University of Washington
Department of Astronomy
Seattle, Washington 98195

This report summarizes activities during the academic year 1995-1996. For more detail please see the Department's web site at http://www.astro.washington.edu

1. STAFF AND STUDENTS

During the Academic Year 1995-96, the teaching faculty of the Department included Professors B. Balick, K. H. Böhm, P. Boynton, D. Brownlee, P. Hodge, C. Hogan, G. Lake, B. Margon, G. Nelson, C. Stubbs, W. Sullivan, P. Szkody and G. Wallerstein. T. Jacobsen and E. Böhm-Vitense were faculty emeritus. The research faculty included S. Anderson, W. Baum, J. Brown, N. Katz and T. Quinn. B. Moore and A. Silber continued as postdoctoral research associates. Twenty-three graduate students were registered as members of the Department. Two Ph.D. degrees were granted, to D. Ingram, currently at Texas Christian University, and M. Rugers, who joined the Department as a Research Associate. T. Smith (UW), F. Governato (U. Rome), E. Magnier (MIT), D. Richardson (U. Virginia) and V. Dwarkadas (U. Virginia) were also appointed as Research Associates. J. Hughes was appointed Lecturer Part-Time. C. Impey (U. Arizona) was appointed Visiting Professor, and H. Kang (Pusan U., Korea) as Visiting Scientist. J. Brown left to assume a faculty position at Washington State University, and N. Katz left to assume a faculty position at the University of Massachusetts.

2. RESEARCH

2.1 Solar System

Smith, Hodge and D. Joswiak completed an extensive sampling program of the Odessa Meteorite Craters in Texas. A total of 240 soil samples was collected. A preliminary analysis of the samples led to the surprising discovery of microscopic impactite particles. Electron microprobe measurements of the Fe, Ni and Co abundances have been carried out on the metallic spherules that are embedded in the impactite. The unique character of the Odessa impactite has allowed them to conclude that variations in temperature, not the partial pressure of oxygen, in the melt is the primary variable that produces the range of elemental fractionation observed in the spherules.

Brownlee and Joswiak are continuing work on stratospheric interstellar dust particles (IDPs) of probable cometary origin. Along with J. Bradley (MVA Inc, U. Alabama) they are using new sulfur embedding techniques that allow detailed study of carbonaceous matter and its relationship with other IDP components. With R. Pepin and D. Schlutter (U. Minnesota) work is continuing on the use of He release temperatures to distinguish cometary IDPs from asteroidal ones. Spectral reflectance work with Bradley and others has provided a means to compare collected particles with asteroid reflectance types. Most of the IDPs have C, P or D spectral reflectances consistent with their moderate to high carbon content.

Brownlee is the PI of the STARDUST Discovery mission to collect cometary and interstellar particles and return them to Earth. Using a low cost spacecraft developed by Lockheed-Martin Aerospace and managed by JPL , the STARDUST project will collect comet samples during a 6 km/s flyby of comet Wild 2. Over 10,000 particles in the 10 micron to 1mm size range will be captured by impact into ultra low density silica aerogel. STARDUST will also detect and capture contemporary interstellar dust that Ulysses and Galileo spacecraft have recently discovered to be streaming through the solar system. The mission will be launched in early 1999 and is fully described at http://pdc.jpl.nasa.gov/stardust/home.html

M. Hammergren continued his thesis work studying the physical properties of near-Earth objects. He used the Apache Point Observatory (APO) 3.5-m telescope to carry out an ongoing spectroscopic survey of near-Earth objects, and has supplemented the compositional information provided by these spectra with rotational lightcurves obtained with the Manastash Ridge Observatory (MRO) 0.8-m telescope. He finds that several near-Earth asteroids display spectra significantly different from main-belt asteroids, but identical to ordinary chondrite meteorites.

Hammergren obtained reflectance spectra of the unusual high-eccentricity object 1996PW, finding that while the object shows no coma or molecular emissions characteristic of comets, its spectrum is consistent with known cometary nuclei and other distant asteroids.

Richardson is working with Lake, Quinn, and J. Stadel on direct *N*-body simulations of the formation of the inner Solar System. Using a parallel tree code developed for cosmological simulations, it will be possible to follow the evolution of an unprecedented number of planetesimals. These simulations will help determine whether planets grew via the uniform evolution of a homogeneous mass distribution or by a process of runaway growth. It will also be possible to investigate radial mixing, the origin of planetary spin, and the nature of the primordial surface density distribution.

Richardson is completing research started at CITA on tidal disruption of Earth-crossing asteroids (ECAs) with implications for the formation of lunar and terrestrial crater chains and doublet craters, as well as for ECA shapes and spins, and the ECA mass distribution. This research is being performed in collaboration with W. F. Bottke and S. G. Love (both at Caltech).

Richardson is collaborating with G. A. H. Walker (UBC) to observe τBoo in the infrared with UKIRT to try to detect the Doppler shifted emission spectrum of the giant planet inferred to exist in a 3-day orbit about the star.

Quinn and A. Dolphin are integrating the orbits of the planets for the lifetime of the Solar System including general relativity and the earth–moon system. This is 1000 times longer than any previous accurate integration. As well as providing a definitive answer to the question of the stability of the planetary orbits, they will gain insight into other fundamental questions of non-linear dynamics and solar system evolution. In particular, the Solar System displays a small instability with a time-scale of 5 Myr. What this means for the evolution of the system over 5 Byr is not clear, but is something they can answer with this integration. Additional products of their research will include: a time history of the Earth's orbital elements to be used in investigation of Milankovitch climate cycles and a first look at the generic stability of other planetary systems with an eye toward the relationship of the formation and stability of the Earth to the massive planets that can be detected in other planetary systems.

B. Rogers and Quinn are investigating the stability of the outer planets of Solar System over billion year timescales. Of particular interest is the sensitivity of stability to the planetary orbital parameters such as eccentricity and inclination. Questions to be investigated include: 1) How much of the current eccentricities and inclinations of the outer planets must have been imparted in their formation rather than being acquired by dynamical evolution over the subsequent 4.5 Gyr? 2) What are the maximum eccentricities and inclinations that the outer planets can have before they are globally unstable, and one planet is ejected? Answers to these questions are necessary for interpreting the significance of the recent discoveries of planets around other solar-like stars.

Quinn has formed a working group for Solar System science within the Sloan Digital Sky Survey. This group is investigating techniques for detecting Solar System objects in the survey. It is expected that the survey will discover thousands of small bodies including Kuiper belt objects, Centaur asteroids, main belt asteroids, near-earth objects and long period comets. The large sky coverage and 5 color photometry of the SDSS will bring new light to the orbital dynamics, taxonomy, and origins of these objects.

2.2 Stars and Compact Objects

C. Abia (U. Grenada, Spain) and Wallerstein worked on the abundances of heavy elements in stars of type SC. With very nearly equal abundances of C and O these stars show only weak molecular bands in the visual region. The atomic lines are extremely strong due to their low boundary temperatures. Blending is severe. Heavy elements were analyzed successfully in six SC stars, as well as the S star S UMa and two cool Ba stars for comparison.

Balick, along with K. Davidson (U Minnesota) and several others are continuing their imaging and spectroscopic studies of eta Car, a luminous blue variable which has expelled a striking bipolar nebula after its eruption in the 1830s. Their UV spectra, obtained with 0.2″ spatial resolution, show a forest of emission and broad absorption lines. The absorption lines are of stellar origin. Some of the emission lines might be UV lasers.

Balick, Rodgers, A. Hajian (U.S. Naval Obs.), Y. Terzian (Cornell U) and L. Bianchi (STScI) published their discovery of hourly line profile shape changes in the stellar wind of the WC8 nucleus of the planetary nebula NGC 40. The observations show that blobs of material are radiately accelerated to a terminal velocity of 1500 km/sec in about an hour. The requisite column densities of carbon show that the mysteriously low ionization of the nebula by this very hot central star can be explained by extreme softening of the UV radiation in the stellar photosphere.

Böhm-Vitense and B. Beck-Winchatz in collaboration with N. R. Evans (CFA), K. Carpenter (GSFC), and R. Robinson (GSFC) are continuing to measure radial velocities of Cepheid companions by means of HST spectra, in order to determine dynamical masses of Cepheids. So far dynamical masses have been determined for S Mus ($P = 9.6$ days, $M = 5.9 \pm 0.9$ solar masses), for V350 Sgr ($P = 5.1$ days, $M = 5.0 \pm 2$ solar masses) and for the beat Cepheid Y Car (periods are 3.64 and 2.46 days, $M = 4.1 \pm 1$ solar masses). Taken at face value these masses indicate excess mixing in the main sequence progenitor stars corresponding to convective overshoot mixing by 0.7 ± 0.3 pressure scale heights.

Böhm-Vitense in collaboration with T. Ake (GSFC), Carpenter and Robinson is also obtaining short wavelength HST spectra of Barium and CH peculiar stars in order to look for the suspected white dwarf companions.

Szkody, with E. Sion (Villanova) continued the LTSA collaborative effort to study the heating that white dwarfs in magnetic and non-magnetic close binaries undergo with changes in accretion. With M. Huang and F-H. Cheng (Villanova), and I. Hubeny (Goddard), HST FOS ultraviolet observations of VW Hyi after outburst and superoutburst showed a sustained accretion belt, implying a deep source of heating is required (compression and shear mixing) and a lower limit to the viscous spindown timescale of 10 days. Higher resolution HST GHRS observations of U Gem during 2 different outbursts revealed surprising double-peaked emission line profiles with central absorption suggestive of a photo-ionized truncated disk at outburst, but were featureless during the rapid change in the disk structure during the decline from outburst. Szkody, Sion, S. Howell (PSI) and W. Sparks (Los Alamos) obtained 4 sets of FOS observations of AL Com during its decline from a superoutburst following 19 yrs of quiescence. AL Com appears to undergoa more rapid return to its quiescent state than its counterpart WZ Sge. The first FOS observations of a detailed time-resolved program to resolve the accretion spot during high and low states of AM Her were accomplished with B. Gaensicke and K. Beuermann (U. Gottingen).

Szkody, K. Long (STScI), Sion and J. Raymond (CfA) analyzed EUVE data at outburst and ASCA data at quiescence of the dwarf nova U Gem. Both data sets showed unexpected absorption dips during the orbit, which appear to be caused by material far from the orbital plane that is blocking the inner hot boundary layer. This could be due to an extreme extended hot spot or to the mass transfer stream putting material up over the plane. From the analysis of the optical, UV, X-ray energy balance, it appears that U Gem is one of the few systems that conform to standard disk theory, with half the energy emerging from the disk and the other half from the boundary layer.

Szkody, S. Vennes (CEA), Sion and Long obtained and analyzed EUVE data on the magnetic AM Her system BL Hyi in a high accretion state. The accretion spot area appears to be much cooler in this system than in other observed AM Hers, while the EUVE light curve shows a different structure than the X-ray, implying a better view of 2 poles in the EUVE.

Szkody organized and conducted a large coordinated multiwavelength campaign to follow the cataclysmic variable V1159 Ori throughout its 45 day supercycle. A superoutburst, 8 normal outbursts and 9 quiescent intervals were covered with 38 XTE, 34 ROSAT, 27 IUE, 8 EUVE and 9 optical observations. These data are being analyzed with collaborators K. Honeycutt and J. Robertson (Indiana U), Silber, D. Hoard and Linnell, J. Cannizzo and Hubeny (Goddard), J. Drew (Oxford), and C. la Dous (Sonneborg).

XTE observations of the longest period AM Her star RXJ0515+0105 were conducted by Szkody and P. Garnavich (CfA) in order to measure the amount of thermal bremsstrahlung emission from this soft source.

Further ROSAT IDs were accomplished by Szkody, P. Barrett and K. P. Singh (Goddard) and E. Schlegel (CfA) using the 3.5m APO telescope to search the error boxes of very soft ROSAT sources. Several new white dwarfs and a few quasars were identified.

Following up the very bright ROSAT identified source AR UMa with optical photometry, spectroscopy, polarimetry and IUE data led Szkody, Silber and Hoard, together with G. Schmidt and P. Smith (U. Arizona), G. Tovmassian (UNAM), Gansicke and de Martino (Vilspa) to the discovery of the first high field (230 MG) magnetic cataclysmic variable. The properties of this system at low and high states suggests that the accretion occurs in the form of dense filaments which thermalize their energy below the white dwarf surface, rather than through a normal shock in the accreting column. ASCA observations of AR UMa were also recently obtained during a low state to study the hard component radiation.

Hoard and Szkody have completed the current program of data acquisition for their ongoing investigation of the SW Sextantis subclass of cataclysmic variables. Data on six of the SW Sex stars has been obtained from APO, MRO, and the International Ultraviolet Explorer (IUE). Analysis of two of these stars (PG0859+415 and BH Lyn) has prompted Hoard and Szkody to propose a model for the unusual characteristics of the SW Sex stars that involves the presence of ''bulges'' with significant vertical extent at one or more locations in their accretion disks.

Hoard and D. Alves (Lawrence-Livermore National Laboratory) investigated the bipolar proto-planetary nebula IRAS 07131-0147 via optical spectroscopy and near-infrared imaging. They found this object to show point-reflection symmetry and an anomolous relation between the color indices and brightnesses of the nebular lobes that suggests the presence of a precessing bipolar jet emanating from the heavily obscured central star.

E. Deutsch has started a dissertation project to systematically discover eclipsing binaries in the four globular clusters NGC 288, 362, 4590, and 6362, in order to investigate variation in binary fraction with cluster structural parameters and metallicity. There are hints of such variation from previous work, but an intensive study of several carefully-chosen clusters will address this problem directly. In addition, the binaries discovered will themselves be useful for future work in determining fundamental distances to these clusters and in deriving Pop II stellar masses.

Deutsch, Margon, S. Wachter, and Anderson obtained multi-color HST imaging of three intense galactic X-ray sources located in crowded fields, X2129+47, CAL 87 and GX17+2, with the objective of understanding if superpositions of unrelated nearby objects may have confused previous analyses. Although V1727 Cyg, the optical counterpart of X2129+47, appears to be a single object even at HST resolution, the other two fields yielded significant results. CAL 87 proves to consist of 3 stars within 1″, and at some wavelengths the optical companion of the X-ray source contributes only a minority of the total light during X-ray eclipse. Therefore previous ground-based inferences that the system has a large mass function, and perhaps contains a black hole, are now highly suspect. NP Ser, the widely cataloged counterpart of GX17+2, also remains a single image; but careful astrometry now indicates that it may not coincide with the non-thermal radio source that was the primary past evidence for the optical identification.

Further HST observations of the prototypical magnetic cataclysmic variable DQ Her were obtained by Silber, Anderson, Margon, and R. Downes (STScI). These data include the first UV observations through eclipse minimum. The UV continuum emission region is very compact, and is eclipsed only briefly; none of the emission lines are completely eclipsed. The UV continuum and emission lines also show sporadic 71 s pulsations, analogous to the well-known optical behavior. The mechanisms which determine the pulsation amplitude are clearly complex.

Wachter, Deutsch, Hughes, Margon, and A. Layden (McMaster U.) reported the recovery of QX Nor, the faint optical counterpart of the intense transient X-ray source 4U 1608-52. Data obtained in 1996 May and June show the object at $I=20$, about 2 mag fainter than during the last appearance in 1977. However, these recent observations are 2-3 months after the X-ray outburst, whereas the 1977 counterpart was observed only 1 month later; thus a similar maximum optical brightness at both X-ray outbursts is plausible. A search for short-term variability in about 10 nights of data is underway.

Wachter obtained a series of high resolution near-IR spectra of HZ Her, the optical counterpart of the pulsing X-ray source Her X-1, with the Apache Point 3.5m telescope. The goal is to redetermine the orbital velocity amplitude of the companion star, and thus the system masses, using the Ca IR-triplet, which is hopefully less distorted by X-ray heating than the more traditional blue spectral features usually employed for this task. Although several workers have very recently reobserved the orbit with spectral observations in the blue, there has surprisingly been no published velocity amplitude determination for the system since the invention of the CCD.

Deutsch, Anderson, Margon, and Downes discovered the probable optical counterpart of the intense bursting X-ray source in the core of the globular cluster NGC 1851, using multi-color HST imaging. The markedly UV-excess object with $B\sim21$, $(U-B)\sim-0.9$ lies only 2″ from the X-ray position. Previous inferences that some globular cluster X-ray sources are optically subluminous with respect to low-mass X-ray binaries in the field are now strengthened.

With this work in NGC 1851, less than a handful of the luminous ($L_x > 10^{36}$ erg s^{-1}) X-ray sources in globular cluster cores remain optically unidentified. Deutsch, Anderson, Margon, and Downes have also used HST to suggest a counterpart for one of these last few, specifically the source in the core of NGC 6441. Multicolor WFPC2 images reveal a markedly UV-excess object with $m_{336}=17.69, m_{439}=18.09$, well within the X-ray error box. As this cluster contains a large number of UV-excess objects of a wide range of luminosities (itself an interesting phenomena), there is a significant probability of a chance superposition of such an unrelated object in the X-ray box, and further observations will be needed to confirm the identification.

Anderson, Margon, Deutsch, Downes, and R. Allen (U. AZ) used HST Faint Object Spectrograph observations of the UV counterpart of the bright X-ray source in the core of the globular cluster NGC 6624 to discover a highly-statistically significant UV flux modulation with an 11.5 min (±0.2 min) period. This variation is consistent with the 685 s period of the known X-ray modulation. The ultraviolet amplitude is very large compared with the observed X-ray oscillations: X-ray variations are generally reported as 2-3% peak-to-peak, whereas their data show an amplitude of order 15 ± 4% in the range 125-250 nm. Although these UV oscillations have been theoretically predicted in this shortest known period binary star, due to the cyclically changing aspect of the X-ray-heated face of the secondary star, this predicted modulation has never before been observed.

D. Fox, W. Lewin (MIT), Margon, J. van Paradijs (U. Amsterdam), and F. Verbunt (Utrecht U.) obtained sensitive high resolution ROSAT X-ray observations of the globular clusters M13 and M92. The low luminosity ($10^{32.5}$ erg s^{-1}) source in M92, previously observed only with low spatial resolution, remains unresolved in these more sensitive data, contrary to the situation in many other clusters. In both clusters there is a high probability that further unresolved emission is present in addition to the known core sources.

Wallerstein extended his observations of the M supergiants in h and χ Per using the D.A.O. 1.2-m coude spectrograph to include lines of Al. Observations of O I and Na I lines will be obtained later this season. Observations of ^{12}C/^{13}C using near IR spectra of the CO bands, in cooperation with V. Smith (Univ. of Texas), will permit a detailed examination of mixing in these stars which show a wide range of Li I line strengths.

Wallerstein obtained high resolution spectra of moderate S/N, about 60, of two red giants in the globular cluster M54, one of the clusters associated with the recently discovered Sgr galaxy. They will be analyzed in cooperation with Brown for abundances of the elements.

Wallerstein extended his observational base of stars in the retrograde globular cluster NGC 3201. He now has high resolution spectra of 14 red giants for abundance analysis.

Boynton, in collaboration with J. Deeter has just concluded analysis of four years of *Ginga* pulse-timing observations of PSR B0540-69, commonly referred to as the 50 ms pulsar. This work has produced an improved estimate of the braking index, n = 2.080 ± .003. This analysis also provides the first clear indication that X-ray and optical pulses from this source are closely aligned in phase.

2.3 Interstellar Material and Ejecta

Balick, Hajian, Terzian, and A. Frank (U Minnesota) discovered additional faint halos around old planetary nebulae. The distances and expansion velocities of the halos are consistent with models of He-flash burning in the nuclei of PNe. They show how the angular spacing between the halos and interior shells can be used to derive unusually accurate distances to PNs – a long-standing observational problem.

Balick, J. Alexander, Hajian, Terzian, M. Perinotto (U. Firenze), and P. Patriarchi (Oss. Arcetri) have obtained WFPC2 images of planetary nebulae with high-velocity, low-ionization knots of gas on opposite sides of the central star (''FLIERs''). The narrowband WFPC2 images show that the paradigms suggested to account for the properties of FLIERs are highly suspicious. Quantitative analysis of the images is just starting.

Balick, Frank, and M. Livio (STScI) have shown on theoretical grounds that much of the microstructures in planetary nebulae whose origins have never been satisfactorily explained can develop during the cooler proto-PN phase of evolution. In this case the gas compressed by the wind will cool efficiently. If the geometry is slightly prolate, then winds are refracted into a converging streams at the ends of the ellipsoid. These streams will form ansae and jets with the observed properties. More detailed numerical models are in development.

Balick, A. Riera (U. Barcelona), G. Mellema (Stockholm Obs.) and Terzian took deep, long slit spectra of planetaries selected for their very strong nitrogen-to-hydrogen line ratios. Allegedly, these PNe are highly enriched in nitrogen owing to stellar processing. However, their spectra indicate that other elements, such as sulphur, are equally enriched. Since sulphur enrichment is unlikely in the parent stars, this result suggests that abundance measurement methods may be based on faulty assumptions.

Balick, Alexander, Riera, Mellema, and Dwarkadas are exploring the reality of large abundance variations reported in NGC 3242. They are using model nebulae (with assumed abundances) to generate synthetic data that match the long-slit observations of NGC 3242. The model results will be compared to the abundance based on direct observations in order to asses the systematic errors in the standard abundance estimation techniques.

Together with A. Noriega-Crespo (IPAC), Garnavich, A. Raga and J. Cantó (UNAM, Mexico), Böhm has studied the imaging of HH110 in the H_2 1-0 S(1) (2.121 μ) and 2-1 S(2) (2.248 μ) lines. A comparison of these images with those in [SII] 6716/6731 is used to show that the H_2 emission is generated in a turbulent mixing layer which is probably due to a grazing collision of the HH jet with a cloud core.

Böhm, together with A. Moro-Martin (Maria Mitchell Observatory), Noriega-Crespo and Raga, has made an attempt to explain the spatial dependence of the UV line intensities (obtained earlier with IUE) of HH objects in terms of simple bow shock models.

Böhm, together with Raga and Cantó, has produced a detailed compilation of the available optical spectrophotometric data of Herbig-Haro objects and used the result for a comparison with the predictions of the shock wave theory. They found that, though in general the agreement with the shock wave theory is reasonably good, there are serious discrepancies (for many HH objects) in explaining quantitatively the fluxes of the [SII] 6716/6731 lines and also the high ionization lines e.g. of [OIII], [NeIII] and [SIII]. Böhm and J. Solf (Tautenburg Obs.) have now completed their spectroscopic study of the peculiar Herbig-Haro object HH255 (''Burnham's nebula'').

D. Zucker, K. Olsen, Böhm and S. Curiel (UNAM) are studying the spatial variation of the shock conditions in the HH7-HH11 complex, using high resolution long-slit spectra from the APO 3.5m telescope and narrow band images from the Whipple Observatory 1.2m telescope.

Magnier continued his study of young stellar objects, including the remarkable object known as Holoaea, using the APO 3.5m telescope, as well as telescopes at several other observatories.

2.4 The Galaxy

Sullivan, with J. Cordes (Cornell), K. Wellington (ATNF), and P. Backus and S. Shostak (SETI Institute) analyzed the data from a June 1995 SETI experiment towards the galactic center region using the Parkes 64-m radio telescope. The Project Phoenix spectrometer was used to cover the range 1415-1435 MHz with a channel separation of 0.7 Hz. Altogether 190 positions over a 5.0×0.6 degree area were searched, but no ETI signals (pulses or narrowband) were detected.

Sullivan, with D. Werthimer and S. Bowyer (UCB), and D. Anderson and D. Gedye (Big Science, Inc.) worked on the development of an innovative SETI project that will involve massively parallel computation on desktop computers scattered around the world. A subsample of SETI data, as continuously being collected by Berkeley's Project Serendip at Arecibo, will be taped and broken down into small chunks for distribution over the Internet to whomever wishes to sign up. Individuals will download a screensaver program that will not only provide the usual attractive graphics when their computers idle, but will also perform sophisticated analysis of SETI data. Funding to develop the server and the software is currently being sought.

The University of Washington is a leading participant in the MACHO project, a search for Galactic dark matter via gravitational microlensing. Stubbs is one of the project's Principal Investigators, and graduate students M. Pratt and A. Becker work with D. Reynolds of the UW technical staff as members of the MACHO team.

The project uses a dedicated telescope at the Mount Stromlo Observatory in Australia and a dual color 32 Mpixel mosaic CCD camera to monitor over 20 million stars per night to search for the transient brightening that is the signature of gravitational microlensing. The data from the project are also of tremendous value in variable star studies, as described below.

The MACHO project published their microlensing results for the first two years of photometry of 8.5 million LMC stars, and reported 8 candidate microlensing events in the direction of the LMC. This greatly exceeds the ~1 event expected from known Galactic populations, and if taken at face value corresponds to a detection of half of the dark matter halo of our Galaxy, based on typical parameter assumptions. Of equal importance was the null result reported by the MACHO project: no microlensing events were observed with timescales of less than 20 days, and this essentially precludes a Galactic dark halo of objects with masses between 0.01 and 10^{-6} solar masses.

Along lines of sight towards the Galactic center the experiment is sensitive to lensing by disk objects, and the MACHO project has detected over 100 examples of this. The majority of these are now detected in real time, and they carry out coordinated follow-up observations (A. Becker) in collaboration with a number of observatories worldwide.

A number of the Galactic center lensing events exhibit ''light curve fine structure'' that arises when the point-deflector, point-source approximation breaks down. These exotic lensing events provide important constraints on the spatial, velocity and mass distributions of the lensing population. A. Diercks and Stubbs used the APO 3.5m telescope to determine radial velocities of lensed objects in the Galactic Center.

This past year has also seen the publication of a number of interesting variable star results from the MACHO data set. The structure of the Sagittarius dwarf galaxy was mapped with RR Ly stars, multimode LMC RR Ly stars were identified, and a set of eclipsing binary stars were extracted from the data set. Pratt is working to identify variable stars in binary systems by looking for time delays in their light curves.

The MACHO observations have been extended to run through the year 2000, and the UW participants look forward to continuing interesting results from the project.

2.5 External Galaxies and QSOs

Böhm-Vitense studied extragalactic distances obtained from Cepheid observations, adopting a period-luminosity relation, which is independent of the heavy element abundances Z. The consideration of the dependence of the B and V magnitudes on Z changes the derived interstellar extinctions and correspondingly the derived distance moduli. For the three M31 fields studied by Freedman and Madore, one then finds distance moduli, which agree to within 0.02 magnitudes.

Adopting a foreground reddening of E(B-V) = 0.8 for M31, the comparison of M31 and the LMC requires for the LMC Cepheids an average E(B-V) = 0.18.

Baum, Hammergren, and several HST–WFPC team colleagues are engaged in an intensive analysis of very deep WFPC2 exposures of IC 4051, which is a giant elliptical galaxy about 14′ from the center of the Coma Cluster. This is the second elliptical in Coma they have studied in an effort to measure the Hubble Constant using globular clusters as distance indicators, thereby directly linking the Coma Cluster to objects in the Milky Way without involving intermediate distance markers such as the Virgo Cluster. Coma has a mean redshift of $\sim$7200 km/sec relative to the cosmic microwave background and is $\sim$6 times farther than Virgo, so it offers an opportunity to measure the Hubble flow with less uncertainty due to local motions. Baum and Hammergren's data in IC 4051 reach a threshold of $V \approx 28.4$ mag, which is 0.8 mag fainter than they achieved last year in the Coma elliptical NGC 4881. Preliminary results for IC 4051 yield a Coma luminosity distance of 107 Mpc and a Hubble Constant $H_0 = 67$ km/s per Mpc.

Baum, Hammergren, and T. J. Kreidl (N. Ariz. Univ.) mapped the interstellar reddening and extinction in ''Baade's Window.'' Baade's Window lies only about 4° from the direction to the Galactic center, and is the prime field for observing the stellar population of the central bulge of the Milky Way.

Baum collaborated with S. Sakai (IPAC), B. F. Madore (IPAC), W. L. Freedman (OCIW), T. R. Lauer (NOAO), and E. A. Ajhar (NOAO) on analysis of deep WFPC2 observations in the halo of NGC 3379, which is the nearest giant elliptical galaxy. The tip of the red–giant branch implies a distance of 11.4 ± 1.3 Mpc and (after stepping out to the Coma Cluster) a Hubble Constant of 68 ± 13 km/s per Mpc.

Baum collaborated on an WFPC2 project led by C. J. Grillmair (JPL) for investigating the color–magnitude diagram of M32, the elliptical companion of M31. The red giants of M32 were found to have a broad color distribution, indicating a wide range of metallicities from [Fe/H] ≈ -1.5 at the blue edge to [Fe/H] ≈ -0.2 to $+0.1$ (depending on assumed age) at the red edge. Overall, the M32 color–magnitude diagram is consistent with an average luminosity–weighted age of 8.5 Gyr. No blue horizontal branch is seen.

Baum collaborated with D. A. Hunter (Lowell Observatory) and some HST–WFPC team colleagues on a 3–color (UVI) WFPC2 study of the intermediate mass stellar populations of NGC 206 which is a giant OB association in M31, and of NGC 604 which is a giant H II region in M33. The estimated mean age in NGC 206 is 6 Myr while that in NGC 604 is somewhat younger. In both cases the slope of the initial mass function was similar to that found for OB associations in the Milky Way and the Magellanic Clouds. Although NGC 206 is the most conspicuous star cloud in M31, its deprojected stellar density is 20 times lower than that of NGC 604 and is 3000 times lower than that of R136 (30 Dor) in the LMC.

Baum collaborated with WFPC team colleagues on two WFPC2 studies (now concluded) of four globular clusters in M31. One study headed by E. A. Ajhar (NOAO) pertained mainly to the color–magnitude diagrams, and the other study headed by C. J. Grillmair (JPL) pertained to the interpretation of their core radii and tidal radii.

N. Schartel (ESA), P. Green (CfA), Anderson, Margon, P. Hewett (IoA), C. Foltz (MMT), W. Brinkmann, H. Fink, and J. Trümper (MPIE) developed and applied a novel method to study the X-ray spectral properties of 908 QSOs in the Large Bright Quasar Survey that were observed in the soft X-ray ROSAT All-Sky Survey. Radio-loud QSOs show flatter X-ray photon indices, in agreement with previous work, and a flattening of X-ray spectral index of QSOs towards higher redshifts is also marginally confirmed. This latter effect is shown not to be due to an increasing fractional contribution from the class of radio-loud QSOs.

T. Wyder and Hodge determined a deep HII region luminosity function for the HII regions of M33 using KPNO 4-m CCD data. The material extends the luminosity function to levels nearly two orders of magnitude fainter than previously published and uses completeness corrections for the first time in this kind of analysis. As a by-product of the production of an identification atlas of M33, Hodge cataloged over 1000 new emission regions inthat galaxy, most of them too faint or small to have been detected earlier.

Magnier and Hodge used HST images to study several star formation regions in a northern arm area of M31. Ages were determined for the associations and for several young open star clusters, reddenings were measured and the recent star formation history was deduced.

With W. Waller, S. Heap, E. Malumuth (all at GSFC) and others, B. Skelton and Hodge continued their HST study of the stellar components of giant HII regions in M33. Skelton has recently obtained spectra at the APO 3.5m telescope of a sample of the bluest stars in these clusters in order to determine their temperatures and thus the number of Lyman continuum photons which they are emitting into their gaseous environment. She used the same telescope to observe these GHRs through narrow band interference filters to facilitate the correlation of the nebular properties with the stellar population of the ionizing cluster.

Skelton, with W. Waller (GSFC), has completed a study of the LMC bubble N70. The Fabry-Perot observations allow excellent spatial mapping of H-alpha, [NII]6584, [SII]6717,6731, and [OIII]5007 emission. Various wind and shock models are tested against the measured line ratios.

Zucker, Magnier, Skelton and Hodge are studying an anomalous superbubble in the periphery of M33 using long-slit spectra from the APO 3.5m and narrow-band images from the KPNO 4m telescope.

Hodge and Zucker have obtained spectra of several stars in IC 10 with the APO 3.5m telescope, searching for an identification of a X-ray source discovered by N. Brandt (CfA) and collaborators.

J. Collier, working with P. Battinelli (Obs. of Rome) and R. Capuzzo Dolcetta (U. of Rome) applied various statistical methods for automatic, impersonal identification of stellar associations in galaxies, especially the LMC.

With Gallagher (Wisconsin), T. Smecker-Hane (UC Irvine) and P. Stetson (DAO), Hodge studied the star-formation history of areas of the LMC, using data from the CTIO 1.5m telescope. The photometry reaches to below the oldest MS turn-off and indicates the presence of an old (at least 12 Gyr), relatively metal-rich component. It also confirms the well-known star-burst event dated at 2-3 Gyr ago.

In an HST collaboration with M. Mateo, N. Suntzeff, R. Schommer, A. Walker, and E. Olszewski, Hodge is measuring the ages of 5 of the oldest LMC globular clusters using

WFPC2 multicolor images. Olsen is using these images to study the LMC field stars to explore the early star-formation histories of different parts of the LMC.

Olsen is using the above material, together with various archival LMC HST images to measure the total extinction caused by the dust, as determined by photometry of galaxies seen through the Cloud. Many galaxies have been detected, including a compact cluster of galaxies, allowing a statistical determination of both the extinction and reddening.

Wyder, K. Krienke (Seattle Pacific U.) and Hodge are studying the distribution of ages of stars across the arms of the galaxy NGC 4321 using HST archival images. They find that the youngest stellar populations are found in the arms and just behind the arms, while the stars in front of the presumed density wave are generally older.

2.6 Cosmology

Quinn, J. Stadel, Katz and Lake have completed 47 million particle simulations of the Sloan Digital Sky Survey volume with various cosmological parameters. The dynamic range of these simulations is large enough to study the formation and structure of clusters (100 kpc) in a volume large enough to contain a fair sample of the Universe (1000 Mpc). Quinn, Lake, I. Szapudi (Fermilab) and A. Stebbins (Fermilab) are analyzing the large scale structure statistics of these simulations, such as counts-in-cells, high order correlation functions and weak lensing. M. Crone (Pittsburgh), Governato, Stadel, and Quinn are investigating how well cluster profiles in these simulations can be measured using weak lensing. Cluster maps made by weak lensing may be used to put constraints on cosmological parameters such as Ω.

Governato, Moore, Cen, Stadel, Lake and Quinn are looking at the dynamics of a Local Group as a test for cosmological models. They have made simulated catalogues of isolated Local Group size binary systems and binary systems close to Virgo size clusters. The small velocity dispersion around Local Group provides very strong constraints on cosmological models in that neither standard Cold Dark Matter ($\Omega=1$) nor open Cold Dark Matter ($\Omega=.3$) can produce a group that is embedded in a region with such small peculiar velocities.

Moore, Katz and Lake are continuing their work on ‘‘galaxy harassment’’ (frequent high speed galaxy encounters of galaxies in clusters). Previously, they showed that this effect was responsible for the blue galaxies seen in clusters at $z\sim0.4$. Recently, they completed a detailed comparison of the properties of the remnants with spheroidal galaxies in clusters. They are now studying methods of detecting the tidal debris in clusters of galaxies. This includes direct detection of the stellar debris using HST as well as the consequences of the stripped gas for X-ray emission from clusters.

Katz continued his work with L. Hernquist (UCSC), D. Weinberg (OSU) and others on simulating formation of quasar absorbers and creating synthetic spectra to test models statistically. They are pursuing a larger grid of models including different ionization histories, cosmologies, and abundances.

Ingram completed his thesis on starlight correlated with damped Lyman-α absorbers. Using the 3.5m for multislit spectroscopy, as well as multicolor optical and infrared photometry, he discovered a sample of galaxy images which are plausibly stellar populations associated with the damped absorbers in front of several quasars at high redshift. These will be used to constrain theories of galaxy formation and clustering.

Hogan, Anderson and Rugers obtained a high resolution HST spectrum of Q0302-003, which showed for the first time clear Lyman-α lines of HeII correlated with the HI Lyman-α forest. The discrete lines of the forest (with redshifts identified from a Keck spectrum of the same object) account for the main helium absorption edge and the bulk of the helium opacity near the quasar. The effects of the quasar on the surrounding gas were detected through its effect on helium ionization. Some flux was detected everywhere, setting an upper limit on the diffuse gas opacity. Lower and upper limits were placed on the density of diffuse gas, the background radiation spectrum and the helium abundance. These results are being compared with theoretical predictions of synthetic spectra generated in the cosmological simulations of Katz and collaborators.

Rugers and Hogan continued their studies of the cosmic deuterium abundance in quasar absorbers. A statistical study has confirmed that the cosmic abundance is fairly high, of the order of 10^{-4}, in keeping with the predictions of Big Bang cosmology. These results form the core of Rugers' Ph.D. thesis. Followup work with D. Norman includes using the simulations of Katz and collaborators to estimate the systematic biases in the technique of abundance estimation by Voigt profile fitting.

Norman and Impey are collecting a new sample of deep wide-field images to study the association of galaxies and background quasars caused by gravitational lensing.

Stubbs, Hogan, Reiss and Diercks have joined forces as part of a mulitnational effort to find and monitor type Ia supernovae at high redshift, in order to measure global spacetime parameters from their Hubble diagram. The UW contribution to this effort mainly involves measurement of light curves at Apache Point. The program has started successfully with the study of about a dozen supernovae out to a redshift of about 0.5.

Reiss, Hogan and Stubbs are working with B. Schmidt and L. Germany (Mt. Stromlo Observatory) to search for supernovae in Abell clusters. The objectives of the project are to measure the luminosity function of SNe, to explore the correlation of spectral characteristics and light curve shape with their absolute luminosity, to measure the bulk motion of the local group using SNe Ia as distance indicators, and to directly compare SN Ia distances with brightest cluster galaxy distances. This project has detected 7 supernovae to date.

2.7 Miscellaneous

Baum continued to serve on the HST-WFPC team, headed by J. A. Westphal (Caltech), of which Baum has been a member since its inception in 1977.

Margon continued as Chairman of the Board of Directors of the Association of Universities for Research in Astronomy (AURA). In the past year, a major transition has occurred to a substantially smaller Board, together with creation of a group, the Member Representatives, to more directly represent the interests of the individual AURA universities.

Sullivan continued as Chair of the AAS Historical Astronomy Division and Vice-President of IAU Commission 50 (Protection of Observatory Sites).

Stubbs was presented the Award for Initiative in Research by the National Academy of Science. He continues as a an Adjunct Fellow of the Mount Stromlo Observatory, as Deputy Director of the Center for Particle Astrophysics, as a member of the Gemini telescope CCD consortium, and as Telescope Scientist for the Apache Point 3.5m telescope.

Hogan, with G. Fuller (UCSD) and W. Haxton (UW Physics), organized a summer workshop at the Institute for Nuclear Theory on ''Nucleosynthesis in the Big Bang, Stars, and Supernovae,'' with about 70 visitors in residence.

Members of the department gave a series of public lectures, organized by Nelson and sponsored by the Walker-Ames fund, which were taped and widely broadcast on UWTV, NASA TV, and PBS.

3. RESEARCH TOOLS

3.1 Instrumentation

Balick, along with W. Kimura and G. Kim (STI Optronics) completed their studies of techniques that are used to clean large mirrors. This year's efforts centered on tarnish control of silver and the analysis of data obtained at Apache Point Observatory's 3.5m telescope. Ultraviolet laser cleaning of silver surfaces was found to be too close to the damage threshold to be useful. Optical cleaning (550 nm) worked nearly as well for most applications.

The UW Telescope Engineering Group (P. Waddell, E. Mannery, W. Siegmund, R. Owen, C. Hull, S. Limmongkol, and M. Evans) continue to provide the primary engineering support for the *Sloan Digital Sky Survey* 2.5m telescope, optics, structures, and portions of the multifiber spectrograph. Prominent milestones in the past year include the delivery of the primary and secondary telescope optics, as well as most of the complex correctors. First light is expected shortly.

Margon and Anderson are members of the *High Throughput X-ray Spectroscopy* mission study team, lead by H. Tananbaum (CfA) and N. White (GSFC). This study, selected in response to the NASA New Mission Concepts in Astrophysics opportunity, involves a very large area, broad bandpass, high spectral resolution facility for cosmic X-ray astronomy, based on six identical, modest satellites launched into solar orbit.

The spectrograph at the Apache Point 3.5m telescope was provided with a slit jaw viewing camera by Silber, Mannery, Hastings and Stubbs. A new wider field and higher sensitivity offset guider is presently under construction.

The experimental cosmology team was awarded a generous grant from the M. J. Murdock Charitable Trust for purchasing the critical components of an advanced wide-field mosaic CCD imager for the 3.5m telescope, and also received significant support from the NSF for its construction and operation. P. Doherty and Diercks delivered to the site and commissioned a prototype 2048$\times$2048 imager (the Seaver Prototype Imaging camera, ''SPIcam''). This instrument is being used for a variety of observational programs, and is serving as a prototype for the electronics and software for the full field imager that is under construction.

Stubbs is working with J. McCarthy and his colleagues at Caltech to develop a fast-guiding camera that actively moves the CCD within the dewar, using piezoelectric actuators. Preliminary tests on the Palomar 200 inch telescope produced a significant improvement in image quality.

3.2 Numerical Methods

Quinn and Stadel have implemented a parallel multi-step integration algorithm for cosmological N-body simulations which will run on massively parallel machines such as the Cray T3D and IBM SP-2. This is a first step toward implementing an efficient parallel smooth-particle hydrodynamics code.

Quinn continues to work with the team at Princeton University on the development of the photometric pipeline for the Sloan Digital Sky Survey. He has written a fast method for object classification that distinguishes between stellar, de Vaucouleur, and exponential profiles. For the galactic profiles, the algorithm gives a maximum likelihood estimate for the scale length, axis ratio, and orientation.

Craig J. Hogan, Chair