The University of Oklahoma
Department of Physics and Astronomy

Norman, Oklahoma 73019

This report covers the period September 2002 through August 2003 and comprises an account of astronomical research carried out in the Department of Physics and Astronomy.

1. INTRODUCTION

Seventeen years before Oklahoma became a state, the University of Oklahoma was founded by the first legislature of the Territory of Oklahoma. The first classes were held in 1892 with 119 students and four faculty members. More than 100 years later, OU enrolls more than 27,000 students and has approximately 1,830 full time faculty. The Department of Physics and Astronomy was founded in 1909, and currently employees 29 full time faculty in four cohesive research groups: astrophysics; atomic, molecular and chemical physics; high energy physics; and solid state physics.

2. PERSONNEL

Astrophysics faculty in the department include Ed Baron, David Branch, John Cowan, Dick Henry, Emeritus Professor Tibor Herczeg, Karen Leighly, Bill Romanishin, and Yun Wang. Faculty members Ron Kantowski, Chung Kao and Kim Milton from the particle physics group also participate in astrophysical research.

Postdocs in the Astronomy group are Pia Mukherjee, who continued her position working with Yun Wang, and Chiho Matsumoto, who continued her position as a postdoctoral research associate with the AGN group led by Karen Leighly.

During the past year, Baron supervised research by graduate student Sebastien Bongard. Branch supervised research by graduate students Rollin Thomas and Dean Richardson. Thomas earned a Ph. D. degree and is presently in a postdoctoral position with the Supernova Factory at Lawrence Berkeley National Laboratory. Cowan has supervised research by graduate student Larry Maddox, Henry supervised research by graduate student Aida Nava, Leighly supervised research by graduate students Darrin Casebeer and Boon Kuan Woo, and Wang supervised research by graduate student Veselin Kostov.

Several faculty conducted research with undergraduates. Branch and Baron supervised research by Brigham Young University undergraduate student Peter Brown, who participated in the Department's NSF REU summer program, and by OU undergraduate student Jerod Parrent, who was supported by an NSF REU supplement. Cowan supervised research by Stacey Long and Juliette Rupert, who were both accepted into the graduate program at OU, and by Faith Jordan and Jason Collier. Leighly supervised research by Carnegie Mellon undergraduate student Andrea Crews, who participated in the REU program, and OU undergraduate John Moore. Wang supervised research by Jason Tenbarge from Indiana University, now accepted into the graduate program at UT Austin, and Bobby Fleshman.

The Department also hosted long-term visitors. Toshihiro Kawaguchi, currently a postdoc at Meudon Observatory, visited for 6 weeks during June and July 2003.

The astrophysics group has access to a number of resources for their research. They have been successful in obtaining observing time on both groundbased observatories including KECK, the VLA, and NOAO Kitt Peak, and on satellite observatories, recently including *HST*, *Chandra*, *XMM-Newton*, and *FUSE*, among others. The Department maintains modern computing facilities as well, including a network of nearly 70 UNIX workstations. On-line access is available to the NSF supercomputer network as well as other supercomputers in those groups with approved projects. Researchers also have access to supercomputer time at Livermore, San Diego, Los Alamos, Pittsburgh and NCSA.

The astrophysics group continued to be well funded through the 2002–2003 academic year, primarily through NSF and NASA. Once starting research, all graduate students were supported by research assistantship stipends, and funding has been available for travel to international meetings.

3. RESEARCH

3.1 Solar System

Romanishin continued to study minor bodies in the outer solar system, in collaboration with S. C. Tegler of Northern Arizona University. Using telescopes in Arizona and Keck, they have accumulated almost 100 measured colors. With this large sample of accurate colors, interesting patterns of color with orbital parameters are emerging.

3.2 Abundances and Nucleosynthesis

Cowan and collaborators have been making a large number of observational and theoretical studies of the heavy element abundances in Galactic halo stars. The observations have been made from the ground (Keck, McDonald, Kitt Peak) and from space (*HST*). Using the *HST*, they have identified gold for the first time and uranium for only the second time in any halo star (BD+17 3248). Their abundance observations indicate the presence of rapid-neutron capture (i.e., r-process) elements in old Galactic halo and globular cluster stars. These observations demonstrate that the earliest generations of stars in the Galaxy, responsible for neutron-capture synthesis and the progenitors of the halo stars, were rapidly evolving. Abundance comparisons among large numbers of stars provide clues about the nature of neutron-capture element synthesis both during the earliest times and throughout the history of the Galaxy. In particular, these comparisons suggest differences in the way the heavier (including Ba and above) and lighter neutron capture elements are synthesized in nature. Understanding these differences will help to identify the astrophysical site (or sites) of and conditions in the r-process. The abundance comparisons also demonstrate a large star-to-star scatter in the neutron-capture/iron ratios at low metallicities (which disappears with increasing [Fe/H]) and suggests an early, chemically unmixed and inhomogeneous Galaxy. Our very recent neutron-capture element observations indicate that the early phases of Galactic nucleosynthesis, and the associated chemical evolution, are quite complex, with the yields from different (progenitor) mass-range stars contributing to different chemical mixes. Stellar abundance comparisons indicate a change from the r-process to the slow neutron capture (i.e., s-) process at higher metallicities (and later times) in the Galaxy. We are also using the observed abundances of the radioactive elements thorium and uranium in halo and globular cluster stars to determine the radioactive ages of the oldest stars in the Galaxy. These age estimates, clustering around 14 ± 4 Gyr, provide lower limits on the age of the Galaxy and provide constraints on cosmological age determinations.

During the last year, Cowan and collaborators have focused on making more accurate abundance determinations in Galactic halo stars by utilizing new laboratory atomic data (in collaboration with J. E. Lawler at U. of Wisconsin and C. Sneden at U. of Texas.) They have also been examining abundance trends of certain neutron-capture elements, including La and Eu, in the Galaxy as a function of metallicity. Employing new recent *HST* and Keck observations of a number of metal-poor Galactic halo stars, they are extending their studies to the lighter neutron-capture elements Ge and Ga. New chemical evolution studies, specifically for the elements Sr, Y and Zr, have recently been completed in collaboration with C. Travaglio (MPI and Torino), R. Gallino (Torino) and C. Sneden. Two undergraduate students, Jason Collier and Faith Jordan, were involved in these recent research projects.

Henry continued to work this year on understanding heavy element production and distribution in galaxies. A major portion of his time was dedicated to the preparation and presentation of an invited review on ''Element Yields of Intermediate-Mass Stars,'' at the conference on the ''Origin and Evolution of the Elements,'' held at the Carnegie Observatories in Pasadena in February. Preparation for this talk and the writeup accompanying it (see Publications below) involved the compilation and analysis of theoretical stellar yield predictions by numerous authors, along with comparisons of these results with abundances observed in planetary nebulae. The latter objects comprise material shed during the final stages of intermediate-mass star (IMS) evolution, material which contains some of the nuclear products synthesized during the lifetimes of the progenitor stars. Much of the theoretical and observational evidence today strongly implicates IMS as the main source of the element nitrogen in the universe. In addition, these stars appear to be a significant source of helium, competing effectively with massive stars in this role, while the part they play in carbon production is currently unclear: some current work assigns the major production of this element to massive stars, while other outcomes favor IMS as the principal source for this element. Stellar rotation is also beginning to play a major part in theoretical calculations as models attempt to approach a more realistic level of analysis. Early results with rotation indicate that nitrogen production may be significant in some of the lower mass members of the IMS group, stars that are more like the sun. A major consequence of pushing the production responsibilities to lower stellar masses is the increase in delay time between star formation and nuclear product deposition into the interstellar medium.

Another major thrust of Henry's work was in the study of sulfur, chlorine, and argon abundances in planetary nebulae. The motivation for this work was to perfect a way to probe the distribution of these elements in the disk of the Milky Way. In addition, it is hoped that these studies will allow the hypothesis that measurable amounts of these elements are produced by Type Ia supernova events to be tested. Henry has been working on this project with Karen Kwitter (Williams College), Jackie Milingo (Franklin & Marshall), and Bruce Balick (U. Washington) since 1997. The past year, however, has been one of culmination for the work, which began by obtaining extensive spectroscopic observations of disk PNe in both the northern and southern hemispheres of disk. The final sample of objects included over 80 PNe. An interesting and major result of the study is the discovery that the abundance of sulfur relative to oxygen (an important metallicity indicator) in most PNe is not in accord with values found in H II regions, in contradiction to what is expected. Since S is produced in the same massive stars that produce O, their abundances should increase together in lockstep. This is supported by H II region studies, but often not in PNe, as now revealed. Henry and his team concluded that the discrepancy is caused by the current inability to measure the abundance of the S^{+3} ion in nebulae, although significant amounts exist in PNe. Thus many PN S abundances are underestimated. This development will continue to be followed, as it may lead to the discovery of important properties of PNe and their ionization structure.

Another PN project just getting underway involves the use of *HST* is an attempt to discover PNe in nearby dwarf galaxies of very low metallicity, such as I Zw 18. Other team members for this work include Reggie Dufour (PI; Rice U.) and Karen Kwitter. The motivation is to extend the study of nitrogen and other elements found in PNe to very low metallicity environments to further test hypothesis about IMS nuclear production.

Finally, Henry has continued his involvement this year in the study of nitrogen in damped Lyman alpha systems (DLAs). These objects are high redshift systems seen in absorption against bright background QSOs. Twenty to thirty of these objects have been analyzed for nitrogen as well as alpha elements. Interestingly, the nitrogen abundances in some cases appear anomalously low and discovering the reason for this is the motivation of the current research. Henry is calculating chemical evolution models which assume different star formation scenarios and various stellar yield predictions for both massive stars and IMS in order to see if the low N DLAs are either: 1) unevolved objects (in which case the N produced by IMS has not been released into the environment); or 2) possess stellar populations characterized by a relative paucity of IMS (thus N production is suppressed). Henry is being assisted in this work by graduate student Aida Nava, who currently is involved in recalculating N abundances for dwarf irregulars and H II regions using extant spectroscopic data. Her results will be used to refine the sample of N abundances used to compare with DLA abundances. This effort is being supported by NSF.

3.3 Observations of Supernovae and External Galaxies

OU graduate student Dean Richardson, together with Baron, Branch, and other OU students, continued to develop **Suspect**, the Online **Su**pernova **Spect**rum Archive, a website (*http://www.nhn.ou.edu/∼suspect*) at which astronomers can deposit, view, and extract supernova spectra and photometry. The motivation for **Suspect** is to facilitate systematic comparative studies of supernova data by OU personnel as well as astronomers elsewhere.

Richardson also continues to work on the absolute visual magnitude distributions of Type Ib and Type Ic supernovae, by collecting data on the apparent magnitude, distance, and interstellar extinction of each event. The limited sample size and the considerable uncertainties, especially those associated with extinction in the host galaxies, still prevent firm conclusions regarding differences between the absolute magnitude distributions of Type Ib and Type Ic supernovae, and regarding the existence of separate groups of overluminous and normal-luminosity events. Three of the four overluminous events had unusual spectra, while most but not all of the normal luminosity events had typical spectra.

Using the Very Large Array (VLA) Cowan and collaborators have been following the long-term radio behavior of intermediate-age (i.e., 10–100 year old) extragalactic supernovae. They have found that these supernovae, such as SN 1970G in M101 and SN 1923A in M83, are still emitting in the radio decades after the supernova explosion. These observations are designed to understand how supernovae evolve into supernova remnants (SNRs), which typically take at least 100 years to become radio emitters. The observations also provide an indication of the circumstellar mass-loss rate, which affects the level and duration of the radio emission, from the supernova progenitor star.

In collaboration with You-Hua Chu (U. of Illinois), Cowan and collaborators have also been examining in some detail the radio and optical emission of one very unusual supernova, SN 1961V, in NGC 1058. Combining *HST* and radio observations they are attempting to determine the exact nature of this object — whether it is in fact a supernova or a luminous blue variable star similar to Eta Carinae.

Cowan and collaborators have been making coordinated multi-wavelength (Kitt Peak, VLA and *Chandra*) observations of point sources in nearby face-on galaxies. They are trying to identify previously undetected supernovae or SNRs. Their VLA observations are also being used to distinguish High & Low Mass X-ray Binaries (HMXBs & LMXBs) from supernova remnants (SNRs). They are also trying to identify the population of SNRs, HMXBs, and LMXBs in spiral galaxies and whether there are massive black holes (MBHs) in these spiral galaxies. In addition to their recent *Chandra* and radio observations, new observations are scheduled at the VLA during the coming year to extend and expand this research project. Chris Stockdale (Marquette University) and OU graduate student Larry Maddox contributed to these projects.

3.4 Type I Supernovae

Branch and Baron, in collaboration with P. Garnavich (Notre Dame), Thomas Matheson (Harvard), and others, published optical spectra of the normal Type Ia SN 1998aq, which was extensively observed by the Harvard group. They used **Synow**, the parameterized supernova synthetic-spectrum code, to study line identifications in the early photospheric-phase spectra. The results included evidence for lines of singly ionized carbon at ejection velocities as low as 11,000 km s^{-1}, which would be inconsistent with published 1-D delayed-detonation explosion models. Almost all of the features in the early spectra were securely identified, so that SN 1998aq can serve as a benchmark for spectroscopic studies of other Type Ia supernovae.

Thomas, Branch, and Baron, in collaboration with others, studied the spectra of the Type Ia SN 2000cx, which exhibited multiple peculiarities including a lopsided B–band light–curve peak that does not conform to current methods for using shapes of light curves to standardize luminosities of Type Ia supernovae. Thomas *et al.* established the presence of Ca II infrared–triplet features forming above velocity $\sim$20,000 km s^{-1}, much higher than the photospheric velocity of $\sim$10,000 km s^{-1}. Branch *et al.* identified Ti II features forming at the same high velocity. High-velocity line formation is partly responsible for the photometric peculiarities of SN 2000cx: for example, B-band flux blocking by Ti II absorption features that decreases with time causes the B light curve to rise more rapidly and decline more slowly than it otherwise would. SN 2000cx serves to illustrate the importance of learning how much of the spectroscopic (and photometric) diversity of Type Ia supernovae is caused by line formation at velocities much higher than the photospheric velocity. SN 2000cx contained an absorption feature near 4530 Å that appears to have been produced by Hβ, forming at the same high velocity. The lack of conspicuous Hα and Pα signatures does not necessarily invalidate the Hβ identification if the high-velocity line formation is confined to a clump that partly covers the photosphere and the Hα and Pα source functions are elevated relative to that of resonance scattering as they generally are in Type II supernovae. The Hβ identification is tentative because of the lack of independent evidence for the presence of hydrogen. If it is correct, the high–velocity matter evidently was stripped from a non-degenerate companion star.

The presence of a small amount of hydrogen is expected in most single-degenerate scenarios for producing a Type Ia supernova (SN Ia). While hydrogen may be detected in very early high-resolution optical spectra, in early radio spectra, and in X-ray spectra, Baron, Branch, former OU student Eric Lentz (University of Georgia) and collaborators examined the possibility of detecting hydrogen in early low-resolution spectra such as those that will be obtained by proposed large-scale searches for nearby SNe Ia.

Motivated by recent three-dimensional calculations of the explosion of Type Ia supernovae via a pure deflagration, Baron, Lentz, and P. Hauschildt (Hamburger Sternwarte) calculated the observed spectra at 15-25 days past maximum light of a parameterized model that has a considerable fraction of unburnt C+O in the central regions. Rather than attempting a self-consistent three-dimensional calculation, which is beyond the scope of current computer codes, they modified the composition structure of the one-dimensional deflagration model W7. In exploratory parameterized calculations, they found that a central concentration of C+O is not ruled out by observations for the epochs studied.

SN 2001el is the first normal Type Ia supernova to show a strong, intrinsic polarization signal. In addition, during the epochs prior to maximum light, the Ca II IR triplet absorption is seen distinctly and separately at both normal photospheric velocities and at very high velocities. The high-velocity triplet absorption is highly polarized, with a different polarization angle than the rest of the spectrum. The unique observation allows Baron and collaborators to construct a relatively detailed picture of the layered geometrical structure of the supernova ejecta, using parameterized 3-D synthetic spectropolarimetric calculations.

3.5 Type II Supernovae

In a continuing project to use detailed theoretical modeling of spectroscopic observations, Baron, Branch and collaborators calculated a large grid of synthetic spectra and compared them to early spectroscopic observations of SN 1993W. This supernova was discovered close to its explosion date and is located in the Hubble flow. They showed that very early spectra combined with detailed models can provide constraints on the value of the power-law index, the ratio of hydrogen to helium in the surface of the progenitor, the progenitor metallicity, and the amount of radioactive nickel mixed into the outer envelope of the supernova. The spectral fits reproduce the observed spectra exceedingly well. The ability to obtain the metallicity from early spectra make SNe II-P attractive probes of chemical evolution in the universe, and by demonstrating the ability to pin down the parameters of the progenitor and mixing during the supernova explosion, it is likely to make SNe II-P useful cosmological distance indicators that are at the same time complementary to SNe Ia.

3.6 Active Galaxies

Leighly has devoted most of her research time during the past year to continuing research on Narrow-line Seyfert 1 galaxies (NLS1s). This optically identified subclass of Active Galaxies has been shown to exhibit peculiar properties, including narrower optical permitted lines (an identifying feature), steeper soft and hard X-ray spectra, and higher amplitude/more rapid X-ray variability than Seyfert galaxies with broader optical permitted lines. The now-accepted explanation for these properties is that NLS1 have accretion rates higher relative to the Eddington limit than Seyfert 1 galaxies with broad optical lines. Thus the study of these objects is motivated by the desire to understand the effect of the rate of accretion, one of the primary intrinsic parameters for accretion driven systems, on observed properties.

Leighly continues work on the UV emission lines from NLS1s. Of particular interest are ''windy'' NLS1s: objects that have high-ionization lines such as C IV that are dominated by a broad, blueshifted component. Besides having blueshifted high ionization lines, these objects also have quite strong low-ionization lines including Si II and Fe II. During this year, it was realized that the low-ionization lines in these objects would naturally be enhanced if the continuum is filtered through the wind before it illuminates the intermediate- and low-ionization line-emitting region. Photoionization modeling has been performed to confirm this inference. Leighly finds that this filtering can effectively increase by roughly an order of magnitude the ionization parameter appropriate for the intermediate- and low-ionization gas. This discovery has potentially wide ranging applications. For example, it may naturally explain why low-ionization emission lines are so strong in low-ionization broad absorption line quasars. Leighly has also performed a PCA analysis on archival UV spectra of a sample of NLS1s. She finds that the first three eigenvectors account for 70% of the variance, with the first eigenvector being associated with the line blueshift. An interesting finding is that α_{ox}, the point-to-point slope between 2500 Å and 2 keV, is anticorrelated with the blueshift of the line. This is interpreted as support for a resonance-line driving mechanism for the wind. Objects with steep α_{ox} have strong UV, necessary for driving the wind, and weak X-rays, required to keep the wind from being overionized. OU undergraduate John Moore contributed to this work.

OU undergraduate John Moore is leading a project involving analysis of a sample of $\sim$900 narrow-line quasars drawn from the Sloan Digital Sky Survey (SDSS). The motivation for the project is to investigate systematics in the ratio of the Fe II to Mg II. This has potentially important implications, since this ratio is frequently used to gauge the chemical abundances in the early Universe. Furthermore, the complicated multiplets of Fe II potentially hold information about the excitation and optical depths for low-ionization line emission in the broad-line region. Narrow-line quasars are the best objects to use to study low-ionization line emission, because these lines are frequently strong, and because the narrow lines reduce ambiguity arising from blending. The sample was chosen from quasars with redshifts between 1.2 and 1.8, and with Mg II FWHM less than 3000 km s^{-1}. Further screening rejected objects with lines having FWHM greater than 2600 km s^{-1}, poor signal-to-noise ratios, and intrinsic Mg II absorption lines. After refining the redshifts using the narrow Mg II line, and removing Galactic absorption lines, a composite spectrum was constructed. Fitting the Fe II using a template created from *HST* spectrum of I Zw 1 revealed an Fe II-to-Mg II ratio of 3.9 in the composite. This is comparable to values measured in high redshift quasars, somewhat lower than in nearby Narrow-line Seyfert 1 galaxies, and somewhat larger than in the SDSS early-release quasar composite spectrum. Further work planned includes a study of the distribution of Fe II to Mg II ratios, correlations with continuum shape, line width, and luminosity, and a systematic search for objects with Fe II emission differing from that of I Zw 1 (and therefore potentially revealing different conditions in the low-ionization line emitting gas).

OU postdoc Chiho Matsumoto, in collaboration with Leighly and Toshihiro Kawaguchi (Meudon Observatory) is leading a project involving *XMM-Newton* observations of luminous Narrow-line Seyfert 1 galaxies. While the properties of NLS1s are generally explained in terms of an enhanced accretion rate, luminous NLS1s are of special interest because they are expected to have the highest accretion rate of all. PHL 1811, a very luminous NLS1, has been found to be intrinsically X-ray weak, and they speculate that X-ray weakness may be a consequence of a high accretion rate. In order to characterize the X-ray and broad-band properties of optically-luminous NLS1s, they carried out *XMM-Newton* observations of 4 such objects. Their absolute magnitudes range from -25 to -27. All objects were detected, and the observed spectra are rather steep, as is typical among NLS1s. Utilizing simultaneous UV observations by the *XMM-Newton* optical monitor, they could also investigate the spectral energy distributions in the UV-X-ray band. One object (RX J1225.7+2055) out of four was found to be quite X-ray weak during their observations. They infer that not all luminous NLS1s are X-ray weak; however, they may suffer transient X-ray weak states more often than less luminous NLS1s.

Work continued on the X-ray properties of the ultrasoft NLS1 1H 0707−495. REU student Andrea Crews (Carnegie Mellon) contributed to the project by analyzing the archival *XMM-Newton* data. These data were taken when the object was in a $5\times$ lower flux state than during the *Chandra* observation. Analysis revealed other differences: the soft excess had a lower temperature, and the power law component appeared flatter. The source was variable during the observation. Previously, a variance analysis showed energy-independent variability. Our reanalysis indicated short time-scale flares in the hardest bands, similar to that observed during the *Chandra* observation. We interpret this as evidence that the hard power law component is distinct from the soft component, and that 1H 0707−495 shows interesting similarity to soft state X-ray binaries.

OU graduate student Darrin Casebeer, in collaboration with Branch, Baron and Leighly, has begun to model the absorption lines in subclass of low-ionization broad absorption-line quasars characterized by absorption by metastable Fe II (Fe II LoBals). The line profiles in these objects appear to be similar to P Cygni profiles, suggesting an origin by resonance scattering in outflowing gas. Initial work on this line of investigation was performed last year by Branch using the empirical code *SYNOW*; Casebeer is now extending this work by trying to model these lines self-consistently using the exact radiative transfer code *Phoenix*.

Work continues on the *XMM-Newton* observation of the Seyfert 2 galaxy NGC 6300. The analysis of the central engine is being led by OU postdoc Chiho Matsumoto. The X-ray spectrum is typical for a Seyfert 2 galaxy, consisting of a heavily absorbed hard component dominating the 3–10 keV band, and a soft component seen in the 0.2–2 keV band. In the hard band, the spectrum is well fitted by a power-law model with photon-index of 1.85, intervened by a Compton-thin absorber ($N_{\rm H}\simeq 2.2\times 10^{23}$ cm^{-2}). A narrow iron line is detected at 6.42 keV with normal intensity; the width is marginally resolved to be $\sigma\sim 60$ eV. Rapid and rather high amplitude variability is observed in the hard X-ray band, whereas both the iron line and the soft emission is consistent to be constant. The iron line emission thus is considered to originate from the rather large radii of the disk and/or the torus.

Hisamitsu Awaki (Ehime University), in collaboration with Leighly and Matsumoto, performed time series analysis on the *XMM-Newton* data from NGC 6300. They find that above 2 keV, the continuum shows rapid variability with a time scale of about 1000 seconds. Interestingly, the amplitude and shape of the power spectruum is quite similar to that of the low-luminosity broad-line Seyfert 1 galaxy MCG–6-30-15. It is also interesting to note that NGC 6300 and MCG–6-30-15 are also similar in that they both have very narrow [O III] emission lines. Both of these findings support the interpretation that NGC 6300 has a Seyfert 1 nucleus heavily obscured by thick matter, and that it has a black hole mass similar to that of MCG–6-30-15.

3.7 Cosmology

Wang studied dark energy effects on the Lyman-alpha forest with M. Viel, S. Matarrese, Tom Theuns, and D. Munshi. In quintessence models, the dark energy content of the Universe is described by a slowly rolling scalar field whose pressure and energy density obey an equation of state of the form $p=w\rho$; w is in general a function of time such that $w<-1/3$, in order to drive the observed acceleration of the Universe today. The cosmological constant model LCDM corresponds to the limiting case $w=-1$. They explored the prospects of using the Lyman-alpha forest to constrain w, using semi-analytical techniques to model the intergalactic medium (IGM). A different value of w changes both the growth factor and the Hubble parameter as a function of time. The resulting change in the optical depth distribution affects the optical depth power spectrum, the number of regions of high transmission per unit redshift and the cross-correlation coefficient of spectra of quasar pairs. These can be detected in current data, provided that independent estimates of the thermal state of the IGM, its ionization parameter and the baryon density are available.

Wang and OU postdoc Pia Mukherjee studied the model-independent reconstruction of the primordial power spectrum using wavelets in three papers. Measuring the primordial matter power spectrum is the primary means of probing unknown physics in the very early universe.

In the first paper, Mukherjee and Wang measured wavelet band powers of the primordial power spectrum from Cosmic Microwave Background Anisotropy (CMB) data. They allowed the primordial power spectrum to be an arbitrary function, and parametrized it in terms of wavelet band powers. Current cosmological data correspond to 11 such wavelet bands. They derive constraints on these band powers as well as H_0, $\Omega_b h^2$ and $\Omega_m h^2$ from the latest available CMB data using the Markov Chain Monte Carlo (MCMC) technique.

Their results indicate a feature in the primordial power spectrum at $0.008 \lesssim k/(h\mathrm{Mpc}^{-1}) \lesssim 0.1$. This paper was published before the release of the WMAP CMB data.

In the second paper, Mukherjee and Wang reconstructed the primordial power spectrum as a free function from CMB data alone (WMAP, CBI, and ACBAR), and from CMB data together with large scale structure data (2dFGRS and PCSZ). They used two complementary methods: the wavelet band power method and the conventional top-hat binning method. They found that the shape of the reconstructed $P_{in}(k)$ is consistent with scale-invariance, although it allows some indication of a preferred scale at $k \sim 0.01$ Mpc^{-1}. While consistent with the possible evidence for a running of the scalar spectral index found by the WMAP team, their results highlight the need of more stringent and independent constraints on cosmological parameters (the Hubble constant in particular) in order to more definitively constrain deviations of $P_{in}(k)$ from scale-invariance without making assumptions about the inflationary model.

In the third paper, Mukherjee and Wang used a further improved method, the direct wavelet expansion of the primordial power spectrum, to reconstruct the primordial power spectrum from CMB (WMAP, CBI, and ACBAR) and large scale structure data (2dFGRS and PCSZ). The multiresolution and good localization properties of orthogonal wavelets make them suitable for detecting features in $P_{in}(k)$. They expanded $P_{in}(k)$ directly in wavelet basis functions. The likelihood of the data is thus a function of the wavelet coefficients of $P_{in}(k)$, as well as the H_0, $\Omega_b h^2$, $\Omega_c h^2$ and the τ_{ri}, in a flat ΛCDM cosmology. They derived constraints on these parameters from CMB anisotropy data (WMAP, CBI, and ACBAR) and large scale structure (LSS) data (2dFGRS and PSCZ) using the Markov Chain Monte Carlo (MCMC) technique. The direct wavelet expansion method is different and complimentary to the wavelet band power method of Mukherjee & Wang (2003a,b), and results from the two methods are consistent. In addition, as they demonstrated, the direct wavelet expansion method has the advantage that once the wavelet coefficients have been constrained, the reconstruction of $P_{in}(k)$ can be effectively denoised, i.e., $P_{in}(k)$ can be reconstructed using only the coefficients that, say, deviate from zero at greater than 1σ. In doing so, the essential properties of $P_{in}(k)$ are retained. The reconstruction also suffers much less from the correlated errors of binning methods. The shape of the primordial power spectrum, as reconstructed in detail by them, reveals an interesting new feature at $0.001 \lesssim k/\mathrm{Mpc}^{-1} \lesssim 0.005$. It will be interesting to see if this feature is confirmed by future data. The reconstructed and denoised $P_{in}(k)$ is favored over the scale-invariant and power-law forms at $\gtrsim 1\sigma$.

Wang studied future type Ia supernova data as tests of dark energy from modified Friedmann equations, in collaboration with Katherine Freese, Paolo Gondolo, and Matthew Lewis. In the Cardassian model, dark energy density arises from modifications to the Friedmann equation, which becomes $H^2 = g(\rho_M)$, where $g(\rho_M)$ is a new function of the energy density. The Universe is flat, matter dominated, and accelerating. The distance redshift relation predictions of generalized Cardassian models can be very different from generic quintessence models, and can be differentiated with data from upcoming pencil beam surveys of Type Ia Supernovae such as SNAP. Wang *et al.* have found the interesting result that, once Ω_m is known to 10% accuracy, SNAP will be able to determine the sign of the time dependence of the dark energy density. Knowledge of this sign (which is related to the weak energy condition) will provide a first discrimination between various cosmological models that fit the current observational data (cosmological constant, quintessence, Cardassian expansion). Further, they have performed Monte Carlo simulations to illustrate how well one can reproduce the form of the dark energy density with SNAP. To be concrete, they study a class of two parameter (n,q) generalized Cardassian models that includes the original Cardassian model (parametrized by n only) as a special case. They gave examples of MP Cardassian models that fit current supernovae and CMB data, and prospects for differentiating between MP Cardassian and other models in future data are discussed. They also noted that some Cardassian models can satisfy the weak energy condition $w > -1$ even with a dark energy component that has an effective equation of state $w_X < -1$.

Wang explored the effects of dark energy on galaxy clustering with Dipak Munshi and Cristiano Porciani. They studied the evolution of galaxy clustering in various cosmological models with quintessence. They investigated how the analytical predictions vary with change of dark energy equation of state w_X. Comparing these predictions against available data, they tested the possibility of constraining the equation of state with future galaxy surveys and to what extent the problems of galaxy bias can be modeled in such studies. They used a compilation of various surveys to study the number density and amplitude of galaxy clustering from observations of the local universe at $z \sim 0$ to that of the Lyman break galaxies and Ly-α emitters at $z \sim 4.9$. They found that objects are more biased in models with more negative values of dark energy equation of state w_X. They concluded that, while future all sky CMB observations will determine cosmological parameters with unprecedented precision, and cross correlation of weak lensing experiments and galaxy surveys will provide a cleaner and accurate picture of bias associated with collapsed objects, the rate of growth of large scale structure in such surveys can be directly used to constrain the equation of state of dark energy and the potential of the scalar field associated with quintessence. In particular, they showed that the abundance and spatial distribution of galaxy clusters are a sensitive probe of dark energy at intermediate redshifts. Galaxy clustering studies will provide constraints on dark energy that are independent and complementary to type Ia supernova studies.

Wang and two undergraduate students Jason Tenbarge and Bobby Fleshman obtained simple and accurate formulae for distances in inhomogeneous universes. Weak gravitational lensing due to the inhomogeneous matter distribution in the universe is an important systematic uncertainty in the use of standard candles in cosmology. The matter inhomogeneity can be parametrized by a local smoothness parameter $\tilde{\alpha}$, then the magnification of a standard candle at redshift z is given by $\mu = |D_A(\tilde{\alpha}=1|z)/D_A(\tilde{\alpha}|z)|^2$, where the angular diameter distance $D_A(\tilde{\alpha}|z)$ is the solution to the Dyer-Roeder equation. Wang *et al.* derived simple and accurate analytical expressions for $D_A(\tilde{\alpha}|z)$, which should be useful in studying the weak lensing of standard candles. Wang, Holz, & Munshi (2003) have used the reduced convergence, $\eta = 1 + \kappa/|\kappa_{min}|$, to derive a universal probability distribution (UPDF) for weak lensing amplification. In this work, Wang *et al.* derived the relation of the local smoothness parameter $\tilde{\alpha}$ to η. It is likely that the use of $\tilde{\alpha}$ can lead to an improvement in the accuracy of the UPDF.

PUBLICATIONS

Branch, D., ''When a White Dwarf Explodes,'' *Science*, 299, 53 (2003)

Branch, D., Garnavich, P., Matheson, T., **Baron, E., Thomas, R. C.**, Hatano, K., Challis, P., Jha, S., & Kirshner, R. P., ''Optical Spectra of the Type Ia Supernova 1998aq,'' AJ, 126, 1489 (2003)

Branch, D., Thomas, R. C., **Baron, E.**, Kasen, D., Hatano, K., Nomoto, K., Filippenko, A. V., Li, W., & Rudy, R. J., ''Direct Analysis of Spectra of the Peculiar Type Ia Supernova 2000cx,'' ApJ, submitted (2004)

Baron, E., Lentz, E. J., & Hauschildt, P. H., ''The Detectability of Mixed Unburnt C+O in Type Ia Supernova Spectra,'' ApJ, 588, L29 (2003)

Baron, E., Nugent, P., **Branch, D.**, Hauschildt, P. H. Turatto, M. & Cappellaro, E., ''Determination of Primordial Metallicity and Mixing in the Type IIP Supernova 1993W,'' ApJ, 586, 1199 (2003)

Cowan, J. J., ''Elements of Surprise,'' *Nature*, 423, 29 (2003)

Cowan, J. J., & Sneden, C., ''Abundances: The r-Process and Supernovae,'' To appear in 3-D Signatures in Stellar Explosions, eds. P. Kumar, C. Wheeler & P. Hoeflich, (Cambridge: Cambridge Univ. Press) (2003)

Cowan, J. J. & Sneden, C., ''Advances in r-Process Nucleosynthesis,'' To appear in *Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements*, eds. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press) (2003); *astro-ph/0309802*

Cowan, J. J. & Sneden, C. ''r-Process Abundance Signatures,'' To appear in *Proceedings of the Third International Conference on Fission and the Properties of Neutron-Rich Nuclei* (2003); *astro-ph/0212149*

Gezari, S., Halpern, J. P., Komossa, S., Grupe, D., & **Leighly, K. M.**, ''Follow-up Hubble Space Telescope/Space Telescope Imaging Spectroscopy of Three Candidate Tidal Disruption Events,'' ApJ, 592, 42 (2003)

Grupe, D., Wills, B. J., **Leighly, K. M.**, & Meusinger, H., ''A Complete Sample of Soft X-ray Selected AGN: I. The Data,'' AJ, in press (2004)

Halpern, J. P., **Leighly, K. M.**, & Marshall, H. L., ''An Extreme Ultraviolet Explorer Atlas of Seyfert Galaxy Light Curves: Search for Periodicity,'' ApJ, 585, 665 (2003)

Den Hartog, E. A., Lawler, J. E, Sneden, C., & **Cowan, J. J.**, ''Improved Laboratory Transition Probabilities for N II and Application to the Neodymium Abundances of the Sun and Three Metal-Poor Stars,'' ApJS, 148, 543 (2003)

Henry, R. B. C., ''Element Yields of Intermediate-Mass Stars,'' To appear in *Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements*, eds. A. McWilliam and M. Rauch (Cambridge: Cambridge Univ. Press) (2003); *astro-ph/0305513*

Henry, R. B. C., Kwitter, K. B., Balick, B., ''Sulfur, Chlorine, and Argon Abundances in Planetary Nebulae. IV: Synthesis and the Sulfur Anomaly,'' AJ, in press (2003)

Jenkins, E. B., Bowen, D. V., Tripp, T. M., Sembach, K. R., **Leighly, K. M.**, Halpern, J. P., & Lauroesch, J. T., ''Absorption-Line Systems and Galaxies in Front of the Second-brightest Quasar, PHL 1811,'' AJ, 125, 2824 (2003)

Kasen, D., Nugent, P., Wang, L., Howell, D. A., Wheeler, J. C. Höflich, P., Baade, D., **Baron, E.,** & Hauschildt, P. H., ''Analysis of the Flux and Polarization Spectra of the Type Ia Supernova SN 2001el: Exploring the Geometry of the High-Velocity Ejecta,'' ApJ, 593, 788 (2003)

Kratz, K.-L., Pfeiffer, B., **Cowan, J. J.**, & Sneden, C., ''R-Process Chronometers,'' to appear in New Astronomy Reviews (2003)

Kwitter, K. B., **Henry, R. B. C.**, & Milingo, J. B., ''Sulfur, Chlorine, and Argon Abundances in Planetary Nebulae. III. Observations and Results for a Final Sample,'' PASP, 115, 80 (2003)

Leighly, K. M., & **Moore, J. R.** ''*HST* STIS Ultraviolet Spectral Evidence for Outlow in Extreme Narrow-line Seyfert 1 Galaxies,'' ApJ, submitted (2004)

Lawler, J. E., Sneden, C., & **Cowan, J. J.**, ''Improved Atomic Data for Ho II and New Holmium Abundances for the Sun and Three Metal-Poor Stars,'' ApJ, submitted (2004)

Lentz, E. J., **Baron, E., Branch, D.,** & Hauschildt, P. H. ''Detectibility of Hydrogen Mixing in Type Ia Supernova pre-Maximum Spectra,'' ApJ, 580, 374 (2002)

Matsumoto, C., **Moore, J.**, **Leighly, K. M.**, Grupe, D., & Wills, B. J., ''A Study of a Complete Soft X-ray Selected Sample of AGN,'' to appear in *Proc. 35th COSPAR*, in press (2003)

Mukherjee, P., & **Wang, Y.**, ''Wavelet Band Powers of the Primordial Power Spectrum from CMB Data,'' ApJ, 593, 38 (2003)

Mukherjee, P., & **Wang, Y.**, ''Model-Independent Reconstruction of the Primordial Power Spectrum from WMAP Data,'' ApJ, in press (2003); *astro-ph/0303211*

Mukherjee, P., & **Wang, Y.**, ''Direct Wavelet Expansion of the Primordial Power Spectrum,'' ApJ, in press (2003); *astro-ph/0301562*

Munshi, D., Porciani, C., & **Wang, Y.**, ''Galaxy Clustering and Dark Energy,'' MNRAS, submitted (2003); *astro-ph/0302510*

Noll, K. S., Stephens, D. C., Grundy, W. M., Millis, R. L., Spencer, J., Buie, M. W., Tegler, S. C., **Romanishin, W.**, & Cruikshank, D. P., ''Detection of Two Binary Trans-Neptunian Objects, 1997 CQ29 and 2000 CF105, with the Hubble Space Telescope,'' AJ, 124, 3424 (2002)

Sneden, C., **Cowan, J. J.**, & Lawler, J. E., ''Observations of Neutron-Capture Elements in the Early Galaxy,'' Nucl. Phys. A, 718, 29c (2003)

Sneden, C., **Cowan, J. J.**, Lawler, J. E., *et al.*, ''The Extremely Metal-Poor, Neutron-Capture Rich Star CS 22892–052: A Comprehensive Abundance Analysis,'' ApJ, 591, 936 (2003)

Sneden, C., Preston, G. W., & **Cowan, J. J.**, ''Binary Blue Metal-Poor Stars: Evidence for AGB Mass Transfer,'' ApJ, 592, 504 (2003)

Tegler, S. C., & **Romanishin, W.**, ''Resolution of the Kuiper Belt Object Color Controversy: Two Distinct Color Populations,'' Icarus, 161, 181 (2003)

Tegler, S. C., **Romanishin, W.**, & Consolmango, G. J., ''A Primordial Origin for the Colors of Kuiper Belt Objects,'' ApJ, in press (2003)

Thomas, R. C., **Branch, D., Baron, E.**, Nomoto, K., Li W., & Filippenko, A. V., ''On the Geometry of the High Velocity Ejecta of the Peculiar Type Ia Supernova 2000cx,'' ApJ, in press (2003)

Travaglio, C., Gallino, R., Arnone, E., **Cowan, J. J.**, **Jordan, F.**, & Sneden, C., ''Galactic Evolution of Sr, Y, Zr: a multiplicity of stellar neutron capture components,'' ApJ, in press (2003)

Viel, M., Matarrese, S., Theuns, T., Munshi, D., & **Wang, Y.** ''Dark energy effects on the Lyman-alpha forest,'' MNRAS, 340, L47 (2003)

Wang, Y., Freese, K., Gondolo, P., Lewis, M., ''Future Type Ia Supernova Data as Tests of Dark Energy from Modified Friedmann Equations,'' ApJ, 594, 25-32 (2003)

Wang, Y., **Tenbarge, J.**, & **Fleshman, B.** ''Simple and Accurate Formulae for Distances in Inhomogeneous Universes,'' PRD submitted (2003); *astro-ph/0307415*

Karen M. Leighly