Yale University
Department of Astronomy

New Haven, Connecticut 06511

1. FOREWORD

The Department of Astronomy at Yale University is one of the oldest astronomy programs in the country, and has granted Ph.D.s since the nineteenth century. Yale has tradition strengths in stellar physics, stellar populations and astrometry, and newly invigorated programs in high-energy astrophysics and extragalactic astronomy and cosmology. The department is housed on the second floor of the Gibbs Laboratory in New Haven, Connecticut, and owns telescopes at Kitt Peak in Arizona and Cerro Tololo in Chile. The Yale Southern Observatory operates telescopes in Argentina, and Yale is part of consortium that operate telescopes in Venezuela and on Mt. Palomar in California. Yale also has a joint program with the University of Chile, through which researchers have access to the Chilean share of the many telescope facilities located in that country. Further information on all departmental activities can be found at http://www.astro.yale.edu.

Yale offers undergraduate and graduate degrees in Astronomy. We typically enroll 3-4 new graduate students studying for the PhD each year. Undergraduate majors have numbered between 2 and 7 per year in recent years. Remarkably, 18 out of the last 24 undergraduate majors have been women. The relatively small size of the undergraduate major and the graduate program allow an unusual level of personal attention from the faculty.

An event of particular importance over the past two years has been the founding of the Yale Center for Astronomy and Astrophysics (YCAA). This Center, directed by Prof. Meg Urry, is designed to bring together efforts in astrophysics underway in the Departments of Astronomy, Physics and Applied Physics at Yale. As part of the development of the YCAA, the Yale Department of Physics has initiated a major increase in its astrophysics group, including new faculty and post-doctoral positions. While this report is primarily focussed on the Department of Astronomy, it should be noted that considerable effort, particularly in astronomical instrumentation and cosmology, is being conducted at the YCAA outside the purview of the Astronomy Department proper. Many department members, including graduate students, are also members of the YCAA.

2. PERSONNEL

2.1 Yale Faculty

- Charles Bailyn (Chair) — Observational High Energy Astrophysics and Galactic Astronomy
- Charles Baltay* — Observational Extragalactic Astronomy and Cosmology
- Sarbani Basu (Dir. Graduate Studies) — Theoretical Solar and Stellar Physics
- Paolo Coppi — Theoretical High Energy Astrophysics and Extragalactic Astronomy
- Pierre Demarque (emeritus) — Theoretical Solar and Stellar Physics
- Jeffrey Kenney — Observational Extragalactic Astronomy
- Richard Larson (Dir. Undergraduate Studies) — Theoretical Galactic and Extragalactic Astronomy
- Priyamvada Natarajan — Theoretical Extragalactic Astronomy and Cosmology
- Peter Parker* — Nuclear Physics, Laboratory Stellar Physics
- Sabatino Sofia — Observational and Theoretical Solar Physics
- Jeffrey Snyder* — Astronomical Instrumentation, Observational Extragalactic Astronomy
- Andrew Szymkowiak* — Astronomical Instrumentation, Observational High Energy Astrophysics
- Meg Urry* — Observational High Energy Astrophysics and Extragalactic Astronomy
- William van Altena — Astrometry, Observational Galactic Astronomy
- Pieter van Dokkum — Observational Extragalactic Astronomy and Cosmology
- Robert Zinn — Observational Galactic Astronomy and Stellar Populations

(* = primary appointment in Physics)

2.2 Post-Docs and Research Staff 2003-4

Michelle Buxton, Eleni Chatzichristou*, Dana Dinescu, Gordon Drukier, Eric Gawiser, Terry Girard, Dorrit Hoffleit, Vladimir Korchagin, Linghuai Li, Nicholas Morgan*, Sean O'Brien, Katherine Rhode, Kenneth Rines*, Frank Robinson, Christian Straka, Rebeccah Winnick

(* = YCAA Fellow)

2.3 Graduate Students 2003-2004

Pedro Capelo, Bethany Cobb, Juan Cortes*, Hugh Crowl, Sonia Duffau*, Andres Escala*, Leonor Huerta*, Dipankar Maitra, Eric Murphy, Kwang-Ho Park, Ryan Quadri, Brooke Simmons, Ezequiel Triester*, Jeffrey van Duyne, Katherine Vieira, Jong-Hak Woo, Bing Zhao

(* = Yale/Chile joint graduate program)

3. FACILITIES

3.1 WIYN Telescope

Yale owns 1/6 of the 3.5m WIYN telescope, located at Kitt Peak Observatory in Arizona. This modern alt-azimuth telescope has exceptionally fine image quality, with a median delivered image quality of 0.7″. Current instrumentation includes the ''mini-mosaic'' imager, which covers a 10′ field, the Hydra Multi-Object Spectrograph, and the sparsepak and densepak fiber arrays. Yale researchers also use the Rochester Institute of Technology speckle interferometer at WIYN. Arrangements have also been made to borrow IR imagers. Current instrumentation plans include development of a high throughput spectrograph at Yale, and a One Degree Imager as a WIYN consortium project. Much of Yale's observing time at WIYN is devoted to graduate student research.

3.2 Joint Program with the University of Chile

Yale and the University of Chile have established a Joint Program in education and research in Astronomy. The research program provides for the creation of joint projects involving researchers from both institutions. Through these joint projects Yale researchers have access to the wide range of astronomical instrumention in Chile, including the European VLT, and telescopes at CTIO, Las Campanas and La Silla. Current joint projects include the MUSYC Deep Surveys project, the Local Group group, and a smaller project on active galactic nuclei.

3.3 SMARTS

Yale has a 14% share in the SMARTS consortium, which operates four small telescopes, including the Yale 1m telescope, at Cerro Tololo Interamerican Observatory in Chile. Yale faculty member Charles Bailyn serves as principal scientist of the SMARTS consortium. In 2004, it is expected that the SMARTS instrumentation configuration will include the CTIO 0.9m + 2K CCD; the Yale 1.0m + 4K CCD; the 1.3m (2MASS) telescope + ANDICAM dual channel optical/IR imager; and the CTIO 1.5m + RC spectrograph and 2K IR imager.

3.4 Yale Southern Observatory

The Yale Southern Observatory operates the 51-cm double astrograph at Cesco Observatory in El Leoncito, Argentina. CCD observations have now begun with this facility, which is primarily used by the Yale astrometry group, directed by Prof. van Altena. Major improvements in hardware and software have greatly increased the efficiency of this facility over the past year.

One of the original instruments of the YSO, the Schlesinger 26-inch refractor was destroyed by a firestorm on January 18, 2003, along with the other telescopes on Mount Stromlo, the workshop, library and many of the residences. This event was a sad ending to a telescope that played a major role in defining our knowledge of the distances, motions and masses of the brighter stars during the middle of the 20th century. van Altena and Hoffleit (2003) have summarized the history of Schlesinger's telescope.

3.5 QUEST

The QUEST group, under the direction of Prof. Charles Baltay, has built two large astronomical imagers over the past few years. The first is operating on the 1m Schmidt telescope at the Venezuelan national observatory at Llano del Hato. The second is now in operation at the 1.5m Schmidt telescope at Mt. Palomar, as part of a consortium including Yale, Caltech, and JPL. In driftscan mode, this camera can obtain four-color data down to 19th magnitude over > 300 square degrees in a single night.

3.6 Computing

In addition to an extensive network of linux workstations, the department is a major player in a university-wide high-performance computing cluster now under construction. Further details can be obtained from Prof. Paolo Coppi.

4. SCIENTIFIC ACCOMPLISHMENTS

4.1 Astrometry

van Altena continued speckle interferometry at the WIYN telescope in collaboration with E. Horch (U. Mass Dartmouth) and Z. Ninkov (Rochester Institute of Technology). Yale Graduate student R. Meyer received his Ph.D. for a dissertation on binary star photometry, based on speckle interferometry. The observations at WIYN during the last years are a part of our long-term effort to provide high-precision relative astrometry of binary stars. Relative astrometry has now been published for nearly 800 speckle observations at WIYN. A second major speckle program involves observing Hipparcos double star discoveries since the publication of the Hipparcos Catalogue (ESA, 1997). Of the targets observed, a substantial fraction of the Hipparcos stars observed have exhibited large changes in separation and/or position angle since the Hipparcos observation (1991.25). To date 23 Hipparcos doubles with probable or definitive orbital motion have been discovered. An NSF award has just been made to Horch, van Altena and Ninkov (RIT) to use the existing WIYN speckle archive in addition to new observations and other information in the literature to investigate the statistics of binaries in the nearby region of the galaxy.

Recent advances in understanding the nature of ω Centauri - the most massive Milky Way globular cluster - have now placed on a firmer ground its accretion origin as opposed to formation within the Milky Way. Unlike the majority of the Milky Way globular clusters, ω Cen is a complex chemical system with an extended star formation history. Korchagin and Dinescu, in collaboration with T. Tsuchyia of the Astronomishes Rechen-Institut, have explored an accretion origin for omega Cen by N-body modeling of the orbital decay and disruption of a Milky-Way dwarf satellite. A range of models with two different density profiles for the satellite, (King and Hernquist), were used in the analysis. It was found that a capture scenario can produce an ω Cen-like object, exhibiting the current low-energy orbit of the cluster. The best model is a nucleated dwarf galaxy with a Hernquist density profile that has an initial mass of $8 \times 10^9\ M_\odot$, and a half-mass radius of 1.4 kpc.

The Southern Proper Motion (SPM) Program continued, on several fronts, under the supervision of van Altena with significant effort from Girard and Dinescu, as well as Carlos López of the Universidad de San Juan, Argentina and Paulo Holvorcem of the Universidade Estadual de Campinas, Brazil. CCD observations have begun using the 51-cm double astrograph at Cesco Observatory in El Leoncito, Argentina. These will eventually fill in the approximately two thirds of the SPM survey region for which second-epoch photographic observations do not exist. A new version of the SPM Catalog has also been released this year, one which is based solely on photographic material, as in previous versions. However, this version, the SPM3 Catalog, is near-complete to V=17.5, and contains absolute proper motions, positions, and B and V photographic photometry for 10.7 million objects in the Southern sky. The SPM3 Catalog is available at www.astro.yale.edu/astrom/.

Based on SPM plate material, absolute proper motions of 4 globular clusters (NGC 6266, NGC 6304, NGC 6316, and NGC 6723), located in the bulge region, have been determined with uncertainties ranging between 0.3 and 0.6 mas/yr. The absolute proper motions are on the Hipparcos system, and, in combination with distances and radial velocities already published, yield space velocities. Interestingly, only NGC 6723 of the two metal-poor clusters has kinematics consistent with halo membership, while that of NGC 6266 indicates membership to a rotationally supported system of the thick-disk type. The kinematics of the two metal-rich clusters are consistent with their metallicity-based bulge membership, however NGC 6304 seems to have significant rotation, more closely resembling the thick disk, rather than the bulge.

Girard, Korchagin, and van Altena submitted 88 minor-planet position measurements to the Minor Planet Center, based on observations with the YALO 1-m telescope at CTIO. This is part of a NASA-funded program at Yale to make Southern-sky observations of Near Earth Objects. This program is continuing, using the SMARTS 1.3-m telescope at CTIO.

4.2 Stellar Populations and Galactic Astronomy

The research of Robert Zinn concentrated in two areas: the stellar populations of the satellite galaxies of the Milky Way and the detection of substructure in the Milky Way's halo. The major goals were to document the star formation and chemical enrichment histories of dwarf galaxies and to determine whether the galactic halo contains stellar streams from disrupted satellite galaxies. As part of the Yale-U. de Chile joint project on the Local Group galaxies, both spectroscopic and photometric observations of the Fornax dwarf spheroidal (dSph) galaxy were obtained with 8m VLT. Color-magnitude diagrams that extend ~ 2 magnitudes below the main-sequence turnoff of the oldest stars were constructed for three fields in Fornax. The spectroscopic observations of 117 red giants at the infra-red Ca II triplet reveal a surprisingly large variation in Ca II line strength. The colors of the red giants of the highest metallicities are much bluer than the colors of very old red giants of the same metallicity, such as the ones in galactic globular clusters. This indicates that the metal-rich Fornax stars are considerably younger. An age-metallicity relation was constructed from the combination of the spectroscopy of the red giants and the deep color-magnitude diagrams. It suggests that the metallicity of Fornax climbed quickly to $[Fe/H] \sim -1$ when Fornax formed and then rose more slowly over the past ~ 10 Gyrs.

Zinn also participated in the QUEST survey in Venezuela, searching for RR Lyrae variables. This effort constituted the Ph.D. thesis of A. Katherina Vivas. 380 sq. deg. of the sky were surveyed for these stars in a band 2.3° wide in declination, centered at dec. $= -1°$, and covering ~ 11 hours in right ascension. The bright (due to CCD saturation) and the faint limits of the survey are V ~ 13.5 and ~ 19.7 respectively, which correspond to distances of ~ 4 and ~ 60 kpc from the Sun. A total of 498 RR Lyrae variables were discovered in the survey, 86% of which are new. This survey has identified several substructures in the galactic halo that may have been produced by the tidal disruptions of satellite galaxies or globular clusters. The most prominent feature is a clump of about 80 RR Lyrae variables at roughly 50 kpc from the Sun. This feature, which is about 30 kpc long, is part of the northern tidal stream from the Sagittarius dSph galaxy, which had been detected previously in other types of surveys. Other features have also been identified.

A large program to measure the radial velocities and the metallicities of the the RR Lyrae variables in the most conspicuous features revealed by the QUEST survey was begun as part of the Yale-U. de Chile project on the Local Group. Observations have been obtained with the 8m VLT, the 1.5m ESO, the 3.5m WIYN, and 1.5m CTIO (SMARTS) telescopes. The VLT observations have shown that the radial velocities of the RR Lyrae variables in the 50 kpc clump (see above) are in good agreement with the predictions of models of the tidal streams from the Sgr dSph. The WIYN observations were obtained at the infra-red Ca II triplet during the same observing runs as some of the observations of the Draco and Ursa Minor dSph galaxies. Graduate student Sonia Duffau, Zinn, and Vivas have developed a technique to measure the metallicities of the stars using the Ca II lines, which are blended with Paschen series hydrogen lines, and unblended Paschen lines as a temperature index.

Winnick completed her PhD thesis under the direction of Zinn, and continued to work at Yale as a SMARTS post-doc. Using the 3.5m WIYN telescope and the Hydra multiobject spectrograph, she measured the metallicities of numerous stars in three nearby dwarf spheroidal galaxies. The large samples of stars in each of Draco, Ursa Minor and Sculptor allow a more detailed study of the metallicity distributions. Despite similar abundance spreads, each galaxy exhibits a different distribution. The differences suggest that star formation and chemical enrichment processes proceeded somewhat differently in these galaxies.

Also as part of the Calan-Yale Local Group Key Project, Demarque has published three papers on LMC cluster CMD's, based on VLT photometry. The first paper (Gallart *et al.* 2002) presents the observations. For comparison, two independent analyses, one using the Yale models (Woo, J.H. *et al.* 2002), the other using the Padua models (Bertelli *et al.* 2002), Papers 2 and 3 respectively, were made.

Drukier, Bailyn, van Altena, and Girard finished their study of the proper motions in the center of the globular cluster NGC 6752. The resulting central velocity dispersion for this unusual cluster is about 12 km s^{-1}, indicating a higher-than-expected central mass-to-light ratio. In connection with this Drukier and Bailyn have estimated the number of high-velocity stars to be expected in the central part of globular cluster hosting a massive black hole. They have begun reduction of HST data with the aim of testing this hypothesis.

Graduate student B. Zhao continued his Ph.D. thesis research with Bailyn on binary stars in globular clusters. By analyzing HSF images of the cores of clusters, Zhao has demonstrated interesting differences in the binary populations of M3 and M13, a so-called ‘‘second parameter’’ pair of clusters, similar in most respects, but quite different in horizontal branch morphology. The techniques thus developed are now being extended to 47 Tucanae.

Korchagin, Girard, Dinescu and van Altena in collaboration with T. Borkova from the Institute of Physics, Rostov University, Russia, re-estimated the surface density of the Galactic disk in the solar neighborhood within $\pm$ 0.4 kpc of the Sun using parallaxes and proper motions of a kinematically and spatially unbiased sample of 1476 old bright red giant stars from the Hipparcos catalog which have measured radial velocities. The vertical distribution of the sample together with its accurately measured velocity dispersion combine to yield a determination of the surface density of gravitating matter in the Galactic disk as a function of the Galactic coordinate *z*. The surface density of the disk increases from $10.5 \pm 0.5\ M_{\odot}$ / pc^2 within $\pm$ 50 pc to $42 \pm 6\ M_{\odot}$ / pc^2 within $\pm$ 350 pc. The estimated volume density of the Galactic disk within $\pm$ 50 pc is about 0.1 $M_{\odot}$ / pc^3 which is close to the volume density estimates of the observed baryonic matter in the solar neighborhood.

Korchagin in collaboration with N. Orlova (Institute of Physics, Rostov University, Russia), S.M. Miyama and N. Kikuchi (National Astronomical Observatory, Tokyo, Japan) and A. Moiseev (Special Astrophysical Observatory, Russia) have tested the applicability of the global modal approach in the density wave theory of spiral structure for a sample of spiral galaxies with measured axisymmetric background properties. Using the observed radial distributions for the stellar velocity dispersions and the rotation velocities, they have constructed equilibrium models for the galactic disks in each galaxy and implemented two kinds of stability analyses - the linear global analysis and 2D-nonlinear simulations. In general, the global modal approach is able to reproduce the observed properties of the spiral arms in the galactic disks. The growth of spirals in the galactic disks can be physically understood in terms of amplification by over-reflection at the corotation resonance. The results support the global modal approach as a theoretical explanation of spiral structure in galaxies.

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4.3 Solar Physics

Investigations into solar physics are conducted at Yale by faculty members Sofia, Demarque and Basu, and research staff Li and Robinson. Two principal objectives guide the solar research in our department. One, is to determine and understand the details of the structure and dynamics of the solar interior. The second is to determine internal variability mechanisms that change the structure and the global parameters of the Sun (mainly luminosity) and may have significant consequences for climate change and other terrestrial phenomena. To accomplish these tasks, we use primarily theoretical tools, which we complement with the helioseismic analysis and interpretation of data available from space-based and from ground-based observatories. For the case of one specific global parameter, the solar diameter, which our studies suggest to be critical, but for which at the present time no adequate national or international observational program exists, we have established our own program to fill in this lacuna. This is a balloon-based observational program, called the Solar Disk Sextant (SDS) that we have been pursuing in collaboration with the NASA/Goddard Space Flight Center for the last 20 years, and more recently, in collaboration with colleagues at the University of Rome at Tor Vergata. Since one of main uncertainties in solar and stellar models is that which results from the incomplete treatment of convection, we perform full, compressible, three-dimensional simulations of convection to study the properties of convective transport in the Sun and other stars at different states of evolution.

Helioseismology: We have been studying the structure and dynamics of the Sun using data from both the Global Oscillation Network Group (GONG) project and the Michelson Doppler Imager (MDI) on board SOHO. We find that although solar frequencies change with solar activity, there is no observable change in the structure of the inner layers of the Sun, the evidence points to changes only in the outer 3-4% i.e., in the near-surface layers. Solar dynamics however shows considerable change — solar zonal flows from the mid-latitude regions converge towards the equator as solar activity increases, while the high latitude flows moved towards the poles. The meridional flows changed too — the maximum flow velocity decreased with increase in solar activity. We have paid particular attention to studying the base of the convection zone, where the solar dynamo is believed to be located. We find that there is no significant temporal variation in the depth of the convection zone. This implies that any variation in the magnetic field at base of the convection zone has to be small. We do not see any significant temporal variations in the dynamics of this region (the ‘tachocline’) either.

Using local helioseismic techniques we have investigated the differences in the acoustic properties of solar active regions. Frequencies of acoustic oscillations are higher in active regions when compared to those in the quieter regions of the Sun. On inverting the frequency differences between active and quiet region, we find that active regions have lower sound-speeds (and hence temperature) than quiet regions immediately below the surface, but the sound-speed (and temperature) rises sharply in the active regions at depths below 5-7 Mm. We have also studied the evolution of active regions that produce flares. We find that in most cases, during the period of high flare activity, power in acoustic modes is larger compared to that in a non-flaring region active region of similar magnetic field strength.

Solar Variability Models: The main purpose of monitoring the solar-cycle related changes in the Sun is ultimately to try and understand what causes the changes. To this effect we have been constructing solar models that include magnetic fields as a part of the structure equations. We therefore, do not treat the effects of magnetic fields as a perturbation on the structure of a non-magnetic star. We have looked at the effect of placing magnetic fields of various strengths at different depths inside the Sun, and compared the results with observations related to the irradiance, effective temperature and frequency changes in the Sun as a function of activity. Given that most evidence points to changes taking place in the outer layers of the Sun, we have paid particular attention to convection and turbulence. Our best models include properties of convection and turbulence as obtained from 3-D simulations of convection in the outer layers of the Sun. We find that a variable magnetic field is not enough to reproduce the observable solar cycle related changes in the Sun. While the irradiance and effective temperature variations can be reproduced by many magnetic-field configurations, the changes in the oscillation frequencies are not easy to reproduce. A variable magnetic field at the base of the convection zone that can reproduce the observed irradiance and temperature changes produces observable changes in the position of the base. Such changes are not seen in the Sun. Additionally, the frequency changes are not reproduced. The shape of the frequency changes as a function of frequency requires a shallow magnetic field. However, this does not reproduce the sign of the changes. Observations show that solar frequencies increase with increase in activity, while in the models an increase in the magnetic field led to decrease in frequencies. We find that a crucial role is played by turbulence in the sub-surface layers. To reproduce the sign of the frequency change, we need to introduce a negative feedback between turbulence and magnetic fields. A negative feedback is not surprising since magnetic fields are known to inhibit turbulence. We are currently in the process of developing codes to construct two dimensional solar models that will enable us to test more realistic magnetic field configurations.

The SDS Program: During this past year we have been developing sophisticated techniques to analyze data obtained during all the past flights of the SDS for which the instrument had acquired the final stable configuration. Those flights occurred in 1992, 1994, 1995, 1996, and 2001. We find that the solar diameter during the descending phase of the activity cycle was increasing. Although the phase of the increase agrees with the result from the analysis of the f-mode oscillations, the magnitude is substantially larger. Although both experiments measure the radius changes at different solar layers, it will be interesting to understand those different results.

Convection Simulations: In the case of the Sun we find that the mixing length theory breaks down within about 1000 Km of the solar surface. By putting the turbulent pressure and kinetic energy from the 3D model back into the 1D stellar evolution code, we find that the re-computed adiabatic p-mode frequencies were a better match to the observed values. We also find that the auto-correlation length of the vertical velocity provides a well defined vertical length scale for the solar granules. Extending our ideas to the evolved Sun at 11.3 and 11.6 billion years, we find that the horizontal size of the granules are larger. By extrapolating our result to a supergiant such as Betelgeuse, we tentatively estimate about 600 granules would occupy the surface of a supergiant such as Betelgeuse. This is in rough agreement with the spectral observations by (D.F. Gray 2000, ApJ, 532, 487).

4.4 Stellar Physics

Basu and Sofia have been a program of theoretical research into asteroseismology. This work has been made very relevant by the recent success in observing stellar oscillations from the ground and by the launch of space missions. We have been concentrating on trying to determine what we can learn about stellar parameters using low-degree oscillation modes. We find that we can do reasonable inversions to find the sound-speed profile of stellar cores. We also find that it is possible to determine the envelope helium abundance of low-mass stars using low degree modes. For frequency errors of 1 part in 10^4, we expect errors σ_Y in the estimated helium abundance to range from 0.03 for $0.8M_\odot$ stars to 0.01 for $1.2M_\odot$ stars. The task is more complicated in evolved stars, such as subgiants, but is still feasible if the relative errors in the frequencies are less than 10^{-4}.

Demarque's work on the Yale-Yonsei (Y^2) isochrones has continued, following up on Paper 1 which contains isochrones and luminosity functions for the scaled solar abundances (Yi, Demarque, Kim, Lee, Ree, Lejeune & Barnes 2001, ApJS 136, 417, 2001). Paper 2 (Kim *et al.* 2002), which contains isochrones for mixtures in which α-enhanced elements have twice and four times the solar abundance), and Paper 3 (Yi *et al.* 2003), which contains evolutionary tracks, have recently been published. Paper 4, which deals with the treatment of convective core overshoot in the isochrones, is being prepared for submission. Work is proceeding on extending the isochrone tables to different helium abundances and on updating the equation of state at the low mass end.

The isochrone tables, together with interpolation programs, are available on the web at the address http://www.astro.yale.edu/demarque/yyiso.html. A web interface for the CMD synthesis code based on the Y^2 isochrones, written by graduate student J.H. Woo, is under construction with the help of graduate student Eric J. Murphy.

Christian W. Straka, a visiting postdoctoral fellow from Heidelberg, is investigating the signature of convective core overshoot on the seismic properties of stars near the main sequence. He is focussing on Procyon, a star on the first target list of the asteroseismic space mission MOST. Straka has implemented the Kuhfuss (1986, A&A, 160, 116) theory of core overshoot in the Yale stellar evolution code and compared the predictions with other simpler core overshoot prescriptions.

Also, in anticipation of the MOST observations, evolutionary interior models have been constructed by graduate students Eric J. Murphy (51 Pegasi) and Bethany Cobb (τ Ceti), and their pulsation properties have been calculated. Demarque is currently implementing in these models the effects of turbulence on the pulsation frequencies, starting from the 3D simulations of Robinson *et al.* (2003), and using the formalism of Li *et al.* (2002).

Sean O'Brien continued his work on variable and binary stars, including time-series spectroscopy obtained with the Hubble Space Telescope and Keck, and time-series photometry obtained with the Whole Earth Telescope collaboration. He was also awarded HST time to measure the parallax distance to a neutrino-luminous white dwarf. The ultimate goal of this work is to test lepton theory in dense plasma by using information from pulsation to determine the neutrino luminosity of hot white dwarf stars. O'Brien is also studying the results of LMC microlensing events reported by the MACHO collaboration, to determine whether the events are best explained by a hypothetical population of white dwarfs in the galactic halo or low mass stars within the LMC itself. Yale undergraduate student Meredith Hughes is assisting with this research.

Coppi, Larson and former student Volker Bromm continued their collaboration on understanding primordial star formation. Using an adaptive refinement method developed in his thesis, Bromm carried out a new high resolution simulation of accretion onto a primordial protostar which adds more support to the hypothesis that the very first stars were massive. Bromm received the 2002 Trumpler (Astronomical Society of the Pacific) prize for his work on primordial star formation.

4.5 High Energy Astrophysics

Observational and theoretical research into High Energy Astrophyiscs is carried out at Yale both in the Department of Astronomy, and at the YCAA. Here we describe the research carried out in the department. We note that a very significant effort in Active Galactic Nuclei is being conducted by Meg Urry and her associates in the YCAA, and there is close collaboration between the YCAA and astronomy department members in this area.

Bailyn continued research into black hole candidates and other X-ray binaries. Much of this research centers on SMARTS data from the optical and infrared (OIR) counterparts of these sources. Daily OIR observations are being obtained from over a dozen soft X-ray transients, many of which are dynamically confirmed black hole candidates. Recent highlights of this work include the following.

1) The discovery of an IR reflare coincident with radio emission in the 2002 outburst of black hole candidate 4U1543-47. No X-ray emission was observed at the time, suggesting that this radiation may be synchrotron emission associated with the formation of a radio jet.

2) The 4-year lightcurve of neutron star transient Aql X-1, which has revealed the presence of short ''mini-outbursts,'' which may be interpreted as instability events that start on the inside of the accretion disk and propagate outwards, in contrast to the traditional ''outside-in'' instabilities that trigger X-ray outbursts.

3) Intensive study of the 2003 outburst of the black hole binary V4641 Sgr, which included simultaneous X-ray observations with RXTE and optical observations obtained by A. Chen at the Lu Lin observatory in Taiwan. The X-ray and optical lightcurves were strongly correlated, with the optical delayed by ≈ 25 seconds from the X-rays, strongly implying an origin as reprocessed X-rays.

D. Maitra has begun PhD thesis work under Bailyn's direction, focussing on state changes in X-ray binaries. A paper has been submitted studying in detail the 2001 outburst of Aql X-1, demonstrating clearly that the sequence of X-ray states is somewhat different during the rise as compared to the decline of the outburst.

Post-doc Buxton and Bailyn, along with undergraduate L. Jeanty, are investigating whether the MACHO database can reveal X-ray binaries in quiescence. A series of criteria have been developed to identify potential quiescent X-ray binaries, and promising candidates will be followed up spectroscopically with the WIYN and other telescopes in the future.

Bailyn and van Dokkum have established a collaboration with J. Bloom (CfA) to use the SMARTS telescopes to study the optical/IR afterglows of gamma-ray bursts. The ability to carry out target of opportunity observations in the optical and IR simultaneously from an excellent southern hemisphere site makes SMARTS potentially an excellent facility for this purpose. The first fruits of this effort were a study of GRB 030329, which demonstrated that the absorption from the host galaxy was $<0.3A_V$ (Bloom *et al.* 2003).

Coppi obtained Chandra time to follow up four of the most powerful, narrow-lined $H\alpha$ emitting objects found in the QUEST objective prism survey of 700 square degrees of equatorial sky down to R=19. All objects were detected, but proved to be extremely faint with soft spectra. This result indicates very obscured AGN activity or unusually powerful star formation activity. In either case, these objects are part of a new class of X-ray emitting objects whose $H\alpha$/X-ray emission characteristics lie very far from the correlation between $H\alpha$ luminosity and X-ray emission established by ROSAT.

Together with post-doc Henric Krawczynski, Coppi obtained 700 kilosec of target-of-opportunity (TOO) time on the RXTE X-ray satellite for simultaneous X-ray/TeV observations of TeV blazars. All TOO's were triggered and successfully carried. The most intriguing result was the discovery of an ''orphan'' gamma-ray flare that had no counterpart at X-ray energies, contrary to the predictions of the standard synchrotron-self Compton (SSC) models. Together with Krawczynski and Felix Aharonian (MPIK, Heidelberg), Coppi also carried out a detailed SSC modeling analysis of X-ray/TeV data from the 1997 outburst of Mkn 501. The results strongly suggest that a non-variable, soft X-ray component needs to be considered in future TeV blazar modeling and also raise significant questions about the overall SSC model because of the extreme model parameters found.

Graduate student Maccarone completed and published his thesis with Coppi on spectral and timing constraints on models for galactic black hole binary sources. Maccarone's discovery of a hysteresis effect in the outburst of both neutron star and black hole system drew considerable attention. The results suggest that a common mechanism is responsible for the state transitions in both systems, and that source luminosity, i.e., accretion rate, is not the only quantity responsible for determining which X-ray emission state a black hole finds itself.

Coppi, Larson and graduate student Andres Escala initiated a collaboration to study the impact of gas on the merger of massive black holes using the GADGET smooth particle hydrodynamics (SPH) code. Simulations of galaxy mergers that do not include gas show that while the central black holes of the merging galaxies often move rapidly to the center of the merged system, the black holes can ''hang up'' and form a long-lived binary. Preliminary results from this study were presented at a press release at the May 2003 AAS meeting and indicate that the presence of gas can have a very important effect, allowing the coalescence of the black hole binary to proceed rapidly. This has important implications for supermassive black hole formation scenarios, and the gravitational wave signal rate expected for the LISA space mission.

4.6 Extragalactic Astronomy and Cosmology

Very substantial work in this area is conducted in the YCAA. Meg Urry is a major player in the GOODS survey, which is the focus of PhD thesis work by Astronomy Department graduate students B. Simmons, J. van Duyne and J.-H. Woo. The QUEST group also works out of the YCAA. Below we describe in more detail research being conducted primarily in the Department of Astronomy.

A major effort involving many members of the department, including faculty members Coppi and van Dokkum, and post-docs Castander and Gawiser, and graduate students Quadri and Triester, has been the Yale-Calan Deep Survey collaboration, now called MUSYC. This is the largest of the joint projects between Yale and Chile, and has obtained significant amounts of telescope time to carry out its square degree, ''Phase II'' multi-band imaging (U,B,V,R,I,Z,J,K) and spectroscopy survey. The ''Phase I'' version of the Yale-Calan survey, now completed, followed up faint Chandra X-ray sources in the optical and near infrared. The survey discovered one of the first X-ray selected, optically faint AGN at high redshift ($z=4.2$). Recently, the survey has discovered another at redshift $z=4.6$. A detailed description of this project can be found at http://www.astro.yale.edu/dept/research/calan/deepsurvey.html.

van Dokkum's research focuses on observational studies of the formation and evolution of galaxies, using the Hubble Space Telescope and a large range of ground based facilities. Current projects include studies of a newly discovered population of red galaxies at very high redshift. He is co-PI of the MUSYC survey, a joint project of the Universidad de Chile and Yale, which encompasses a broad range of projects utilizing the excellent telescopes in Chile.

Post-doc Gawiser's work also focussed on the MUSYC survey, with a particular emphasis on optical spectroscopic followup. By studying quasars, Lyman break galaxies, Lyman α emitters, and damped Lyman α absorbers, all of which represent families of protogalaxies selected in different ways, he hopes to determine the extent to which these different types of protogalaxies overlap and cluster with each other.

Natarajan is conducting a wide range of research into theoretical extragalactic astronomy and cosmology, including the following:

1) Gravitational Lensing: combining strong and weak lensing analysis techniques; use of lensing as a probe to study galaxy evolution in clusters via local weak shear effects; weak lensing by large-scale structure; using lensing as a probe of the shapes of dark matter halos; and understanding intrinsic correlations in the shapes of galaxies.

2) Clusters of Galaxies: using lensing, X-ray and Sunyaev-Zeldovich data in conjunction to study the dynamics of galaxies in clusters; velocity anisotropy of galaxy orbits; characterizing cluster growth and evolution in phase space and physics of the relaxation process.

3) Accretion physics: issues of the alignment of the spin of disks and the central black holes; the evolution of warped accretion disks; Lense-Thirring precession; the Blandford-Znajek mechanism, and the accretion history of supermassive black holes.

4) Issues in galaxy formation and the fueling of quasars: the connection between high redshift galaxies, active galactic nuclei and their central black holes; the black hole mass function; role of quasars and their outflows in galaxy formation; kinematic Sunyaev-Zeldovich effect from quasars; the physics of feedback processes in galaxy formation; stellar contributors to the X-ray background and the evolution of neutral gas with redshift.

5) Binary Black Holes: the merger and evolution of supermassive black hole binaries in gas-rich galaxy cores; the electro-magnetic and gravitational wave signatures from these systems; the implications for structure formation at high redshifts.

Kenney continued to work on dynamics and star formation of the inner regions of galaxies, and on the effects of environment on the evolution of galaxies. Much of this work focussed on obtaining a detailed understanding of particular galaxies in the Virgo cluster. Observations with the WIYN telescope, and with the Owen's Valley millimeter wave interferometer are of particular importance. Graduate students Crowl and Murphy are beginning thesis work in this area, under Kenney's direction.

Rhode completed her PhD thesis under the direction of Bailyn and former faculty member Zepf (now at Michigan St) and continued work at the department as an NSF fellow jointly at Yale and at Wesleyan University. Her thesis work was a survey of globular clusters in elliptical and spiral galaxies outside the Local Group. The survey combines images from the WIYN and Mayall telescopes at KPNO with archival HST data to study the global properties of the galaxies' globular cluster systems. With advisors Stephen Zepf (Mich. State) and Charles Bailyn, Rhode quantified the total numbers, spatial and color distributions of globular clusters in each galaxy, in order to test models of galaxy formation. Futre efforts will focus on spectroscopy to study the kinematics of globular clusters in massive galaxies, and also investigate the connection between low-mass X-ray binaries and globular clusters using optical images and data from the Chandra X-ray telescope.

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