z = 5.7$  and used these objects to demonstrate that the reionization epoch had to be at  $z > 5.7$ . Malhotra and Rhoads used the larger LALA sample at  $z = 4.5$  to show that these Ly $\alpha$  galaxies were very young objects with relatively little chemical evolution or dust. Additionally, Rhoads and Malhotra were extending the sample of Ly $\alpha$  galaxies both through a  $z = 6.6$  narrowband search and through a slitless spectroscopic search (the ACS Pure Parallel Ly $\alpha$  Emission Survey, ‘APPLES’) using the ACS in collaboration with a multinational team.

Rhoads continued work on the theory and observation of Gamma Ray Bursts (GRBs) and their long-wavelength afterglows. A. Fruchter, J. Krolik (JHU), and Rhoads modeled the effects of GRBs on interstellar dust grains in their environments, demonstrating that X-ray heating could evaporate grains at distances up to 10 parsecs while Coulomb explosions might destroy them at even larger distances, up to 100 parsecs. Rhoads led GRB observational efforts with 2- and

4-meter telescopes at Kitt Peak and Cerro Tololo, and was an active member of GRB follow-up teams using Hubble and the European Southern Observatory facilities. Finally, Rhoads joined the Swift MidEx collaboration and helped plan optical and near-UV observational strategy for the Swift UV-optical telescope.

M. Stiavelli, C. Scarlata, and N. Panagia defined a sample of candidate Ly $\alpha$  emitters at  $z = 2.4$ . They used the CFH12K camera to find objects with an excess flux in a medium band filter centered at  $4160 \text{ \AA}$ . They focused on a redshift around  $z = 2.4$  because galaxies at this redshift had their optical rest frame lines in the infrared atmospheric windows and were optimal candidates for measuring star formation rates, dust content and metallicity. The main result of this study was that the majority of these candidates had much redder colors than expected for star forming galaxies with strong Ly $\alpha$  emission. This result possibly indicated the presence of an older stellar population or of dust in a complex configuration.

## 9 INSTRUMENTS & SOFTWARE

With G. Li Causi (Osservatorio Astronomico di Roma) and F. Paresce (ESO), G. De Marchi studied the accuracy and reliability of the WFPC2 exposure-time calculator (ETC) with the objective of determining how well it represented actual observations and therefore how much confidence could be invested in it and in similar software tools. In certain circumstances, the ETC gave very optimistic values for the signal-to-noise ratio (S/N) of point sources, overestimating the Hubble performances for deep-imaging observations by up to a factor of 2. The investigators calculated corrective factors to compute the appropriate SN and detection limits, which vary with field crowding and sky background. They discussed the scientific implications for the search for old white dwarfs in globular clusters.

J. MacKenty led the development on the Infrared Multi-Object Spectrometer. IRMOS was planned to be a ZJHK cryogenic spectrometer capable of rapid target selection by the use of a MEMS micro-mirror array positioned at the telescope focal plane. Typically 20 to 100 targets could be observed simultaneously. This collaborative effort between the Institute, GSFC, and KPNO had completed testing nearly all subsystems and was integrating its major components. First light was expected in late spring 2003 at KPNO.

A. Sivaramakrishnan worked on theoretical, numerical, and instrument-related aspects of Extreme Adaptive Optics (ExAO). He developed a theory of the structure of the moderate-to-high Strehl PSF, with J. Lloyd (Berkeley), P. Hodge, and B. Macintosh (LLNL). He led an effort with M. Perrin (Berkeley), R. Makidon, and E. Bloemhof (JPL) to demonstrate the use of this theory in ExAO. The theory dispelled the notion that speckle decorrelation was a viable technique of increasing dynamic range. It uncovered various symmetries in the point-spread function (PSF), which could be used to improve AO instrument design, observing strategy, and data reduction methods. Makidon, Sivaramakrishnan, L. Roberts. (Boeing), B. Oppenheimer (AMNH) and J. Graham (Berkeley) quantified the amount of wavefront

reconstructor-generated waffle-mode error present in the AEOS AO PSF, which helped lead to AO performance improvement. He taught a course on high dynamic range coronagraphy at the SPIE conference on Astronomical Telescopes and Instrumentation at Kona. He led the instrument software effort for a JHK-band ExAO coronagraph for the AEOS 3.6m 941-channel AO telescope on Maui, to explore regions as close as 0.2 arcseconds of stars brighter than  $V = 8$  and to enable protoplanetary disk and companion brown dwarf searches. He also developed the theory of quadrant phase-mask coronagraphy with Lloyd and D. Gavel.

Suchkov, in collaboration with a team of scientists from the Institute, HEARSARC (NASA), and CDS (Strasbourg), worked on creation of a system for automated classification of X-ray sources. That system, ClassX, was envisaged as a prototype of the Virtual Observatory. The areas of research included: (a) conceptual issues, (b) classification methods and algorithms, (c) selection and definition of classes (object types), and (d) identification of strategies to search for source counterparts across multi-wavelength data. Machine learning methods were applied to generate ClassX classifiers from 'training' data. A number of metrics were proposed and used to quantify the quality and efficiency of the classifiers. A concept of a classifiers network was introduced. In a network, each classifier was optimized for a particular research task, outputting its own class assignment and class probabilities for a supplied X-ray source. An experimental set of classifiers was generated from the data from the ROSAT WGA, GSC2, and 2MASS catalogs. That set was integrated into the ClassX pipeline together with an engine that searched and retrieved for a supplied target the multi-wavelength counterparts from the worldwide data storage media. Application of the ClassX experimental version to the real-world problems proved to be quite encouraging. Albeit still halfway to completion, the ClassX demonstrated the soundness of the underlying concepts and the robustness of the design.

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