The University of Oklahoma
Department of Physics and Astronomy

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This report covers the period September 2003 through August 2004 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 Darko Jevremovic, working with Edward Baron, 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. Matsumoto left OU in July 2004 to take a position at Nagoya University.

During the past year, Baron supervised research by graduate students Sebastien Bongard, and Darrin Casebeer (with Leighly), Veselin Kostov, and David Tyndall. Branch supervised research by graduate student Dean Richardson and April Hendley. Richardson earned a Ph. D. degree and is presently visiting faculty member at Marquette University. Cowan supervised research by graduate student Larry Maddox, Henry supervised research by graduate student Aida Nava, Leighly supervised research by graduate student Darrin Casebeer (with Baron), and Wang supervised research by graduate student Veselin Kostov.

Several faculty conducted research with undergraduates. Baron supervised research by Ben Williams (REU and Capstone) and Nicolas Hall. Branch supervised research by Melissa Long (Capstone). Baron and Branch jointly supervised research by Mercy Melakayil, Jerod Parrent, and Texas State University at San Marcos undergraduate Jason Zinn (REU). Cowan supervised research by Jason Collier, an REU participant, now a graduate student at OU, and Emily Wolfing (REU). Leighly supervised research by OU undergraduates Ryan Biesemeyer (REU), Jiehae Choi (Capstone and REU), and John Moore.

The Department also hosted long-term visitors. Peter Hauschildt (Hamburger Sternwarte) visited three times, for two weeks each time. Hauschildt and Baron have been close collaborators on the development of the generalized stellar atmospheres code PHOENIX for 13 years.

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 2003 – 2004 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. Romanishin and Tegler continue to use telescopes in Arizona and the Keck 10m, and now have almost 100 measured colors. With this large sample of accurate colors, interesting patterns of color with orbital parameters are emerging. Romanishin also continues to measure astrometry of minor bodies and report them to the IAU Minor Planet Center.

3.2 Abundances and Nucleosynthesis

Henry and OU graduate student Aida Nava have been studying the chemical evolution of nitrogen in low metallicity environments in an effort to identify unambiguously the portion of the stellar mass spectrum which is most responsible for nitrogen production. To this end, N and O abundances have been recalculated, using published emission line strengths, for 72 blue compact galaxies with $12+\log(O/H) \leqslant 8.1$ (less than 25% of the solar metallicity). Particular attention was paid to the determination of uncertainties. When plotted in the N/O-O/H plane, these objects appear to form two distinct groups. In one group, objects form a horizontal plateau and are distributed in Gaussian fashion in N/O around a mean value, extending over one decade in O/H. Objects in the second group all have higher O/H values and display a broad dispersion in N/O. Of particular interest is whether the scatter on the plateau is real or due to measurement errors, and this issue was studied using χ^2 analyses. Nava and Henry have also calculated detailed chemical evolution models to interpret the distribution of data in the N/O-O/H plane, confirming earlier findings of several teams that low and intermediate mass stars (LIMS) must be playing an extensive role in cosmic nitrogen production if current stellar production rates are correct. An extension of the project now is to interpret the same kind of data for damped Lyman alpha systems, high redshift absorption line objects for which nitrogen and alpha element abundances have been measured. Several of these objects are found to have exceedingly low N/alpha values, either indicating that nitrogen has not yet been released by the slower evolving LIMS residing within them, or that the star formation history of these objects results in a paucity of LIMS. This work is being carried out in collaboration with Jason Prochaska (Lick Obs.) and is funded by NSF grant AST-0307118.

Henry continues to use planetary nebula (PN) abundances to probe both the interstellar environment as well as the chemical production of LIMS. Since the abundances of all but a few elements in PNe reflect ISM levels at the time of progenitor star formation, these objects are useful probes of galactic chemical evolution. Henry, along with Karen Kwitter (Williams College) and Bruce Balick (U. Washington) have published the fifth and final installment in a long series of papers whose purpose was to study the distribution of the elements S, Cl, and Ar in the interstellar medium. While their results showed that the distribution along the disk of Cl and Ar is consistent with patterns displayed by H II regions, S abundances in PNe are observed to be consistently lower than in H II regions. Henry *et al.* concluded that this discrepancy is due to the failure to measure the abundance of the ion S^{+3}, known from models to be abundant in PNe but nevertheless difficult to measure directly. This project is funded by grant HST-GO-09740.02-A from NASA.

Henry is also using PNe to study production of C and N in LIMS. He, along with Kwitter and Reggie Dufour (Rice U.) took WFPC2 images of selected PNe and H II regions in the light of C III] λ1909 and Hα in order to study for the first time the distribution of C^{+2} relative to O^{+2} in these objects, the point being that C abundances can be more precisely determined in these objects once the ionization structure is better understood. At the same time, work continues on the study of nitrogen in PNe. During 2004 a team headed by Jackie Milingo (Franklin & Marshall), along with Kwitter and Steve Souza (Williams College) made spectrophotometric observations of numerous N-rich PNe in hopes of being able to check on stellar production predictions by theorists of this element.

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. Their 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. They 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 has 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) for several elements including Ho and Pt. This work has led to a new comprehensive abundance analysis of the well-known Galactic halo star CS 22892-052. Cowan and collaborators 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.

3.3 Observations of Supernovae and External Galaxies

OU students supervised by Baron and Branch continued to develop **Suspect**, the Online **Su**pernova **SP**ectrum Archive, a web–based (*http://www.nhn.ou.edu/~suspect*) database for the uniform collection, storage, and dissemination of supernova spectra and photometry. The motivation is to facilitate systematic comparative studies of supernova data by OU personnel as well as by astronomers elsewhere.

Due to their intrinsic brightness, supernovae make excellent cosmological probes. The SEAM method for obtaining distances to Type IIP supernovae (SNe IIP) uses detailed synthetic spectral fits. Baron, Branch, and collaborators used SEAM to determine a distance to SN 1999em for which a Cepheid distance exists. They found results consistent with the Cepheid distance, even though they did not attempt to tune the underlying hydrodynamical model; they simply chose the best fits. This is in contradistinction to the expanding photosphere method (EPM) which yields a distance to SN 1999em that is 50% smaller than the Cepheid distance. They examined the differences between SEAM and EPM. Since SNe IIP are visible to redshifts as high as $z \lesssim 6$, with the *JWST*, SEAM may be a valuable probe of the early universe.

Ground-based and Hubble Space Telescope observations for SN 1993J and SN 1998S were presented. SN 1998S shows strong, relatively narrow circumstellar emission lines of N III-V and C III-IV, as well as broad lines from the ejecta. Both the broad ultraviolet and optical lines in SN 1998S indicate an expansion velocity of about 7,000 km/s. The broad emission components of Ly-alpha and Mg II are strongly asymmetrical after day 72 past the explosion, and differ in shape from H-alpha. Different models based on dust extinction from dust in the ejecta or shock region, in combination with H-alpha from a circumstellar torus, were studied. It was concluded, however, that the double-peaked line profiles are more likely to arise as a result of optical depth effects in the narrow, cool, dense shell behind the reverse shock, than in a torus-like region. The ultraviolet lines of SN 1993J are broad, with a box-like shape, coming from the ejecta and a cool dense shell. The shapes of the lines are well fitted with a shell with inner velocity about 7,000 km/s and outer velocity about 10,000 km/s. For both SN 1993J and SN 1998S a strong nitrogen enrichment is found, with N/C $\sim$12.4 in SN 1993J and N/C $\sim$6.0 in SN 1998S. From a compilation of all supernovae with determined CNO ratios, the implications of these observations for the structure of the progenitors of Type II supernovae.

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 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 has also examined in some detail the radio and optical emission of one very unusual object, SN 1961V, in NGC 1058. Combining *HST* (STIS) 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. Their recent observations indicate an SN occurred in the vicinity of SN 1961V a few decades ago.

In addition, 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 supernvova remnants. Their VLA observations are also being used to distinguish High & Low Mass X-ray Binaries (HMXBs & LMXBs) from SNRs. They are also trying to identify the population of SNRs, HMXBs, and LMXBs in spiral galaxies and to determine whether there are massive black holes (MBHs) in these spiral galaxies. To resolve the central region of one galaxy (M83), a new (radio) VLBI experiment has been approved to use the Long Baseline Array (LBA) of Australia Telescope. These observations will assist in the possible detection of coincident radio/X-ray sources in the complex nuclear region. OU graduate students Chris Stockdale (now graduated and a professor at Marquette University) and Larry Maddox and undergraduate student Emily Wolfing participated in these projects. A new collaboration with Steven Tingay (Swinburne University of Technology, Australia) was also established for the LBA experiment.

3.4 Type I Supernovae

Branch and Baron, in collaboration with others, studied the spectra of what has been called the most peculiar Type Ia supernova, SN 2002cx. In spite of the apparent lack of Si II and S II features in its spectra, SN 2002cx was classified as a peculiar Type Ia supernova (SN Ia) on the basis of its overall photometric and spectroscopic behavior. Spectra obtained near maximum light contained Fe III features, as in SN 1991T–like events, but the blueshifts of the Fe III absorptions were exceptionally low. The luminosity also was low. Branch *et al.* used the supernova synthetic–spectrum code Synow to study line identifications in SN 2002cx. They found that the maximum–light spectra contained weak features of Si II, S II, Si III, and Ca II, which strengthens the connection with SN 1991T–like events. They showed that later spectra, obtained 12, 25, and 56 days after maximum, consisted of P–Cygni resonance–scattering features due to permitted Fe II and Co II lines. SN 2002cx had been thought to have made the transition from a permitted–line to a forbidden–line spectrum between 25 and 56 days. Owing to the low expansion velocities the postmaximum spectral features are narrower and easier to identify than they are in other SNe Ia. The study of SN 2002cx will lead to improved line identifications in other SNe Ia and clarify when the transition from a permitted–line to a forbidden–line spectrum occurs. In the context of current SN Ia explosion models, Branch *et al.* suggested that the properties of SN 2002cx may be consistent with 3D deflagration models, which are not favored for normal SNe Ia.

3.5 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 and John Moore, an OU undergraduate, completed work on a project that investigates the nature of blueshifted high-ionization lines in Narrow-line Seyfert 1 galaxies (NLS1s; Leighly & Moore 2004). They present detailed analysis of *HST* and optical spectra from two extreme NLS1s, IRAS 13224−3809 and 1H 0707−495. They find that the high-ionization lines, including N V and C IV, are broad (FWHM$\approx$5000 km s^{-1}) and strongly blueshifted, peaking at around 2500 km s^{-1} and extending up to almost $\sim$10,000 km s^{-1}. In contrast, intermediate- and low-ionization lines, including C III] and Mg II are narrow (FWHM 1000–1900 km s^{-1}) and centered at the rest wavelength. These observations suggest that the blueshifted high-ionization lines come from a wind that is moving toward us, with the receding side blocked by the optically thick accretion disk, and the intermediate- and low-ionization lines are emitted in the accretion disk atmosphere or low-velocity base of the wind. They compared the spectra from these two objects with spectra from a heterogeneous sample of 14 NLS1s drawn from the *HST* archive. They found a number of correlations; the arguably most important one is an anti-correlation between α_{ox}, the point-to-point slope between 2500Å and 2 keV, and the degree of blueshift of the high-ionization lines, such that blueshifted lines are observed more frequently in X-ray weak objects.

Leighly extended this work by presenting modeling and interpretation of the spectra of the extreme NLS1s in a second paper (Leighly 2004). The high-ionization lines and the intermediate- and low-ionization lines were almost disjoint kinematically, so the line equivalent widths and ratios could be modeled separately using the photoionization code *Cloudy*. A large range of densities, photon fluxes, column densities and several combinations of metallicity and spectral energy distribution were investigated. She finds that the high-ionization lines are best matched by a broad range of densities ($-7<\log(n)<11$), a moderately high ionization parameter ($-1.2<\log(U)<-0.2$), low column density ($\log(N_H)=21.4$), and high metallicities illuminated by an X-ray weak continuum. The intermediate- and low-ionization lines could be modeled using dense gas ($\log(n)=10.25$) and a rather low ionization parameter ($\log(U)=-3.2$). However, if the continuum is first filtered through the continuum before it illuminates the intermediate- and low-ionization emitting gas, the emission region is closer to the black hole, and the ionization parameter is larger ($\log(U)=-2$). The photoionization results were used to infer the location of the emission region. The velocity width of the intermediate-ionization lines support a relatively large black hole (1.3×10^8 M$_\odot$) radiating at about 12% of Eddington luminosity. A kinematic model, using resonance scattering as the acceleration of the wind, was used to infer the location of the wind. Both emission regions were found to be located at $\sim10^4$ Schwarzschild radii.

Leighly and Moore also investigated low-ionization line emission in spectra of a large sample of 900 quasars obtained by the Sloan Digital Sky Survey (Leighly & Moore 2004). These objects were selected for their intermediate redshift ($1.2<z<1.8$), which places Mg II and UV Fe II in the optical band pass, relatively narrow Mg II lines, and moderately good signal-to-noise-ratio spectra. The Fe II and Mg II properties and luminosity were measured. They recovered two previously-known correlations: a Mg II Balwin effect, and a correlation between the Mg II equivalent width and velocity width. They discovered a very strong, non-trivial correlation between Fe II equivalent width and Fe II/Mg II ratio. They observe that this correlation is independent of L/L_{Edd}. Composite spectra from each end of the correlation reveal that high Fe II/Mg II objects have stronger Fe II emission from resonance transitions, suggesting differences in opacity or excitation are partially responsible for the range in observed Fe II/Mg II ratio. C II]λ2326 is stronger in the low Fe II/Mg II composite, suggesting that density is also a factor. They will further investigate the properties of the high- and low-Fe II/Mg II objects through pending *Chandra* observations of a subsample of 12 objects. OU undergraduate student Ryan Biesemeyer is extending this work through investigation of SDSS spectra from a higher redshift sample.

OU graduate student Darrin Casebeer, Leighly and Baron completed a paper presenting analysis from simultaneous *FUSE*, *ASCA*, and *EUVE* observations, contemporaneous optical observations, as well as a re-analysis of archival *HST* spectra, from the extreme Narrow-line Seyfert 1 Galaxy RE 1034+39 (KUG 1031+398). RE 1034+39 has an unusually hard spectral energy distribution (SED) that peaks in the soft X-rays. Its emission lines are unusual in that they can all be modelled as a Lorentzian centered at the rest wavelength with only a small range in velocity widths. Their first goal was to investigate whether the unusual SED influences the emission line ratios and equivalent widths. The *FUSE* spectrum was particularly important because it includes the high-ionization line O VI. They then use the photoionization code *Cloudy* and the SED developed from the coordinated observations to confirm that the emission lines are consistent with a hard SED. The best model parameters were ionization parameter $\log(U)\approx-2$ and hydrogen number density $\log(n)=9.75$. They also present a Locally Optimally-emitting Cloud model. This model produced enhanced O VI as observed, but also yielded far too strong Mg II. They develop a series of semi-empirical SEDs, run *Cloudy* models, and discuss the general behavior of emission lines, including density and metallicity indicators, as a function of SED and ionization parameter. They compared the results of these simulations with the observed emission lines from RE 1034+39, and conclude that a hard spectral energy distribution is not only consistent with, but is required by the data.

OU postdoc Chiho Matsumoto, Leighly and Toshihiro Kawaguchi (Meudon Observatory) investigated the X-ray properties of a small sample of high-luminosity NLS1s observed using *XMM-Newton*. High-luminosity AGNs tend to have broader lines than low-luminosity objects, so if the emission-line region is virialized, high-luminosity NLS1s should be accreting at a higher rate relative to Eddington than other NLS1s. A bright, high-luminosity NLS1 PHL 1811 was found to be X-ray weak; thus, they postulated that high accretion rates lead to weak X-ray emission, either through photon trapping or weak coronae. They found that one of the four objects observed was conspicuously X-ray weak. When compared with ROSAT survey constraints on other NLS1s, they tentatively conclude that luminous NLS1s are not consistently X-ray weak, but may be more likely to enter X-ray weak states.

Leighly, in collaboration with Jules Halpern (Columbia University), and Edward Jenkins (Princeton University) continued research on the luminous narrow-line quasar PHL 1811. With magnitudes of $B=14.4$ and $R=14.1$, PHL 1811 is the second brightest quasar known with $z>0.1$ after 3C 273. NLS1s are generally strong soft X-ray emitters, but a BeppoSAX observation of PHL 1811 showed that it is anomalously X-ray weak. Follow-up *Chandra* observations reveal a variable, unabsorbed X-ray spectrum and confirm that it is intrinsically X-ray weak. *HST* STIS spectra of PHL 1811 reveal a very blue continuum with little evidence for absorption or scattering intrinsic to the quasar. High-ionization lines are very weak; C IV has an equivalent width of only ~5Å . Neither forbidden nor semiforbidden emission lines were detected. Fe II is the dominant line emission in the UV. The Fe II and Fe III continuum has an unusual shape compared with the average spectrum from the SDSS narrow-line quasars. They infer that this is a result of a relatively high ionization state in the iron that may be a result of pumping by Lyα. Unusual low-ionization lines, including Na ID and Ca II H & K are present. They infer that the unusual emission line properties are a direct consequence of the soft continuum. They propose that these properties are a consequence of high accretion rate, which powers the UV emission from an optically thick accretion disk, while suppressing the formation of a hot corona.

Leighly, as part of a collaboration led by Ed Moran (Wesleyan University) performed time series analysis on *Chandra* data from the low-luminosity Seyfert 1 galaxy NGC 4395. She found strong evidence for detection of a QPO with period of ~400 s; the estimated global significance of this result is 99.95%. When compared with black hole binaries and the results of analysis of long *EUVE* light curves from three Seyferts, a remarkable correlation with luminosity was found, such that $L=P^{2/3}$. OU undergraduate, Jiehae Choi, is supporting this work by measuring the break frequency in the *ASCA* long observation of NGC 4395.

Leighly began analysis of *FUSE* spectra of a sample of soft X-ray selected AGN, in collaboration with OU graduate student D. Casebeer and D. Grupe, of Ohio State University. The goal of the observations was to investigate the role of the spectral energy distribution on the flux and profile of the O VI emission line. The sample targets were chosen from the Rosat soft X-ray selected AGN sample. This sample has several advantages for O VI line studies: these AGN have little X-ray absorption and are thus unlikely to be intrinsically reddened, a uniform X-ray selection allows an investigation of the breadth of the SED distribution, a range of spectral classes is represented, and a large amount of multiwavelength information has been compiled already. Data for sixteen objects were drawn from the archive, and data from another fifteen were obtained as part of a Cycle 4 survey proposal. Preliminary analysis reveals an anticorrelation between α_{fx}, the point-to-point slope defined between the continuum under the O VI line at 1034Å and 1 keV, and the 1 keV luminosity obtained from *ROSAT* All Sky Survey data. The correlation is quite strong, even though the epochs of the FUV and X-ray observations differ by more than 10 years. In addition, the correlation between α_{fx} and the luminosity is much stronger than that between α_{fx} and either the black hole mass, or the accretion rate.

OU postdoc, Chiho Matsumoto, Leighly, OU graduate students Aida Nava and Larry Maddox completed a paper on an *XMM-Newton* observation of the bright Seyfert 2 galaxy NGC 6300. They found that the X-ray spectrum of the nucleus consists 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 1.83 ± 0.08, attenuated by a Compton-thin absorber ($N_{\rm H}\simeq 2.2\times 10^{23}$ cm^{-2}). A narrow iron line is detected at $6.43^{+0.01}_{-0.02}$ keV width, with an equivalent width of ~150 eV; the line velocity width is marginally resolved to be $\sigma\sim 60$ eV. The soft emission can be modeled as a power-law, and may be emission scattered by surrounding plasma. Rapid and high amplitude variability is observed in the hard X-ray band, whereas both the iron line and the soft emission show no significant variability. They suggest that the nucleus has experienced an overall long-term trend of decreasing hard X-ray intensity on time scale of years.

OU graduate student, Darrin Casebeer, in collaboration with Baron, Branch and Leighly, continues to study iron low-ionization broad absorption line (FeLOBAL) active galactic nuclei, objects that are characterized by low-ionization emission and blue-shifted absorption lines. Some of these objects have features consistent with outflows such as stellar winds or supernovae. Casebeer and collaborators are working on an alternative to the canonical (very parameterized) model for absorption and emission lines for FeLoBALs. Their model consists of a spherically symmetric expanding ball of gas. An advantage of their model is that they use a single line forming region and model the absorption and emission lines simultaneously. In addition, the model includes only a handful of observable parameters such as luminosity and velocity structure. They are using the the stellar atmospheres code PHOENIX to model the spectra. PHOENIX is a generalized NLTE stellar atmosphere code, which is used to calculate spectra of stars across the HR-diagram, as well as novae, and supernovae. PHOENIX self-consistently calculates the radiation field and the NLTE level populations including all special relativistic effects. PHOENIX includes an enormous database of line transitions and up-to-date cross sections for atoms and molecules. Recently PHOENIX has incorporated data from the CHIANTI and APED databases.

3.6 Cosmology

Wang and Mukherjee studied model-independent constraints on dark energy density from flux-averaging analysis of type Ia supernova (SN Ia) data. They reconstruct the dark energy density $\rho_X(z)$ as a free function from current SN Ia data (Tonry *et al.* 2003; Barris *et al.* 2003; Knop *et al.* 2003), together with the Cosmic Microwave Background (CMB) shift parameter from CMB data (WMAP, CBI, and ACBAR), and the large scale structure (LSS) growth factor from 2dF galaxy survey data. They parametrize $\rho_X(z)$ as a continuous function, given by interpolating its amplitudes at equally spaced z values in the redshift range covered by SN Ia data, and a constant at larger z (where $\rho_X(z)$ is only weakly constrained by CMB data). They assume a flat universe, and use the Markov Chain Monte Carlo (MCMC) technique in their analysis. They find that the dark energy density $\rho_X(z)$ is constant for $0 \lesssim z \lesssim 0.5$ and increases with redshift z for $0.5 \lesssim z \lesssim 1$ at 68.3% confidence level, but is consistent with a constant at 95% confidence level. For comparison, they also give constraints on a constant equation of state for the dark energy. Flux-averaging of SN Ia data is required to yield cosmological parameter constraints that are free of the bias induced by weak gravitational lensing. Wang and Mukherjee set up a consistent framework for flux-averaging analysis of SN Ia data, based on Wang (2000). They find that flux-averaging of SN Ia data leads to slightly lower Ω_m and smaller time-variation in $\rho_X(z)$. This suggests that a significant increase in the number of SNe Ia from deep SN surveys on a dedicated telescope is needed to place a robust constraint on the time-dependence of the dark energy density.

Wang and Tegmark derived new dark energy constraints from supernovae, microwave background and galaxy clustering data. Using the spectacular new high redshift supernova observations from the *HST*/GOODS program and previous supernova, CMB and galaxy clustering data, they make the most accurate measurements to date of the dark energy density ρ_X as a function of cosmic time, constraining it in a rather model-independent way, assuming a flat universe. They find that Einstein's vanilla scenario where $\rho_X(z)$ is constant remains consistent with these new tight constraints, and that a Big Crunch or Big Rip is more than 50 gigayears away for a broader class of models allowing such cataclysmic events. They discuss popular pitfalls and hidden priors: parametrizing the equation-of-state $w_X(z)$ assumes positive dark energy density and no Big Crunch, and the popular parametrization $w_X(z) = w_0 + w_0' z$ has nominally strong constraints from CMB merely because $w_0' > 0$ implies an unphysical exponential blow-up $\rho_X \sim e^{3w_0' z}$.

Wang, Kostov, Freese, Frieman, & Gondolo explored probing the evolution of the dark energy density with future supernova surveys. The time dependence of the dark energy density can be an important clue to the nature of dark energy in the universe. Wang *et al.* show that future supernova data from dedicated telescopes (such as SNAP), when combined with data of nearby supernovae, can be used to determine how the dark energy density $\rho_X(z)$ depends on redshift, if $\rho_X(z)$ is not too close to a constant. For quantitative comparison, they have done an extensive study of a number of dark energy models. Based on these models they have simulated data sets in order to show that one can indeed reconstruct the correct sign of the time dependence of the dark energy density, outside of a degeneracy region centered on $1 + w_0 = -w_1 z_{max}/3$ (where z_{max} is the maximum redshift of the survey, e.g., $z_{max} = 1.7$ for SNAP). They emphasize that, given the same data, one can obtain much more information about the dark energy density directly (and its time dependence) than about its equation of state.

Wang and Freese showed that one should probe dark energy using its density instead of its equation of state. The variation of dark energy density with redshift, $\rho_X(z)$, provides a critical clue to the nature of dark energy. Since $\rho_X(z)$ depends on the dark energy equation of state $w_X(z)$ through an integral, $\rho_X(z)$ can be constrained more tightly than $w_X(z)$ given the same observational data. They demonstrate this explicitly using current type Ia supernova (SN Ia) data [the Tonry/Barris sample], together with the Cosmic Microwave Background (CMB) shift parameter from CMB data (WMAP, CBI, and ACBAR), and the large scale structure (LSS) growth factor from 2dF galaxy survey data. They assume a flat universe, and use Markov Chain Monte Carlo technique in their analysis. They find that, while $w_X(z)$ extracted from current data is consistent with a cosmological constant at 68% C.L., $\rho_X(z)$ (which has far smaller uncertainties) is not. Their results clearly show the advantage of using $\rho_X(z)$, instead of $w_X(z)$, to probe dark energy.

Wang derived observational signatures of the weak lensing magnification of supernovae. Due to the deflection of light by density fluctuations along the line of sight, weak lensing is an unavoidable systematic uncertainty in the use of type Ia supernovae (SNe Ia) as cosmological distance indicators. She derived the expected weak lensing signatures of SNe Ia by convolving the intrinsic distribution in SN Ia peak luminosity with magnification distributions of point sources. She analyzed current SN Ia data, and find that weak lensing effects may have begun to set in. However, the statistics are poor because of the small number of observed SNe Ia. Future observational data will allow unambiguous detection of the weak lensing effect of SNe Ia. The observational signatures of weak lensing of SNe Ia that Wang has derived provide useful templates with which future data can be compared.

Wang, Kratochvil, Linde, & Shmakova derived current observational constraints on cosmic doomsday. In a broad class of dark energy models, the universe may collapse within a finite time t_c. Here they study a representative model of dark energy with a linear potential, $V(\phi) = V_0(1 + \alpha\phi)$. This model is the simplest doomsday model, in which the universe collapses rather quickly after it stops expanding. Observational data from type Ia supernovae (SNe Ia), cosmic microwave background anisotropy (CMB), and large scale structure (LSS) are complementary in constraining dark energy models. Using the new SN Ia data (Riess sample), the CMB data from WMAP, and the LSS data from 2dF, they find that the collapse time of the universe is $t_c > \sim 42$ (24) gigayears from today at 68% (95%) confidence.

Mukherjee and Wang examined WMAP non-Gaussianity using wavelets. They study the statistical properties of the 1st year WMAP data on different scales using the spherical mexican hat wavelet transform. Consistent with the results of Vielva *et al.* (2003) they find a deviation from Gaussianity in the form of kurtosis of wavelet coefficients on $3-4°$ scales in the southern Galactic hemisphere. This paper extends the work of Vielva *et al.* as follows. They find that the non-Gaussian signal shows up more strongly in the form of a larger than expected number of cold pixels and also in the form of scale-scale correlations amongst wavelet coefficients. They establish the robustness of the non-Gaussian signal under more wide-ranging assumptions regarding the Galactic mask applied to the data and the noise statistics. This signal is unlikely to be due to the usual quadratic term parametrized by the non-linearity parameter f_{NL}. They use the skewness of the spherical mexican hat wavelet coefficients to constrain f_{NL} with the 1st year WMAP data. Their results constrain f_{NL} to be 50 ± 80 at 68% confidence, and less than 280 at 99% confidence.

Chen, Mukherjee, Kahniashvili, Ratra, & Wang looked for cosmological Alfven waves in WMAP data. A primordial cosmological magnetic field induces and supports vorticity or Alfven waves, which in turn generate cosmic microwave background (CMB) anisotropies. A homogeneous primordial magnetic field with fixed direction induces correlations between the $a_{l-1,m}$ and $a_{l+1,m}$ multipole coefficients of the CMB temperature anisotropy field. They discuss the constraints that can be placed on the strength of such a primordial magnetic field using CMB anisotropy data from the WMAP experiment. They place 3 σ upper limits on the strength of the magnetic field of $B < 15$ nG for vector perturbation spectral index $n = -5$ and $B < 1.7$ nG for $n = -7$.

3.7 Numerical Work

Baron and long-time collaborator Peter Hauschildt (Hamburger Sternwarte) made several major improvements to the PHOENIX code, their generalized stellar atmospheres code.

In moving atmospheres, the radiative transfer equation in the co-moving frame includes the Doppler shift as a derivative with respect to wavelength. They presented two separate wavelength discretization schemes that can be used in the numerical solution of the co-moving frame radiative transfer equation. Their improved second order discretization scheme leads to significantly less numerical diffusion than the previous scheme. Due to the nature of the second order term in some extreme cases it can become numerically unstable. However the scheme can be stabilized by introducing a mixed discretization scheme. Several test calculations were studied.

Recently, with the advances in computational speed and availability there has been a growth in the number and resolution of fully 3-D hydrodynamical simulations. However, all of these simulations are purely hydrodynamical and there has been little attempt to include the effects of radiative transfer except in a purely phenomenological manner because the computational cost is too large even for modern supercomputers. While there has been an effort to develop 3-D Monte Carlo radiative transfer codes, most of these have been for static atmospheres or have employed the Sobolev approximation, which limits their applicability to studying purely geometric effects such as macroscopic mixing. Also the computational requirements of Monte Carlo methods are such that it is difficult to couple with 3-D hydrodynamics. Baron and Hauschildt presented an algorithm for calculating 1-D spherical radiative transfer in the presence of non-monotonic velocity fields in the co-moving frame. Non-monotonic velocity flows will occur in convective, and Raleigh–Taylor unstable flows, in flows with multiple shocks, and in pulsationally unstable stars such as Mira and Cepheids. This is a first step to developing fully 3-D radiative transfer than can be coupled with hydrodynamics.

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