Lawrence Livermore National Laboratory

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1. INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL) is operated by the University of California (UC) under U.S. Department of Energy Contract No. W-7405-ENG-48. The primary missions of the Laboratory involve national defense and energy problems; in addition, basic research in a number of areas is supported full time. Research in astrophysics is carried out in two closely affiliated groups- the Institute of Geophysics and Planetary Physics and V-Division within the Physics and Space Technology Directorate- and on a part-time basis by about 22 other scientists, who have additional responsibilities in the large LLNL programs.

Since 1983, the LLNL branch of the University of California's Institute of Geophysics and Planetary Physics (IGPP) has acted as the focus of most astrophysics activities at LLNL. C. Alcock is the Director of the LLNL branch of IGPP, which is organized into two centers led by Kem Cook (Astrophysics) and F. Ryerson (Geosciences). The goals of the IGPP branch at LLNL are to make available to UC researchers some of LLNL's unique facilities and expertise, and to provide a forum for seminars, workshops, etc. This year IGPP awarded small research grants totaling more than $446,000 to UC campus faculty and staff members, enabling 21 collaborative projects.

The senior staff at the Astrophysics Center at IGPP consists of C. Alcock, K. Cook, C. Max, and W. van Breugel. In addition, there are several full-time postdoctoral fellows and researchers: M. Brotherton, S. Gibbard, M. Gregg, S. Laurent-Muehleisen, B. Macintosh, S. Marshall, D. Minniti, E. Moran, A. Stanford, H. Tran, and a large number of faculty and student visitors from the UC campuses. Among these, R. Becker (UC Davis) spends a considerable portion of his time in the IGPP.

The Physics Department at LLNL has a strong interest in atomic, molecular, and plasma physics, and considerable theoretical and experimental expertise in these areas. The Astrophysics Group has been established in V-Division of the Physics and Space Technology Directorate in order to channel LLNL expertise in ultraviolet, X-ray, and gamma-ray instrumentation, as well as large-scale computing, into astrophysics applications. The Astrophysics Group is a collaborative venture with UC campus scientists, and is presently developing astronomical instruments for X-ray spectroscopy, gamma-ray spectroscopy and imaging, X-ray polarimetry, and multi-object optical spectroscopy. The Astrophysics Group is also involved in a variety of astrophysical investigations including astronomical observations, theoretical modeling, and laboratory measurements. LLNL physicists J. Bixler, K. Cook, D. Dearborn, M. Frank, W. Goldstein, S. Labov, D. Liedahl, C. Mauche, C. Mears, H. Park, E. Wishnow, R. Wurtz and K. Ziock make up the core of the Astrophysics Group. In addition, the Astrophysics Group includes several postdoctoral fellows and graduate students who work on astrophysics related projects.

2. RESEARCH

2.1 Dark Matter

C. Alcock, K. Cook, S. Marshall, and D. Minniti (LLNL) are collaborating with A. Becker, M. Pratt, and C. Stubbs (U Washington); K. Griest and M. Lehner (UC San Diego); D. Bennett (Notre Dame); W. Sutherland (Oxford); P. Quinn (ESO); and R. Allsman, T. Axelrod, K. Freeman, B. Peterson, and A. Rodgers (Mt. Stromlo and Siding Spring Obs.) on a search for dark matter in the galactic halo. Specifically, they are searching for evidence that galactic dark matter is made up of brown dwarfs and related objects, now known collectively as MACHOs (MAssive Compact Halo Objects). The signature of these objects is the rare amplification of background stars by the gravitational lens effect. In order to search for this signature, the 1.3-m ‘‘Great Melbourne Telescope’’ at Mt. Stromlo has been rebuilt and brought into operation. Two cameras, each containing four 2048*2048 CCDs, are used at prime focus; a dichroic beamsplitter allows imaging simultaneously in a red and a blue-green passband. The CCDs are read out through a 16-channel system and the data are immediately passed into the computer system, where reductions are performed, and the images and reduced photometry are automatically archived. The system has been operating for six years, and $>$65,000 images of the Large and Small Magellanic Clouds, and the galactic bulge, have been taken. Preliminary reductions of some of these data have yielded $\sim$200 microlensing events. The estimated event rate toward the Large Magellanic Cloud is higher than can be accounted for by any previously known population of objects. The estimated event rate toward the galactic bulge is significantly higher than upper limits that were previously calculated using standard models for the galaxy.

The Macho Project now routinely detects microlensing events early in their history. ‘‘Alerts’’ are posted at http://darkstar.astro.washington.edu/ and may be followed up at observatories throughout the southern hemisphere (or at low northern latitudes for bulge events). Approximately 200 alerts have been posted. The Macho Project observes events in follow-up mode from CTIO (where 13% of the observing time on the 36‘‘ telescope is used for this purpose), and has obtained additional data in follow-up mode with other southern telescopes.

The results of a comprehensive analysis of two years of observations of 9 million stars indicate that a significant fraction (20%-100%) of the dark matter in the Milky Way is in the form of Machos, with typical mass $\sim 0.5 M_{\odot}$.

The MACHO Project sadly notes the death of Prof. A. Rodgers, a founding member of the science team.

2.2 Active Galactic Nuclei and Quasars

S. A. Laurent-Muehleisen continued her work on the identification and study of BL Lacertae Objects. In collaboration with R. I. Kollgaard (Fermi Lab), E. D. Feigelson (Penn State), and W. Brinkmann (Max Planck Inst. for Extraterrestrische Physik, Garching, Germany), and based on a correlation of the 1987 Green Bank and 1990 Rosat All-Sky Survey catalogs, she has constructed a sample of 118 BL Lacs, the largest sample ever created from one survey. These BL Lacs have been shown to exhibit properties intermediate between the previously disparate subclasses of X-ray- and radio-selected BL Lacs (XBLs and RBLs, respectively). Because this sample bridges the gap between RBLs and XBLs, it has provided useful constraints on the orientation-based unified scheme. Followup work of the parsec-scale radio structure and optical polarization properties continue in collaboration with D. C. Gabuzda (Lebedev Inst.) and P. Smith (NOAO).

S. A. Laurent-Muehleisen has worked with R. H. Becker (UCD) and M. D. Gregg (UCD) on the identification of quasars in the VLA's FIRST (Faint Images of the Radio Sky at Twenty centimeters) survey. The survey has produced a sample of over 500 radio-selected quasars, many of which bridge the gap between radio-loud and -quiet objects. With M. Brotherton, she is pursuing programs to characterize the radio and optical characteristics of these ''radio-intermediate'' quasars and to evaluate the hypothesis that they are relativistically beamed versions of radio-quiet quasars. In addition, Dr. Laurent-Muehleisen has begun a study of the multiwavelength properties of BL Lacs, which have been serendipitously discovered during the FIRST quasar search. Also, in collaboration with R. I. Kollgaard and W. Brinkmann, she has begun a systematic program to spectroscopically identify FIRST sources with X-ray counterparts in the Rosat All-Sky Survey. To date, many quasars, Seyfert and radio galaxies have been found in addition to some BL Lacs and nearby early type galaxies.

W. van Breugel, in collaboration with A. Dey (JHU), W. Vacca (IfA, UH), and R. Antonucci (UCSB) continued his investigations of the origin of the extended (up to 60 kpc), radio-aligned, restframe UV continua in high redshift radio galaxies using the Keck spectropolarimeter. Extremely deep (9 hrs) observations were made of one of the most distant radio galaxies, 4C41.17 at $z=3.800$. The observations showed that the aligned UV continuum was not polarized but instead showed absorption and P-Cygni-like features that are similar to those detected in the recently discovered field galaxies at $z\sim3$ by Steidel and collaborators. HST images showed that the UV light is clumpy and aligned with the radio source, downstream from a bright radio knot, which is the probable location of a strong shock. These combined results suggest that the star formation has been induced by the radio source as it propagates through the dense gaseous medium of the forming galaxy.

W. van Breugel, in collaboration with graduate student C. De Breuck (Leiden Observatory and IGPP/LLNL), H. Röttgering, and G. Miley (Leiden Observatory, The Netherlands) is continuing his search for extremely high redshift radio galaxies using the FIRST 1.4-GHz radio survey, which is being conducted at IGPP by R. Becker (UCD); the NRAO NVSS 1.4-GHz radio survey by J. Condon (NRAO) and collaborators; and a complementary survey at low radio frequencies (WENSS at 365 MHz), which is underway at Leiden Observatory. The objects are selected using a very steep radio spectrum criterion. This method has proven to be very efficient during observations at Lick Observatory in the past year, resulting in the discovery of more than a dozen $z>2$ radio galaxies, including two with $z>3$, and one at z = 4.13 (the highest redshift radio galaxy in the southern hemisphere). This work is the basis for Mr. De Breuck's thesis and provides the basic sample for detailed studies of galaxy formation and the origin and evolution of galaxy/quasar activity using the Hubble Space Telescope and the Keck 10m telescope.

W. van Breugel, in collaboration with A. Stanford (IGPP), H. Spinrad, D. Stern and J. Graham (UCB), has completed a near-IR study of very high redshift radio galaxies with the near-IR camera (NIRC) at the Keck telescope. The observations showed strong morphological evolution at rest-frame optical wavelengths between $2<z<4.4$. At the highest redshifts, $z>3$, the rest–frame optical morphologies display large scale ($\sim 50 kpc$) low surface brightness emission with occasionally bright elongated features aligned with the radio structure. These morphologies change dramatically at $2<z<3$ where the HzRGs have smooth, compact structures without bright, radio-aligned features in the rest-frame optical. Several of these lower redshift objects have elliptical shapes, de Vaucouleurs surface brightness profiles, and half-light radii similar to those of dynamically-relaxed elliptical galaxies in the present epoch. A comparison with present-epoch massive ellipticals shows that the $2<z<3$ HzRGs are 1-2 magnitudes brighter at rest frame V, in agreement with the expected effects of passive luminosity evolution. Together with the spectroscopic evidence for massive star formation in one HzRG (4C 41.17 at $z=3.800$) and the knotty rest-frame UV structures seen by HST in many HzRGs, this provides strong support for hierarchical galaxy formation models in which massive ellipticals form through the merging of sub-galactic stellar systems.

M. S. Brotherton has continued work began at the University of Texas with B. J. Wills on the intermediate-line region (ILR) of QSOs. In order to test the hypothesis that the ILR can be identified with an inner extension of the narrow-line region (NLR) rather than part of the broad-line region (BLR), Brotherton obtained near-infrared spectra of the $H\beta$-[O III] region for 32 QSOs studied by Brotherton *et al.* and Steidel and Sargent. NLR emission is significantly correlated with ILR emission, supporting the hypothesis. Furthermore, the strength of optical Fe II emission is inversely correlated with the strength of ILR and NLR emission. These results show that the first eigenvectors of the principal component analyses of Francis *et al.* and Boroson and Green are the same, hence relating many QSO properties, including radio and X- ray emission. Variation along this sequence may constitute a ''fundamental plane'' for QSOs. Brotherton has explored one possible explanation: the percentage of optically thick BLR clouds. BLR models with a modest covering factor can cover typical biconical geometries, so that optically thick BLR clouds can simultaneously produce Fe II emission and shadow more distant clouds, extinguishing the continuum seen by the ILR and NLR. When the BLR clouds are mostly optically thin, Fe II emission is minimal and the more distant ILR and NLR see more ionizing photons and emit more strongly.

M. S. Brotherton, in collaboration with H. D. Tran, W. van Breugel, A. Dey (NOAO), and R. R. J. Antonucci (UCSB), obtained Keck spectropolarimetry of two rare low-ionization broad absorption line (BAL) QSOs, FIRST J084044.5 +363328 and FIRST J155633.8 +351758, which also exhibit narrow absorption lines from metastable excited levels of Fe II (''Iron Lo-BALs''). These QSOs were discovered in optical followups to a deep radio survey; FIRST J155633.8+351758 is radio-loud, the first BAL QSO so identified. FIRST J084044.5 +363328 is highly polarized and exhibits many features found in other BAL QSOs, and the polarization and its position angle vary in a complicated manner across the metastable Fe II absorption lines, suggesting that more than one mechanism is at work, or that the system geometry is complex. FIRST J155633.8 +351758 may be the most highly polarized BAL QSO known, and exhibits other unusual polarization properties compared to other highly polarized BAL QSOs. The current available data cannot yet discriminate among the possible lines of sight to BAL QSOs (edge-on, pole-on, or random), but may do so with the addition of scheduled VLBA observations in collaboration with S. A. Laurent-Muehleisen, R. H. Becker (UCD), and M. Gregg.

M. S. Brotherton, in collaboration with B. J. Wills (U Texas), A. Dey (NOAO), W. van Breugel, and R. R. J. Antonucci (UCSB), has obtained Keck spectropolarimetry of the highly polarized radio-loud loud QSO 3CR 68.1 ($z=1.228$, $V=19$). The data show that the polarization increases from 5% in the red to $>10\%$ in the blue, that the broad emission lines are polarized the same as the continuum, and that the narrow emission lines are not significantly polarized. They have also discovered a Ca II K absorption feature probably associated with stars in the QSO's host galaxy. Taking into account 3CR 68.1's other unusual properties, such as its extremely red color and its extreme lobe dominance, the data suggest that 3CR 68.1 is representative of a rare class of highly polarized quasars that are neither blazars nor broad-absorption-line QSOs. 3CR 68.1 is probably viewed along a line of sight skimming a partially obscuring dusty torus, and that reddened and scattered quasar light of constant polarization is diluted by even more dust-reddened direct quasar light from the nucleus.

M. S. Brotherton, with the assistance of UC Davis summer student A. de la Cerda, has undertaken a program of near-infrared imaging using Lick Observatory's 3-m Shane telescope in order to investigate the relationships between QSO host galaxies and their radio properties. While accretion onto a supermassive black hole probably powers both radio-quiet and radio-loud QSOs, which look similar at optical wavelengths, there is no accepted paradigm to explain strong radio jets in one class but not the other. The sample under investigation is a carefully selected set of eight QSO triplets, each including a radio-quiet QSO, a core-dominant radio-loud QSO, and a lobe-dominant radio-loud QSO (core dominance indicates jet axis orientation). These observations will test the claim that radio-quiet QSOs inhabit spiral galaxies while radio-loud QSOs inhabit elliptical galaxies; this claim is suspect because of luminosity biases.

H.D. Tran collaborated with P. Ogle (Caltech), M. Cohen (Caltech), J. Miller (Lick), R. Fosbury (ESO), and R. Goodrich (Keck) to discover scattered broad Balmer emission lines in the spectrum of the powerful radio galaxy Cygnus A, using the Keck II telescope. Imaging polarimetry also shows a double fan of polarization vectors that are centrosymmetric relative to the nucleus, and coincident with the ionization cone seen in the HST images. These provide strong support for the hypothesis that narrow-line radio galaxies contain quasar nuclei, which are obscured from direct view and oriented at a large inclination angle.

H.D. Tran, in collaboration with M. Cohen and P. Ogle (Caltech), R. Goodrich (Keck), and S. di Serego Alighieri (Arcetri Observatory) continued his study of both distant and nearby radio galaxies using imaging and spectropolarimetry at Keck. Imaging polarimetry of 3C 265, 3C 277.2, and 3C 324 reveals a rough double-fan morphology of the polarized light coincident with the extended aligned UV continuum emissions, with the position angle perpendicular to the radial structure of the extensions, and with the degree of polarization increasing with radius away from the nucleus. A broad Mg II $\lambda 2800$ emission line is detected in the total and polarized flux spectra of 3C 265 and 3C 277.2. Scattering of radiation from an obscured quasar source appears to be the preferred interpretation over jet-induced star formation for explaining the alignment effect in these distant radio galaxies, with electron scattering playing a significant role. In the more nearby radio galaxies, broad polarized $H\alpha$ is detected in the narrow-line radio galaxies 3C 33, 3C 135, and 3C 195. These results strengthen the view that powerful radio galaxies would be called quasars if viewed from a proper direction.

In collaboration with W. van Breugel, M. Brotherton, and R. Antonucci (UCSB), H.D. Tran began a project to use the Keck spectropolarimeter to search for hidden quasars in the newly discovered, low-ionization ultraluminous IRAS galaxies (ULIRGs) and post-starburst AGN (PSAGN). The low-ionization ULIRGs are discovered from a positional correlation of the IRAS faint source catalog and the FIRST survey catalog. Unlike other ULIRGs of similar radio/far IR luminosities, such as F10214, F15307, and P091047, these objects do not exhibit strong high-ionization lines, but instead appear much like starbursts. Their power source may be primarily from a starburst, but they could also contain quasars for which strong emission lines are obscured. PSAGNs are intermediate type objects between starbursts and quasars, and could represent an important evolutionary link between them.

Graduate student C. De Breuck (Leiden Observatory), in collaboration with H. Tran, M. Brotherton, and W. van Breugel, reported the discovery of a highly polarized red quasar WN J0717+4611 ($z=1.46$) selected from a sample of ultra steep spectrum radio sources. Spectropolarimetric observations obtained with the Keck telescope showed a wavelength-independent polarization of 15% in both the continuum and emission lines. The spectrum resembled that of a compact steep spectrum (CSS) radio source, and showed a broad component of the Mg II line, indicating the quasar nature of the object.

2.3 Gamma Ray Bursts

H. S. Park has been working on a search experiment called LOTIS (Livermore Optical Transient Imaging System), which attempts to detect simultaneous optical counterparts of gamma-ray bursts. In collaboration with NASA/Goddard, Marshall Space Flight Centers, Clemson University, UC Berkeley, and UC San Diego, she constructed a wide-field-of-view (17.6×17.6°) and automatic telescope that rapidly ($<5 sec$) responds to gamma-ray bursts detected by orbiting satellites such as CGRO and Beppo/SAX. The origin and nature of gamma-ray bursts remain unresolved despite much observation and theoretical effort. Measurement of optical emission simultaneous with the gamma-ray emission will provide crucial clues in understanding gamma-ray burst physics. LOTIS has been operating since October 1996 and has responded to many burst triggers by Gamma-ray burst Coordinate Network. The best available upper limit on simultaneous optical flux has been produced by LOTIS. Park is now constructing a second-generation LOTIS, which is an automated 0.6-meter aperture telescope system that is dedicated to the gamma-ray burst study. The expected sensitivity of this system is $M_V \sim 19$, and it will be operational by spring of 1998. While waiting for gamma-ray burst triggers, LOTIS surveys the night sky; this data will be used to create a database for detecting optical transient objects.

S. Marshall is a member of the ROTSE (Robotic Optical Transient Search Experiment) collaboration, which is constructing two independent detector systems to search for gamma-ray burst optical counterparts immediately following a trigger signal from satellite instruments such as BATSE. The first phase of this project, ROTSE-I, comprises a 2×2 array of wide-field cameras with 200 mm, f/1.8, telephoto lenses on a fast-slewing mount. The 16-degree field of view will have a limiting visual magnitude of 15 for nominal 5-second images. This system is installed at the Los Alamos National Laboratory at a temporary site east of the LAMPF accelerator. Automated operation will begin in early 1998. The second phase (ROTSE-II) consists of two 0.45-m aperture telescopes with f/1.9 optics imaging to a cooled CCD camera. For 10-second exposures, the 2-degree field of view will be used to scan the BATSE error box in 16 minutes to a limiting visual magnitude of 18. More accurate initial coordinates will permit faster scans or deeper images. Delivery of the first ROTSE-II telescope is scheduled for November 1997.

2.4 External Galaxies

With M. V. Alonso and collaborators, D. Minniti continued working on the globular cluster systems of distant galaxies. Based on optical HST and ground-based IR photometry, they found a wide variety of ages among the globular clusters of the recent merger galaxy NGC 5128.

With A. Zijlstra, D. Minniti discovered a faint Pop II halo in the dwarf irregular galaxy WLM, using deep optical photometry. They also studied the planetary nebulae of the Sgr dwarf galaxy with J. Walsh, and are pursuing more distant irregulars.

2.5 The Milky Way

D. Minniti finished a large scale spectroscopic survey of bulge giants in two fields, unveiling the dependence of bulge kinematics on metallicity. Based on these data, he presented a formation scenario for the Galactic bulge.

With the MACHO Collaboration, D. Minniti studied the RR Lyrae population in the Galactic bulge, discovering a few RR Lyrae members of the Sgr dwarf galaxy. These RR Lyrae were also used to study the structure of the inner Milky Way. With A. Gould, a new determination of the extinction towards Baade's window was obtained. A large sample of $\delta Scuti$ stars was identified in the MACHO bulge database, stars that were used to study the structure of the bulge.

With G. Meylan and collaborators, D. Minniti is using HST images to measure internal proper motions in the globular cluster 47 Tuc. They discovered an unusual dwarf nova in the core of this cluster. With R. Mendez, D. Minniti has explored the faint stellar population of the Galactic halo using the Hubble Deep Field. With M. Gregg, D. Minniti defined a photometric system for STIS at the HST, which allows deep imaging beyond that possible by the Hubble Deep Field.

With J. Claria and collaborators, D. Minniti continued studying open and globular clusters. They measured accurate compositions for individual stars in seven of the most metal-poor clusters in our galaxy, as well as for three obscured disk open clusters.

S. Labov and M. A. Lindeman (UC Davis/LLNL) are studying the distribution of cold and hot gas in the local interstellar medium (ISM). X-ray, optical, infrared, and radio observations are being used to understand the spatial structure of these different phases of the ISM. Measurements of soft X-ray shadows cast by clumps of neutral material provide a direct method of determining the spatial distribution of the hot gas responsible for the soft X-ray background. The observed contrast of an X-ray shadow depends on the density and size of the cool-absorbing cloud, and on the amount of foreground and background soft-X-ray-emitting gas. Dramatic examples of this shadowing effect have been observed by the ROSAT X-ray telescope and position sensitive proportional counter (PSPC). Optical observations are currently underway to determine the distance to several different clouds that cast shadows in the soft X-ray images.

2.6 Stellar High Energy Astrophysics

C. Mauche used data obtained by the Extreme Ultraviolet Explorer satellite to determine the EUV spectrum of the quasi-coherent oscillations of the dwarf nova SS Cygni. It was found that the spectrum of the oscillations is neither blue nor red nor grey relative to the net (oscillation-phase integrated) spectrum, and hence that the oscillations cannot be explained by variations in the effective temperature, absorbing column density, or effective area, respectively. Instead, it was found that the amplitude of the oscillations is high at the relative maxima of the net spectrum, and low to zero at the relative minima of the net spectrum. This behavior can be explained by either variations in the emission line flux atop a constant underlying continuum, or variations in the optical depth of a haze of overlapping absorption lines, in which case the optical depths must be $\tau < 1$ at the relative maxima of the net spectrum, and $\tau > 1$ at the relative minima.

C. Mauche, Y. P. Lee (STScI), and T. R. Kallman (GSFC) performed a statistical analysis of the ultraviolet emission lines of cataclysmic variables (CVs) based on $\sim$430 ultraviolet spectra of 20 sources extracted from the International Ultraviolet Explorer Uniform Low Dispersion Archive. These spectra were used to measure the emission line fluxes of N V, Si IV, C IV, and He II and to construct diagnostic flux ratio diagrams. The authors investigated the flux ratio parameter space populated by individual CVs and by various CV subclasses (e.g., AM Her stars, DQ Her stars, dwarf novae, nova-like variables). For most systems, these ratios are clustered within a range of $\sim$1 decade for $log(SiIV/CIV) \sim -0.5$ and $log(HeII/CIV) \sim -1.0$ and $\sim$1.5 decades for $log(NV/CIV) \sim -0.25$. These ratios were compared to photoionization and collisional ionization models to constrain the excitation mechanism and the physical conditions of the line-emitting gas. It was found that the collisional models do the poorest job of reproducing the data. The photoionization models reproduce the $SiIV/CIV$ line ratios for some shapes of the ionizing spectrum, but the predicted NV/CIV line ratios are simultaneously too low by typically $\sim$0.5 decades. Worse, for no parameters are any of the models able to reproduce the observed $HeII/CIV$ line ratios; this ratio is far too small in the collisional and scattering models and too large by typically $\sim$0.5 decades in the photoionization models.

C. Mauche wrote a review article concerning EUVE, ROSAT, and ASCA observations of the boundary layer emission of nonmagnetic cataclysmic variables. EUVE spectra reveal that the effective temperature of the soft component of high accretion rate nonmagnetic CVs is kT $\sim$ 10-20 eV and that its luminosity is 0.1- 0.5 times the accretion disk luminosity. Although the EUV spectra are very complex and belie simple interpretation, the physical conditions of the boundary layer gas are constrained by emission lines of highly ionized Ne, Mg, Si, and Fe. It was argued that ROSAT and ASCA spectra of the hard component of nonmagnetic CVs are satisfactorily but only phenomenologically described by multi-temperature thermal plasmas, and that the constraints imposed on the physical conditions of this gas are limited by the relatively weak and blended lines. Finally, using SS Cyg as a case study, it was argued that significant progress in our understanding of the X- ray spectra of nonmagnetic CVs will come with future observations with XMM, AXAF, and Astro-E.

P. Vitello has continued his research on line-radiation winds from cataclysmic variable accretion disks. In collaboration with I. Shlosman (U/Kentucky) and C. Mauche, he has obtained high resolution HST spectra of the cataclysmic variable V347 Puppis. The spectral data covers several orbits of the system and included time-resolved spectra during and out of the eclipse. Preliminary analysis of the spectra show complex periodic profile variations in the CIV, NV, and SiIV resonance lines. Modeling using a kinematic model for the wind from the accretion disk shows that there may be a non-axisymmetric wind flowing from the disk. The kinematic wind model was extended to treat the ionization balance in the wind of silicon. This will allow for multi-line simulations of the wind, which will remove many of the constraints of the kinetic wind model.

D.A. Liedahl is involved with the spectroscopic analysis of ASCA and EUVE data of stars and compact X-ray sources. Current research includes a collaboration with a group at Columbia University (M. Sako, F. Paerels, S. Kahn) to analyze ASCA data from the Seyfert 2 galaxies NGC 1068 and the Circinus galaxy, as well as the high-mass X-ray pulsars Vela X-1 and Centaurus X-3. In addition to deriving source-related information, this research also aims to expose and remedy problems, at the atomic physics level, in X-ray spectral models used in data interpretation. Among the results related directly to atomic kinetics, Liedahl finds evidence that refutes suggestions that non-equilibrium ionization balance operates in the corona/transition region of the Sun (collaboration with R. Mewe and J. Kaastra at the Space Research Organization, The Netherlands). In collaboration with N. Brickhouse at Harvard-Smithsonian CfA, through a joint analysis of EUVE and ASCA spectra from the G-type binary Capella, it is found that omission in X-ray spectral models of X-ray lines originating on high principal quantum numbers has contributed to the poor agreement (i.e., the failure to achieve acceptable fit) between models and data. This finding impacts a large fraction of the ASCA archive.

R. Eastman continued his work on applying detailed hydrodynamic and radiation transport models to understanding the properties of supernovae of all spectroscopic types. Work continued on improving and extending the Expanding Photosphere Method, an important new tool for measuring the cosmic distance scale using observations of photospheric phase Type II supernovae. Eastman and collaborator S. E. Woosley (UC Santa Cruz) have devised a promising model for both Type Ib and Ic supernovae, which explains their spectroscopic differences as being due to mass loss, the non-linear dependence of oxygen shell mass on helium core mass, the oxygen shell's ability to trap the gamma-rays (which are needed to excite the helium lines seen in Type Ib supernovae), and hydrodynamical instabilities during the explosion. Eastman and collaborator P. A. Pinto (Steward Observatory) continued their work on the physics of Type Ia supernovae (SNe Ia) light curves and spectra. SNe Ia explosion models suggest that a number of the correlations found in the behavior of SNe Ia, such as between the maximum luminosity and subsequent rate of decline, could be evidence for variation in progenitor mass. However, due to the complicated opacity mechanisms and non-LTE conditions, radiation transport in SNe Ia remains a challenging problem and quantitatively accurate results are difficult to achieve.

H.D. Tran, in collaboration with A. Filippenko (UCB), G. Schmidt (Steward), K. Bjorkman (U/Toledo), B. Jannuzi (NOAO), and P. Smith (NOAO) completed the analysis of the spectropolarimetry of SN 1993J. With insights gained from the high S/N data, a large temporal baseline in the observations and a new correction in the interstellar polarization, they found that the intrinsic polarization of the SN had evolved from being essentially negligible near the time of the explosion on 1993 March 27.5, to a peak of about 1% in late April 1993, and started to decline by the middle of May. These results are consistent with the models published by Hoflich, and they suggest that the polarization was most likely produced by either an asymmetric helium core configuration of material and/or flux, or scattering from an asymmetric circumstellar distribution of dusty material. These data also suggest a clumpy or stratified distribution of the emitting gas in the ejecta, with emission lines of He I, Fe II, [O II] coming from an asymmetric region deeper than that producing the hydrogen lines. If the supernova had an oblate geometry, the data are consistent with a small viewing angle and with a degree of asphericity that is smaller than previously suggested.

D. Arnett and J. Kane (U/Arizona) continue to develop experiments using the NOVA laser at LLNL to answer specific questions about hydrodynamic instabilities, in particular the Rayleigh-Taylor (RT) instability, as is relevant to the evolution of core-collapse supernovae (SN). In particular, the high velocities of the core elements Ni, Co, and Fe in SN1987A are still unexplained (3000 km/s observed, versus predictions of about half that), and may have a bearing on the observed lightcurve. In collaboration with B. A. Remington and S. G. Glendinnin, the group is conducting experiments on the Nova laser to test the hydrodynamics of the supernova code PROMETHEUS. Initial experiments in two-dimensions (2D) have been successfully completed, and are described in several papers and conference proceedings. The group is now turning to the crucial question of how the instability evolution in 3D differs from that predicted in 2D. This dimensionality could hold the key to unlocking answers to some of the remaining questions surrounding SN1987A. If the velocities of RT spikes in 3D are significantly larger than 2D predictions (note, 3D star calculations are still beyond current computational capabilities), this could enhance the mixing in the exploding star and help explain the observed lightcurve from SN1987A. Furthermore, any progress in advancing our understanding of the time-dependent mixing could shed light on the mechanism by which supernovae explode at all. Initial experiments to compare RT-induced mixing in 3D versus 2D in a hydrodynamic setting similar to an exploding SN are planned for the coming year.

R. McCray (Colorado) and R. P. Drake (Michigan) are conducting experiments on the NOVA laser to benchmark astrophysical codes used to model the radiative hydrodynamics of supernova remnant (SNR) evolution. Of particular interest is the supernova remnant now developing around SN1987A. The ejecta from this supernova is on a collision course with its circumstellar ring nebula, with impact expected within 5 years. The astrophysics codes being used to predict the outcome of this extragalactic collision are being benchmarked with experiments on the Nova laser, where 1 ns (from the laser experiment) scales to 1 year for the SNR, 100 km/s to 10^4 km/s, and 100μ to 0.03 light years. The experiments are in collaboration with B. A. Remington, K. Estabrook, and S. G. Glendinning. Initial experiments were conducted in one dimension (1D), to observe ejecta plasma flowing into a low-density ambient plasma, forming a classic forward shock-reverse shock system, much like in the astrophysical SNR. These first experiments are described in a preliminary overview paper, with details given in a set of recently submitted follow-up papers. The group is now planning 2D experiments to study the Rayleigh-Taylor (RT) instability predicted to occur at the contact discontinuity between the forward and reverse shocks. Such RT-induced clumping could change the nature of the much awaited collision from a smooth, 1D sweeping up of the ring, to something more akin to ‘‘hydrodynamic bullets’’ impacting the ring, in radiative bursts or ‘‘sparkles.’’

2.7 Stellar Evolution

C. Alcock and J. Parriott (U Michigan) have estimated the loss of comets by a star undergoing mass loss on the way to becoming a white dwarf. A significant fraction of the original comets may be retained by the white dwarf, if the mass loss is not asymmetric. Comets around a white dwarf star may have observable consequences for the metal content of its atmosphere, due to the occasional infall of a comet.

P. T. Springer, K. L. Wong, C. A. Iglesias, J. H. Hammer, J. L. Porter (SNL Albuquerque), A. Toor, W. H. Goldstein, B. G. Wilson, F. J. Rogers, C. Deeney (SNL Albuquerque), D. S. Dearborn, C. Bruns, J. Emig, and R. E. Stewart continued astrophysically relevant laboratory experiments to benchmark the opacity and the radiative transfer models for cosmological standard candles, Cepheid Variable pulsation, and type Ia supernova luminosity. In FY97, we created and measured the opacity of plasmas at stellar envelopes conditions, using the 500 kJ SATURN facility at Sandia National Laboratory. In particular, the absorption properties of the M-shell, dn=0 transition arrays important for stellar pulsation instabilities were studied at high spectral resolution and compared to predictions used in Cepheid Variable modeling. Follow-on experiments in FY98 will test the atomic physics and approximations in the radiative transfer modeling for expanding plasmas that are needed to predict supernova luminosity.

The critical region in the star for pulsation instabilities occurs at temperatures of order 20 eV and at equivalent mid-Z densities of order 10-4 g/cc, when the contribution of the M-shell dn=0 absorption to the Rosseland mean opacity is maximal. At low density, the Rosseland mean opacity is very complex as it becomes sensitive to the treatment of individual lines, and the merging of lines into quasi-continua. New methods were developed to obtain LTE opacity data for plasma density 100 times lower than previous measurements. Experimental requirements include: high spectral resolution, large homogenous plasma sources, and Planckian radiation fields lasting tens of nanoseconds. The measurements provide the first direct test of the stellar envelope opacities resolving the long-standing puzzles in stellar pulsation and evolution.

2.8 Solar System

C. Alcock, K. Cook, S. Marshall (LLNL) are collaborating with I. de Pater (UC Berkeley), J. Lissauer (NASA/Ames), T. Lee and C.- Y. Wen (Academia Sinica, Taiwan), and Y.-I. Byun, W.-P. Chen, and W.-S. Tsay (National Central University, Taiwan) on the Taiwan-American Occultation Survey (TAOS). TAOS will perform a census of small objects ($>2km$) in the Kuiper Belt by searching for the brief occultations of stars by these objects. The occultations will be observed with three small telescopes to be located in the Yu Shan National Park in Taiwan. Preliminary design work has been started on the TAOS project.

K. Cook has been working with the Clementine II team, led at LLNL by A. Ledebuhr, to maximize the scientific return from the proposed Clementine II mission. This mission is an Air Force-led mission to fly-by at least two near-Earth asteroids. During one of the fly-bys, an autonomous micro-satellite will fly out to the asteroid, resulting in a high-velocity impact. A sophisticated suite of optical and infrared sensors on the mother ship will produce multi-spectral, high spatial resolution images of the asteriods and the impact. This mission should dramatically increase our knowledge of the surface morphology and mineralogy of these objects as well as providing insight into their internal structure. This mission may also afford the opportunity to do extended observations probing a variety of phenomena ranging from near-Earth objects, which spend most of their time closer to the Sun than to the Earth (Atens), to astroseismological observations of distant stars, to parallax observations of microlensing events.

2.9 Instrumentation

S. Labov, C. A. Mears, M. Frank, J. B. le Grand, H. Netel (LLNL), S. Friedrich (LBNL-LLNL), D. Chow, L. J. Hiller, M. A. Lindeman (UC Davis-LLNL), and A. T. Barfknecht (Conductus, Inc.) are developing superconducting tunnel junction (STJ) detectors for high-resolution UV and X-ray spectroscopy. These energy dispersive X-ray detectors offer spectral resolution far beyond that obtainable with semiconductor-based solid-state detectors and CCDs. When cooled to temperatures below 1 K, these STJ detectors can provide high spectral resolution with high efficiency across a wide energy range. STJ detectors can also provide high spatial resolution, which will allow spectral imaging of extended objects such as supernova remnants and hot gas in clusters of galaxies. An STJ X-ray spectrometer consists of two thin films of superconducting material that are isolated from each other by a thin barrier. An X-ray is absorbed in one film and excites millions of superconducting electrons. These excited electrons (quasiparticles) then tunnel through the thin barrier, resulting in a signal that is measured with high precision. The number of excited electrons is proportional to the X-ray energy. Resolutions of 29 eV at 6 keV, 12 eV at 1 keV, and 6 eV at 1/4 keV have been measured with STJs at LLNL. These detectors have been demonstrated to operate at more than 20,000 counts/sec. In principal, resolving powers as high as 1000 may be obtainable in the X-ray band.

B. Macintosh continues to work with the laser guide star adaptive optics program led by C. Max. In September/October 1996, this system demonstrated the first image improvement by a sodium laser guide star high-order adaptive optics system, producing near-diffraction-limited images on the Lick 3-m telescope. Using the system in natural guide star mode, Dr. Macintosh collaborated with A. Ghez, J. Graham, I. de Pater, B. Zuckerman, and E. Becklin on several science programs, focusing on brown dwarf searches, young stellar objects, and planetary science. In a parallel program of speckle imaging on the 10-m W.M. Keck telescope, a group consisting of B. Macintosh, D. Gavel, S. Gibbard, C. Max, I. de Pater, and A. Ghez obtained diffraction-limited (0.05 arcsecond resolution) images of Io (studying the volcanoes on its surface), Neptune (studying evolution of weather systems), and Titan (looking for liquid hydrocarbon ''seas'' on the surface). Dr. Macintosh also continued to partipate in brown dwarf/extrasolar planet searches using the Keck telescope, in collaboration with B. Zuckerman and E. Becklin. Although no brown dwarfs have been discovered in these searches, they provide a strong constraint on the initial mass function, and also discovered an absence of wide binary systems in the Hyades cluster.

The LLNL laser guide star adaptive optics program, led by C. Max, demonstrated the first ever successful high-order adaptive optics using a sodium laser guide star. The LLNL system is installed on the Lick Observatory 3-m Shane telescope. It is optimized for operation in the near-infrared with 36 subapertures and an LLNL-built deformable mirror. Operating with bright ($V<11$) natural guide stars, it achieves near-diffraction limited performance of 0.15 arcsecond FWHM in the K' (2.1 micron) band, at a Strehl ratio of 0.3. Several science projects in collaboration with University of California astronomers have begun using this system, including studies of young stellar objects (J. Graham, UC Berkeley, and A. Ghez, UCLA), and solar-system objects (I. de Pater, UC Berkeley).

In laser guide star mode, the system uses a 20-W pulsed dye laser installed on the 3-m telescope to produce an artificial guide star in the mesopheric sodium layer 100 km up. The guide star is typically 7-9th magnitude, bright enough to provide a reference for the adaptive optics loop. Adaptive optics operations with a sodium guide star are significantly more complex than natural guide star operations. In October 1996, the team demonstrated laser guide star adaptive optics for the first time, achieving a Strehl ratio of 0.1 at 2.1 microns. Work continues on improving the efficiency and useability of the system. Ultimately it will open up nearly the whole sky to adaptive optics observations, requiring only a tip/tilt reference star as faint as R=15 within 30 arcseconds of a science target to produce near- diffraction-limited observations. The system will be used for adaptive optics studies of active galactic nuclei, dim young stellar objects, and searches for brown dwarf companions to faint stars.

LLNL participants in this work include J. An, K. Avicola, B. Beeman, H. Bissinger, J. Brase, D. Gavel, B. Macintosh, S. Olivier, K. Waltjen, and J. Watson.

Following the successful critical design review in August 1996, implementation and testing of the hardware and software for the Keck Adaptive Optics Wavefront Controller subsystem was carried out by engineers from the AMP and AVLIS programs. The work was led by J. Brase, K. Avicola, and J. An. The baseline optical system has been set up and all the major vendor components have been received. Integration of the hardware and software will begin in October 1997. The current schedule is to deliver the subsystem to Keck for Laboratory integration and test in mid-January 1998.

H. W. Friedman has operated the laser system for generating a sodium-layer laser guide star during the past year. Several upgrades have been made to the cooling system and doubling crystal to ensure a more serviceable laser. Last fall the group successfully closed the Adaptive Optics control loop on a star using both up-link and higher order wavefront correction to obtain the first such improvement in star images. Work will continue in the coming year to improve the correction by reducing the guide star size in the mesosphere and increasing the power out of the laser.

C. Max, H. Friedman, D. Gavel, G. Erbert, and many others from the AVLIS program have been assembling the laser and beam projector for the Keck adaptive optics system. The laser will form an artificial guide star in the mesospheric sodium layer, which will function as a wavefront reference source for the 341 degree-of-freedom adaptive optics system that will be installed on the Keck 10-meter telescope next year. The laser will undergo final acceptance tests at LLNL in November and will be delivered to Keck immediately thereafter.

A group led by S. Olivier, including J. Brase, C. Carrano, D. Gavel, B. Macintosh, and C. Max, are studying the possibilities for direct detection of extrasolar planets. These techniques would use advanced adaptive optics systems to directly image the light reflected by gas-giant planets in the outer parts of other solar systems. Preliminary simulations indicate that the adaptive optics system currently being constructed for the Keck telescope should be able to see Uranus-like planets around approximately ten nearby stars. More complex issues involving PSF stability, detector characteristics, and techniques for extracting these dim planets from the bright light of their parent stars are under study.

Charles Alcock